# 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).

ABSTRACT

Run-off-the-Road (ROTR) type accidents account for a large percentage of highway fatalities nationwide. This situation has become a major concern and a high priority for engineers within transportation departments. Shoulder rumble strips are proven to be effective devices for interstate and limited access roadway systems, which hold great potential in reducing ROTR accidents. Consequently, they have become a critical and advisable subject for highway safety improvements.

Although shoulder rumble strips have been long used as an effective countermeasure [illegible] and several [illegible] documented effects in the literature, limited design guidance is available [illegible] cost-effectiveness have not been quantitatively evaluated and confirmed. [illegible] typical patterns using field tests, implementation surveys, [illegible] and statistical analysis. A model has been developed to determine the optimal pattern. [illegible] revealed that a milled pattern is superior to a rolled pattern with respect to [illegible] and sound, effectiveness, quality control and ease of construction. [illegible] is practical for new construction [illegible] existing [illegible] policy and design criteria for milled rumble strips should be [illegible] is needed to determine the degree of effectiveness.



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

## 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 Commission[2] found that ROTR accidents had risen from 48 percent in 1984 to 57 percent in 1986. Another study from Wyoming[3] 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

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 report[5] 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 study[2] 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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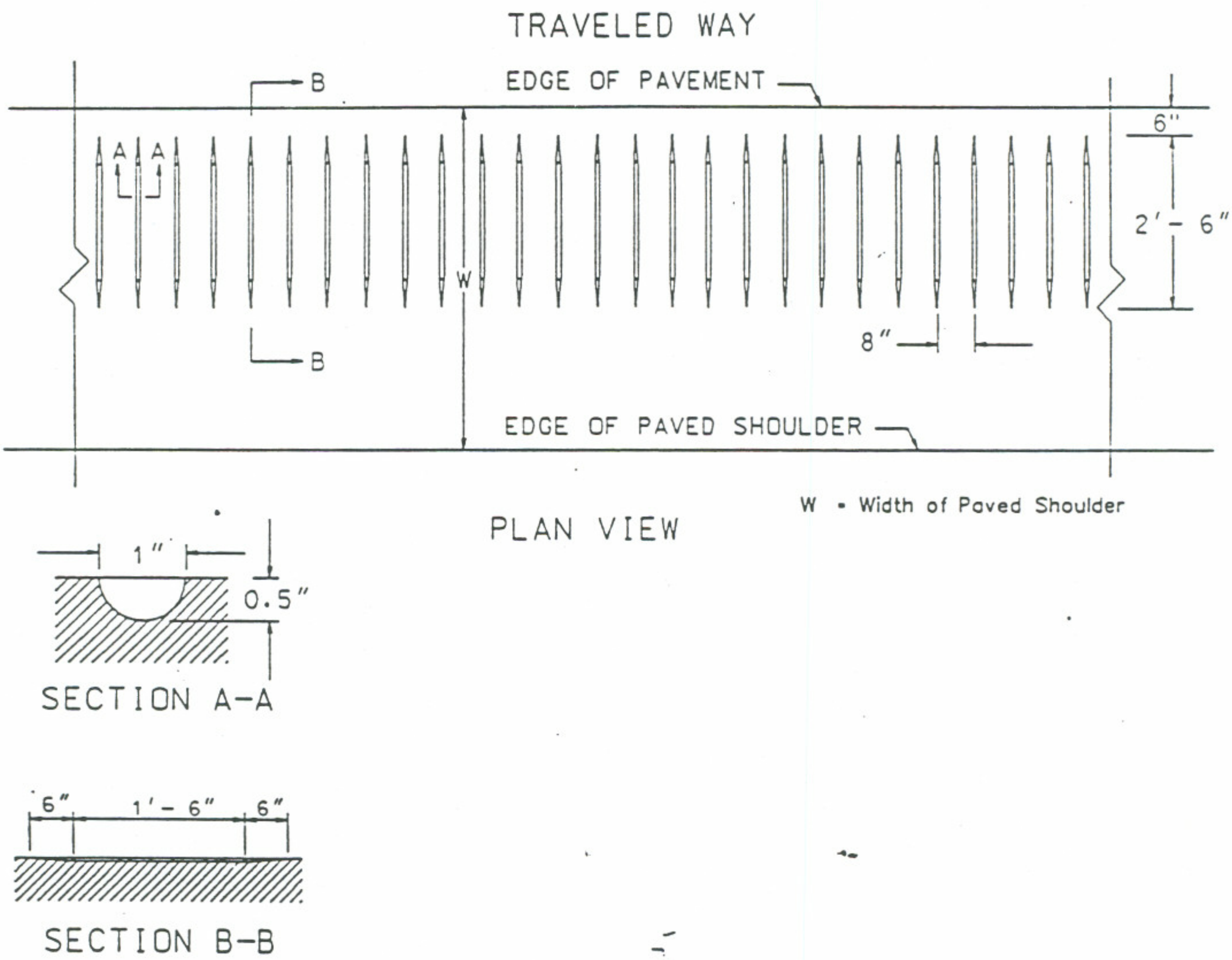


