RESEARCH REPORT
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Evaluation of Rumble Strip Design and Usage

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16. Abstract

The objective of this study was to investigate the following aspects of rumble strips: the optimum height and width of elements in a rumble strip pattern, spacing between them, the effect of grouping elements into sets, the effects of speed on design criteria, and driver reaction to the audible and physical stimuli produced by rumble strips. A survey of design and usage in other states was conducted; and the results show that even though 35 of the 44 responding states have installed rumble strips, only five have warrants for usage.

Two types of rumble strip design were evaluated -- one with a constant spacing between elements and another with variable spacing between elements. Simulated tests using strips of plywood showed that a distance of 10 feet (3.0 m) between elements, a strip width of 4 inches (102 mm), and a strip height of 1/2 inch (13 mm) produced the best results. Based on audible and physical stimuli, it was determined that the rumble time should not exceed 3/4 second of continuous rumble for any pattern.

Evaluation of field installations failed to show a statistically significant difference in speeds for either the constant-spaced pattern or variable-spaced pattern. Based on these installations and controlled-spacing tests, it appears that the constant-spaced pattern should continue to be used. Polyvinyl strips were installed without much success because of adherence problems. A double layer of reflective marking tape performed satisfactorily with regard to durability and reflectivity; however, the rumble effect was slight.

17. Key Words Rumble Strips Optimum Spacing and Dimensions Audible and Physical Stimuli	18. Distribution Statement

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Introduction

A rumble strip is a traffic control device which utilizes sound and vibration to warn drivers of upcoming hazardous situations or unusual traffic conditions. Physically, they are a modification of the pavement texture or profile. They may consist of a series of ridges and grooves or even a series of coarse textured overlays. The mechanism by which a rumble strip works is simple: the tires are "drummed" and elements of the vehicle resound in resonance; noise and vibration are produced above the normal levels. This alarms and warns the driver that he is approaching a situation which will require deliberate action on his part.

Rumble strips have been used as warning devices in a number of situations: stop approaches to rural intersections, railroad crossings, or toll booths; approaches to sharp curves; lane drops on freeway facilities, exit ramps on interstate routes; and warning devices to prevent encroachment onto shoulders or gore areas. Probably the most hazardous in terms of accident frequency is an approach to a stop condition at a rural intersection. The rural driver often travels long distances without encountering any kind of traffic control device. He may be lulled into a feeling of false security; and upon encountering an unexpected rural stop, he may not react in time. Rumble strips restore and command awareness.

Ideally, a rumble pattern should urge the driver to decelerate uniformly at a rate approaching normal vehicle deceleration (i.e., deceleration without braking). A major shortcoming of existing rumble patterns is that driver reaction is not predictable. Some drivers may ignore them; others decelerate too violently. Some have been observed to accelerate. A wide variation in speeds may be expected. Some drivers have rather indifferent regard for rumble strips and other highway safety devices. Many motorists view rumble strips as a nuisance and refuse to acknowledge their presence. If the pattern is too rough, excess deceleration among some drivers might be expected. If the strip is too long or too far away from the stop bar, motorists will be tempted to ignore the rumble or to accelerate. The ideal pattern should, therefore, produce results as unobtrusively and as uniformly as possible.

Studies performed in recent years have attempted to evaluate the effectiveness of various designs of rumble strips. One of the first reports on rumble strips which is still used as a guide by others was by Bellis for the New Jersey State Highway Department *(1)*. Two types of rumble strips were installed in 1965. They were made from an epoxy-sand mixture poured into a form, and a rumble area was made from epoxy, binder, and coarse aggregate. The pattern consisted of 19 elements spaced at 10-foot, 5-inch (3.2-m) centers. The area consisted of seven panels with dimensions of 2.5 feet (0.8 m) by 5 feet (1.5 m).

The Virginia Highway and Transportation Research Council *(2)* found a 10-foot (3.0-m) spacing was best for a stopping situation such as an intersection, and a 5-foot (1.5-m) spacing was best for highway shoulders. They also found that the height of the strips should be not less than 1/2 inch (13 mm).

The North Dakota State Highway Department tested an epoxy rumble strip and a grooved strip *(3)*. Both produced an acceptable sound and attracted the driver's attention. Few problems were experienced with the installation of raised epoxy strips and recommendations were made to continue installation at locations having high rates of accidents involving running a stop sign.

Among several types of rumble strips tested by the Michigan Department of State Highways was a polyvinyl chloride bar 7/16 inch (11 mm) thick, 3 1/2 inches (89 mm) wide, and approximately 10 feet (3.0 m) long *(4)*. Adhesives used to hold the rumble strips in place were generally successful until they were snowplowed. Other types of rumble strips tested in Michigan were plastic bars and a pavement marking tape which was 0.095 inch (2.4 mm) thick. The tape was not sufficiently durable; however, the plastic bars stayed in place until they were snowplowed. Speed reductions obtained diminished with time. This tended to show that the devices were less effective the longer they were in use at a given location.