Fig. 1 Continuous rolled rumble strips

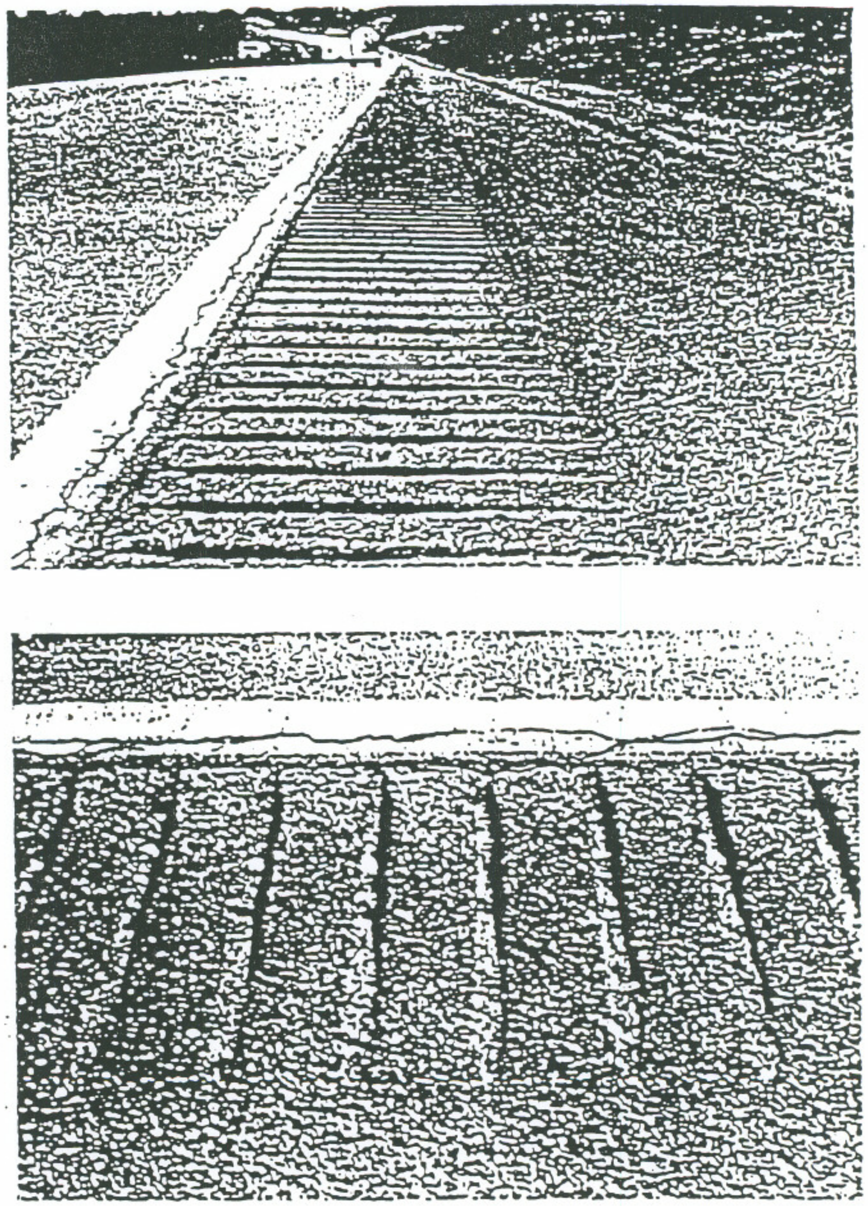

Fig. 2 Asphalt Rolled rumble strips

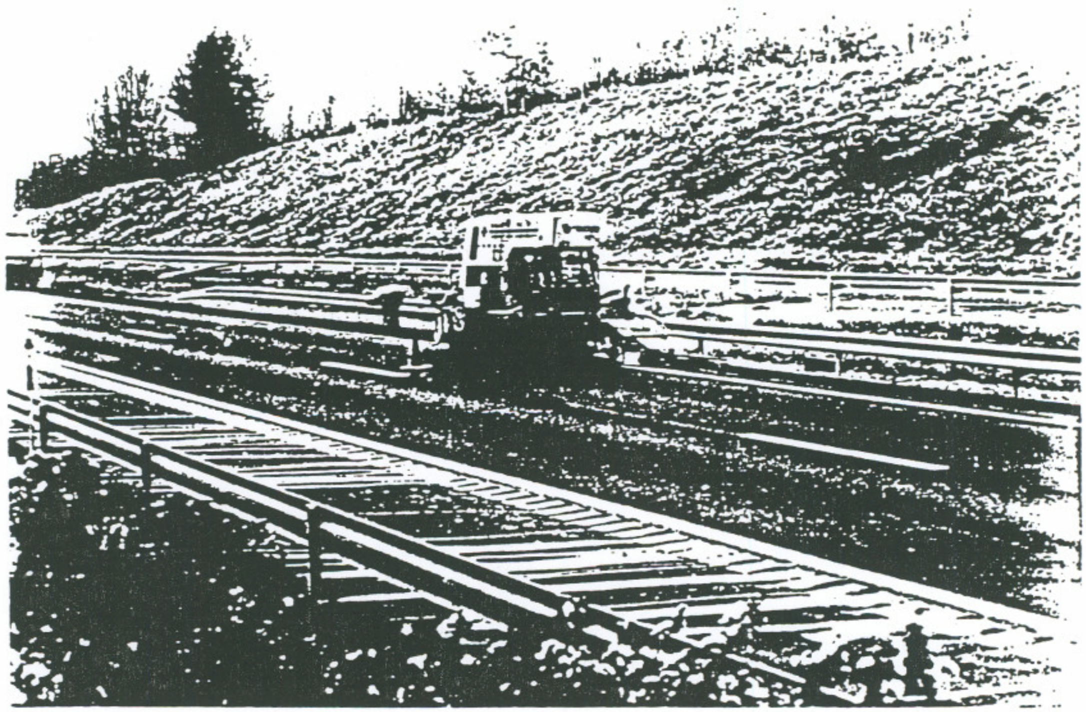

Fig. 3 Milled rumble strips and its construction machine

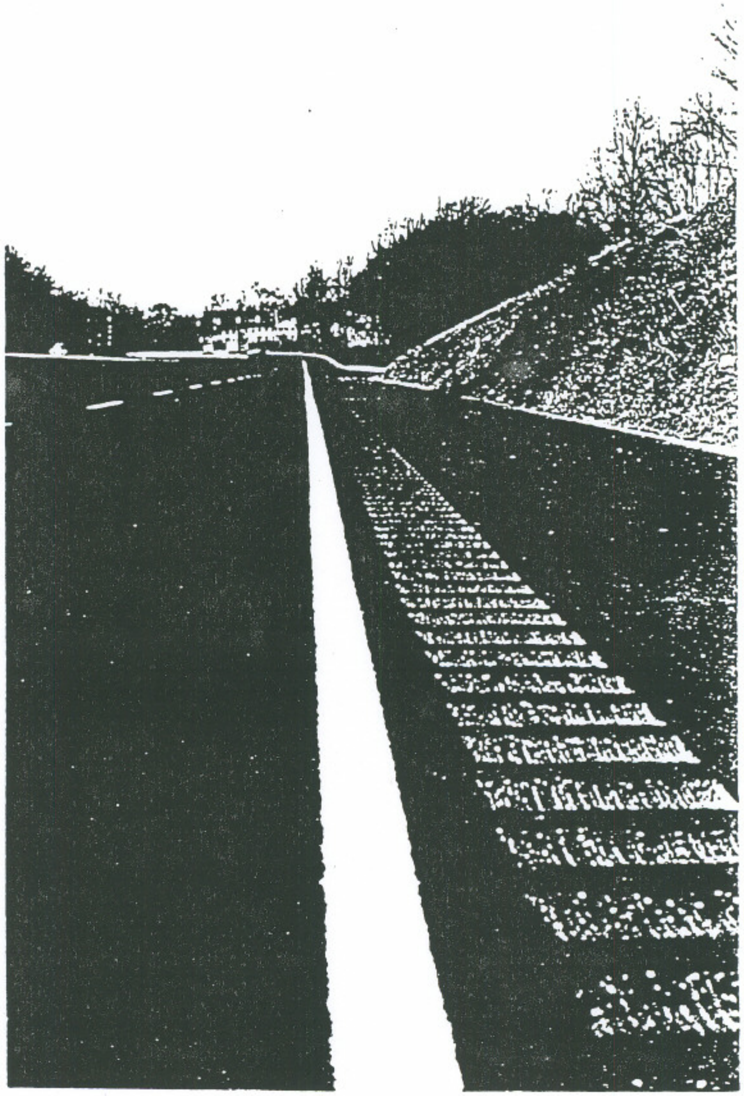

Fig. 4 Continuous Milled rumble strips

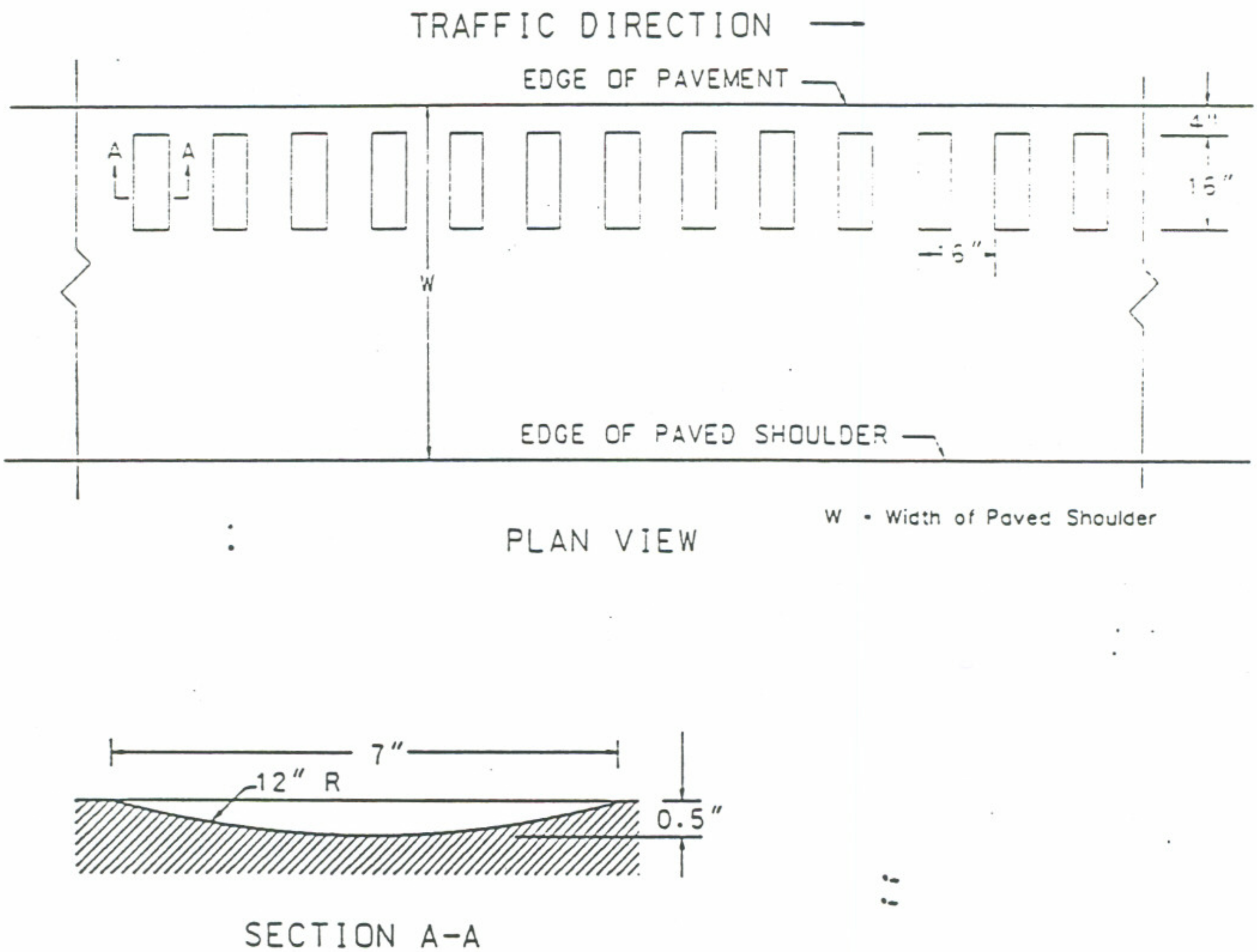


Fig. 5 Asphalt Milled rumble strips

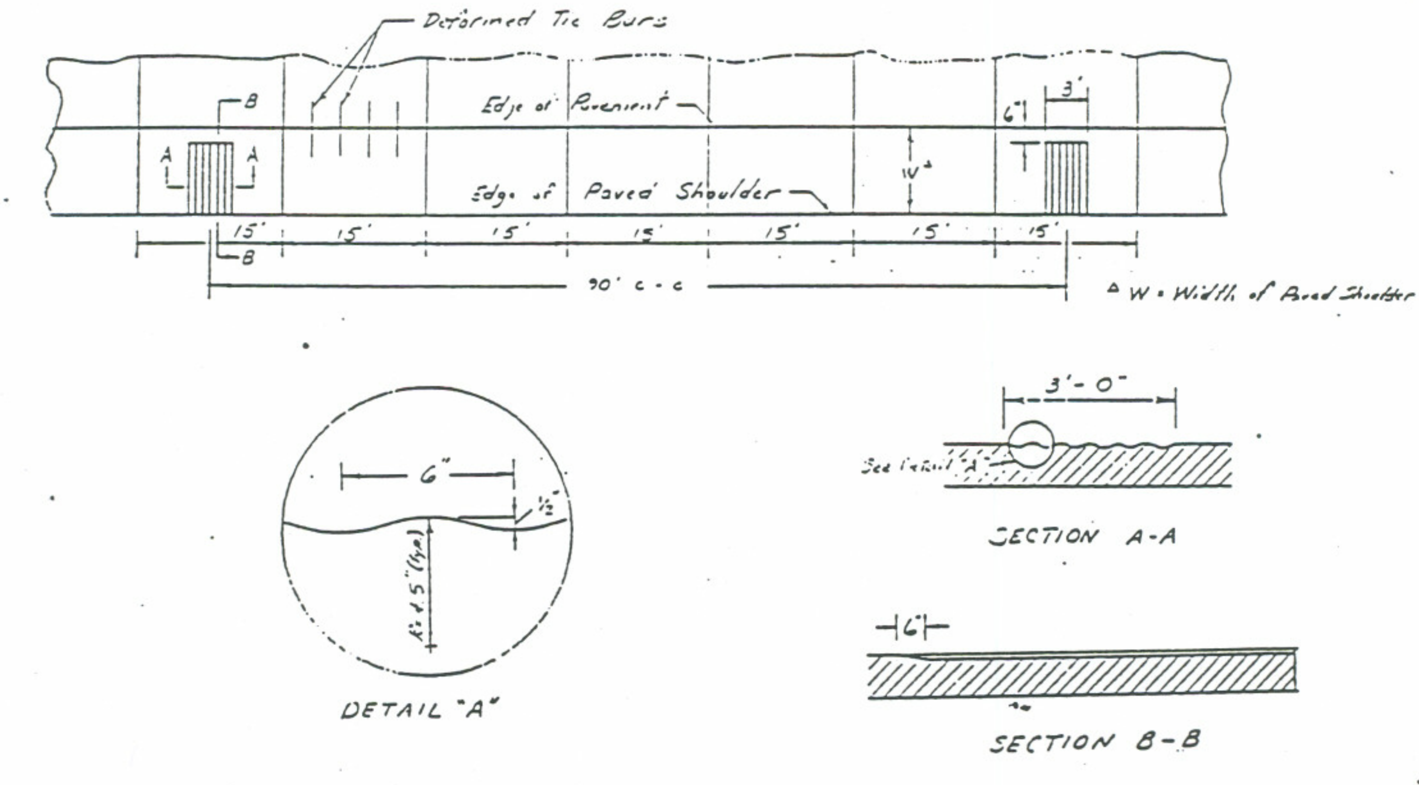


Fig. 6 Concrete Corrugated rumble strips

## 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:

$$P = f\,(a_d, a_r, t_d, t_r) \qquad (1)$$

Where P is the effectiveness of rumble strips; $a_d$ is the audible index of traveled ways, $a_r$ is the audible index of rumble strips; $t_d$ is the tactile index of traveled ways and $t_r$ 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:

$$P_o = \Phi\,[(\bar{a}_r - \bar{a}_d, \bar{t}_r - \bar{t}_d)] \qquad (2)$$

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

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

$\bar{t}_r$ is the sample mean of $t_r$

$\bar{t}_d$ 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.

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

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

It is assumed that the pavement roughness index is the main indicator of the vibration during driving, thus, for the purpose of comparison the tactile index [illegible] is assumed to be in proportion to the roughness index.

The small differences of testing results between the two [illegible] of testing also can be neglected.

The following testing conditions are considered as the typical case for this study:

Testing conditions: [illegible] patterns — continuous asphalt-milled type [illegible], continuous asphalt-rolled type (Fig. 5) and intermittent concrete-cross-cut type (Fig. 6)

Testing speeds: 55 mph and 65 mph

Angle of RCTR: [illegible] degrees

Pavement 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 conducted 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 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.

```
FILE  C:\MDRDATA\RUMB-S.P05

COUNTY 12              ROUTE INTERSTATE-85    DIR North(+) LANE 1

OPERATOR ALR        DRIVER ALR         VEHICLE ED. R62087 EQUIPMENT VA.
MDR4090
FILE NAME RUMB-S          USER REF 2 65-MPH           USER REF 3 SPECIA
L REQUEST
DATE                10/03/1994
TIME                14:29:47
DCF                 18675 C
WAVELENGTH          300 ft  none
```

| FROM | TO | ROUGH DIST | RUT AVG | RUT STD | IRI 1 | IRI 2 | AVG IRI |
|---|---|---|---|---|---|---|---|
| 25.000 | 25.369 | 0.369 | -0.03 | 0.135 | 112.24 | 97.55 | 104.90 |
| 25.369 | 25.996 | 0.627 | 0.32 | 0.156 | 106.58 | 139.91 | 123.24 |
| 25.996 | 26.376 | 0.380 | 0.03 | 0.213 | 119.89 | 121.87 | 120.88 |
| 26.376 | 26.711 | 0.335 | -0.05 | 0.061 | 174.12 | 119.59 | 146.86 |
| 26.711 | 26.894 | 0.183 | -0.00 | 0.051 | 169.31 | 137.56 | 153.44 |
| 25.000 | 26.895 | 1.895 | 0.09 | 0.219 | 128.36 | 124.26 | 126.31 |