An evaluation of rumble strips by the Illinois Department of Transportation showed an overall reduction of accidents following installation; however, their effectiveness over a longer period of time was reduced *(5)*. It was concluded that rumble strips, like many other non-standard traffic control devices, are effective only as long as they are startlingly different from the normal device confronting the driver.

Past usage of rumble strips in Kentucky has generally conformed to guidelines presented in the Division of Design Guidance Manual. Material and construction requirements for raised rumble strips are outlined in Standard Drawing Number RPM-140. Copies of the guidelines and the drawings are presented in APPENDIX A. Even though the guidelines do not contain warrants for installation, they are sufficient to guide decisions concerning placement of rumble strips. The Standard Drawing showing physical dimensions of raised rumble strips has been used for several years, and there was a need to determine if improvements could be made.

Kentucky's first attempt to groove bituminous concrete as rumble strips was on US 60 (Versailles Bypass) in Woodford County. There, the strips were ground into the surface sometime after construction. In addition, rumble strips were troweled into bituminous concrete at the exit ramp from I 75 to US 25 in Madison County (Berea exit). This took place during construction of the ramp in 1966.

Shoulders with grooved rumble strips have been constructed as part of experimental projects on two sections of roadway in Kentucky. Bituminous concrete shoulders were constructed on a 3.4-mile (25.3-km) section of I 275 in Boone, Kenton, and Campbell Counties in 1978.

To assess the usage of rumble strips in Kentucky, a survey of existing installations was conducted; a summary is presented in APPENDIX B. Of the 44 installations identified in June 1979, 25 were of the grooved type. The rumble strips were used primarily as warning devices at toll-booth approaches and at T-intersections or other stop situations.

The following aspects of rumble strips were investigated: the optimum height and width of elements in a rumble strip pattern; spacing between them; the effect of grouping elements into sets; the effect of speed on design criteria; and driver reaction to the audible and physical stimuli.

Survey of Rumble Strip Design and Usage in Other States

The first phase of the study was a survey of rumble strip design and usage in other states. Responses were received from 44 of the 49 states who were sent the questionnaire. A summary is presented in Table 1. A copy of the questionnaire and more detailed information are presented in APPENDIX C. Thirty-five of the 44 states use rumble strips; however, only five had warrants for rumble strip usage. In addition, few states had conducted any research to determine optimum patterns for rumble-strip installations. About half of the states that used rumble strips had a standardized design in effect or under consideration. The primary type of rumble strip used was the raised type; however, the grooved type was also used by several states. Height or depth of the rumble strips varied from 1/4 inch (6.4 mm) to 3/4 inch (19.1 mm), and the width ranged from 3 to 12 inches (76 to 305 mm). Spacings between elements in the rumble strip pattern generally varied from 4 to 12 inches (102 to 305 mm).

The objective of rumble-strip usage was primarily as a device for warning of an impending danger. This was usually an intersection with a history of accidents caused by failure to observe other traffic control devices. Other uses were as a temporary correction device and as means of warning the driver that he had encroached onto a shoulder or into a gore area. Rumble strips are also located at hidden intersections, rural stops, sharp curves, lane drops, toll booths, and approaches to traffic circles. A wide variety of rumble-strip patterns are used by other states; and details pertaining to the number of sets, elements per set, and distance of the sets from the intersection are presented in Table 1.

Preliminary Field Testing of Rumble Strip Designs

Two types of rumble strip design for rural intersections were evaluated: one with a constant spacing between elements and the other with variable spacing between elements. A spacing is desired such that the noise perceived by the driver while passing over the rumble-strip pattern is directly related to the speed at which the vehicle is traveling. A change in noise should create a corresponding increase or decrease of noise or pitch inside a vehicle.

To evaluate the various rumble-strip patterns, a test section was selected on the Bluegrass Parkway in Woodford County (Figure 1). Several thicknesses of plywood were nailed to the pavement in the wheelpaths with distances separating the boards varying from 1 foot to 20 feet (0.3 m to 6.1 m) (Figure 2). The test vehicle was a 1976 Plymouth Fury with a Type 2305 B & K noise-level recorder positioned inside the vehicle. For each spacing, the test vehicle was driven over the

Table 1. Survey of Rumble Strip Design and Usage in Other States.