Fig. 7 Typical computer printout sheet

for rolled rumble strip roughness tests on I-85

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FILE  C:\MDRDATA\RU-STRIP.P05

COUNTY 12                    ROUTE INTERSTATE-85   DIR South(-) LANE 1

OPERATOR ALR          DRIVER ALR          VEHICLE ED. R62087 EQUIPMENT VA.
MDR4090
FILE NAME RU-STRIP          USER REF 2 65-MPH          USER REF 3 SPECIA
L REQUEST
DATE                  10/03/1994
TIME                  13:08:21
DCF                   18675 C
WAVELENGTH            300 ft  none
```

| FROM | TO | ROUGH DIST | RUT AVG | RUT STD | IRI 1 | IRI 2 | AVG IRI |
|---|---|---|---|---|---|---|---|
| 22.000 | 21.710 | 0.290 | 0.14 | 0.067 | 144.45 | 106.91 | 125.68 |
| 21.710 | 21.247 | 0.463 | 0.16 | 0.169 | 108.77 | 1079.98 | 594.37 |
| 21.247 | 20.900 | 0.348 | 0.06 | 0.228 | 525.16 | 181.65 | 353.41 |
| 20.900 | 20.802 | 0.297 | 0.10 | 0.123 | 883.30 | 151.73 | 507.52 |
| 20.802 | 20.493 | 0.109 | 0.09 | 0.155 | 232.23 | 233.81 | 233.02 |
| 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

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.

The testing locations include:

12 locations for asphalt traveled way tests

[illegible] locations for asphalt milled rumble strip tests

20 locations for asphalt rolled 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 measurements; the remaining numbers represent the rumble IRI results of various testing paths during the tests.

The results of roughness tests at 112 locations on I-5 and I-[illegible] are presented in [illegible]

Table 1 Testing Results of Pavement Roughness

| 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 (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. | Asphalt, Rolled Rumble Strips | 55 | 103.06 | I-85 |
| 10. | Asphalt, Rolled Rumble Strips | 55 | 134.70 | I-85 |

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

| 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 Rumble Strips | 65 | 100.62 | I-85 |

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

| No. | Testing Items | Testing Van Speeds (mph) | IRI | Notes |
|---|---|---|---|---|
| 30. | Asphalt, Rolled Rumble Strips | 65 | 143.26 | I-85 |
| 31. | Asphalt, Rolled Rumble Strips | 65 | 108.29 | I-85 |
| 32. | Asphalt, Rolled Rumble Strips | 65 | 155.62 | I-85 |
| 33. | Asphalt, Rolled Rumble Strips | 65 | 123.24 | I-85 |
| 34. | Asphalt, Rolled Rumble Strips | 65 | 146.86 | I-85 |
| 35. | Asphalt, Rolled Rumble Strips | 65 | 124.36 | I-85 |
| 36. | Asphalt, Rolled Rumble Strips | 65 | 142.20 | I-85 |
| 37. | Asphalt, Rolled Rumble Strips | 65 | 97.97 | I-85 |
| 38. | Asphalt, Rolled Rumble Strips | 65 | 130.84 | I-85 |
| 39. | Asphalt, Rolled Rumble Strips | 65 | 96.95 | I-85 |

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

| 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 | I-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

| 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

| 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 | I-295 |
| 5. | Concrete Traveled Way | 55 | 119.84 | I-295 |

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

| 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 | I-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 |

## 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.

Table 2 Testing Results of Sound Levels of Pavements

| 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 | 79 | 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 (Con't) Testing Results of Sound Levels of Pavements

| 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

| 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 (Cont') Testing Results of Sound Levels of Pavements

| No. | Testing Items | Testing Van Speeds (mph) | Sound Level (In decibels) | Notes |
|---|---|---|---|---|
| 1. | Asphalt Milled 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 |

## 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

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

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

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,

$$y = (12^2 - 0.5^2)^{1/2} = 11.99 \text{ inches}$$

$$\Delta y = 12 - 11.99 = 0.01 \text{ inches} < 0.5 \text{ inches}$$

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.

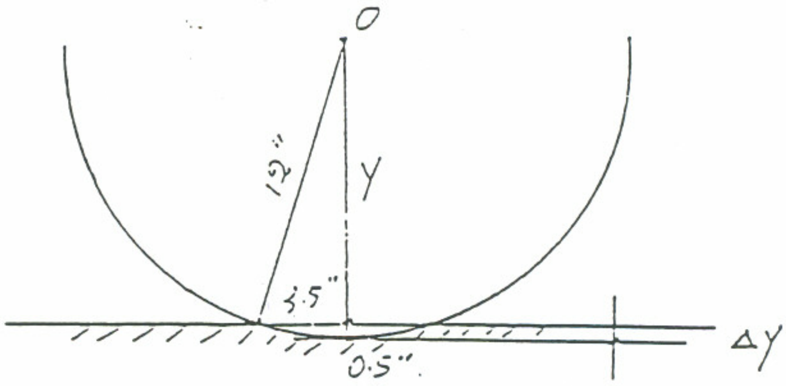


Fig. 9. Tire drops for milled rumble strips

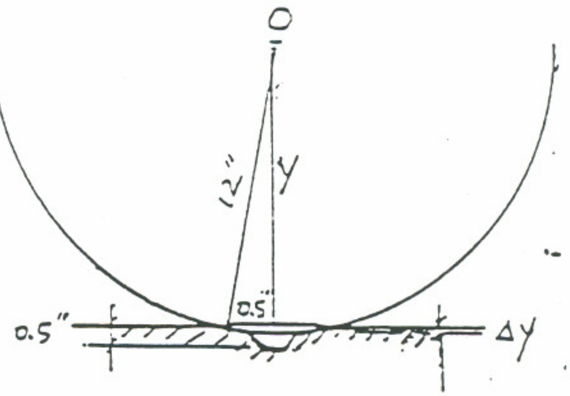


Fig. 10. Tire drop for rolled rumble strips

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 tire drops for the rolled and milled rumble strips vary by 50 times for speeds less than $v_{cr}$. 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-29 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 32.0%, 54.[illegible]% and 44.5% 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, the milled rumble strip exceeds [illegible] or [illegible] times more than that of rolled rumble strips and that the milled rumble strip exceeds [illegible] or [illegible] times more than that of corrugated rumble strips.

(2) For sound level tests under 65 mph, the sound excesses are 2.5 decibels, [illegible] decibels and [illegible] 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 exceeds is [illegible] or 2.15 times more than that of rolled rumble strips and the milled rumble strips exceeds is [illegible] or [illegible] times more than that of corrugated rumble strips.

Table 3 <u>Summary of Field Tests</u>

(For Roughness, Sound Levels and Environmental Effects)

| Testing Items | Means of Roughness (In IRI) | | | | Means of Sound Levels (In dB) 55 mph | | | | Means of Sound Levels (In dB) 65 mph | | | | LOCATIONS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Travel Way | R.S. | Excess | % Increase | Travel Way | R.S. | Excess | % Increase | Travel Way | R.S. | Excess | % Increase | |
| • Roll/Travelway (Asphalt) | 88.72 | 121.3 | 32.6 | 36.7% | 72 | 75 | 3 | 4% | 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 |
| • Mill/ Corrugate (Asphalt) | --- | --- | --- | 716% | -- | -- | -- | -- | -- | --- | --- | 55.3% | I-295<br>I-85 |
| • Enviro Effects | --- | --- | --- | --- | -- | -- | -- | -- | 69 Truck | 60 Van | 9 | -13% | I-85 200 ft away frc Roadway |

(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

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.

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