States	Use Rumble Strips: Yes	Use Rumble Strips: No	Standardized Design in Effect or Under Consideration: Yes	Standardized Design in Effect or Under Consideration: No	Warrants For Use: Yes	Warrants For Use: No	Type of Rumble Strip Used in Design: Raised	Type: Grooved	Type: Mat	Type: Other	Rumble Strip Element Dimensions (inches): Height or Depth	Dimensions: Width	Dimensions: Spacing Between Elements	Objective of Rumble Strip Use: Temporary Corrective Use Only	Objective: Pre-warning to Impending Condition	Rumble Strip Locations: Shoulder-Gore Encroachment	Locations: Hidden Intersection	Locations: Intersection w/History of Accidents Caused by Failure Observe Traffic Control Devices – Also Rural Stop	Locations: Sharp Curve	Locations: Shoulder Encroachment	Locations: Lane Drop	Locations: Approach Traffic Circle	Locations: Location by Engr. Judgment	Number of Sets	Elements per Set	Rumble Strip Patterns (Distance of Sets from Stop)
Alabama	X		X			X	X				5/8	8	10	X			X	X						5	5	200+x, 100+x, 50+x, x
Arkansas	X		X			X	X	X			1/2	3	9		X			X	X					10	1	805, 795, 785, 774, 764, 753, 752, 751, 750
California	X		UC			X	X									X		X		X			X			No specific design specifications
Colorado	X			X		X	X							X									X			No specific design specifications
Connecticut	X			X		X																				No specific design specifications
Delaware	X		X			X			X		3/4	NS	NS		X			X	X					11	24	1035, 910, 785, 660, 535, 460, 385, 310, 235, 160, 85
Georgia	X		X			X	X				NS	4	4		X			X						3	30	750, 605, 420, 400
Hawaii	X			X		X	X				NS	NS	36		X			X						7	9	500+x, 425+x, 350+x, 275+x, 200+x, 125+x, 50+x, x
Idaho	X			X		X																				No specific design specifications
Illinois	X		X		X		X	X			2	4	6	X				X			X			6		1100, 975, 850, 785, 330, 265
Indiana	X		X			X	X				1/4	8	8		X		X	X					X	9	12	2495+x, 1720+x, 900+x, 735+x, 575+x, 490+x, 405+x, 320+x, x
Iowa	X		X			X		X			3/8	4	12		X			X						3	26	500+x, 300+x/2, 300
Kansas	X		X		X		X				1/2	8	8		X			X						6	NS	1273, 1098'-4", 973'-8", 929', 459'-4", 414'-8"
Kentucky	X		X			X	X	X			V	8	V		X	X		X		X			X	V	10	No specific design criteria at time of survey
Maine	X			X		X		X							X								X			No specific design criteria
Massachusetts	X		X			X			X		3/8	NS	NS			X				X				NS	NS	Not stated
Michigan	X		X			X	X				1/2	12	12					X	X					5	4	750+x, 600+x, 450+x, 300+x, 150+x, x
Minnesota	X		UC			X	X	X			1/2	5	7		X			X					X	2	16	1800, 500
Mississippi	X		X			X	X				1/2	6	6		X		X							5	9	See drawing
Missouri	X			X		X	X											X					X			No specific design specifications
Nebraska	X		X		X		X				1/2	6	12		X	X		X		X				2	26	2255, 2140
New Jersey	X		X			X	X				1/2	3	126		X							X	X	1	19	X (preceeded and followed by 5 strips 126" apart)
New Mexico	X			X		X	X				3/4	NS	NS											10	NS	500, 450, 400, 350, 300, 250, 200, 150, 100, 50
North Carolina	X			X		X									X											No specific design specifications
North Dakota	X		X		X		X	X	X		3/8	4	8		X			X						4	16	835+x, 735+x, 410+x, 345+x, 330, 265
Oklahoma	X			X		X																				No specific design specifications
Pennsylvania	X		X		X			X			1/2	4	12		X			X	X							See drawings (design by approach speed)
Rhode Island	X			X		X																				No specific design specifications
South Carolina	X			X		X			X		1/2	48	NS		X			X						11	1	800, 700, 600, 500, 410, 330, 260, 200, 150, 100, 50
Tennessee	X			X		X																	X			No specific design criteria
Texas	X		X			X	X			X						X										No specific design criteria
Utah	X			X		X		X			NS	NS	NS					X					X	3	5	FHWA guidelines used as specifications
Vermont	X			X		X	X				NS	24	NS		X		X	X		X						778, 398, 100 (at one location only)
Virginia	X		UC			X					V	V	V		X											Varies with site
Wisconsin	X		X			X	X	X	X		3/8	4	12		X			X	X					3	5	
Wyoming	X			X		X					3/8	4	NS										X	3	NS	See drawing (design by approach speed) 390, 160, 30
Alaska		X																								
Louisiana		X																								
Maryland		X																								
Montana		X																								
Nevada		X																								
New Hampshire		X																								
New York		X																								
Oregon		X																								
West Virginia		X																								

*See Addendum

UC – Under Consideration NS – Not Stated V – Varies with Site

ADDENDUM FOR TABLE 1 – WARRANTS FOR USE

Illinois – a. In advance of stop signs at intersections having an accident rate of greater than 3.0 for the past 2 years and where at least 50 percent of the accidents have been right-angle collisions. b. At the termination of a freeway facility where the number of traffic lanes is reduced to one.

Kansas – For rural locations in the lower entering ADT range (under 5,000), an average accident rate of 8.0 accidents per ten million entering vehicles.

Nebraska – In front of STOP AHEAD signs where there had been 2-3 run-stop-sign accidents.

North Dakota – The warrant for rumble strips is three or more accidents over a 5-year period at a specific location, such as at a highway junction, and it has been determined this type of installation would be a corrective application.

Pennsylvania – The intersection should have experienced five or more accidents per year which are susceptible to correction by the installation of rumble strips; these accidents consist of run-the-stop-sign angle accidents, hit-fixed-object accidents, and rear-end accidents; or two or more fatal accidents susceptible to correction.

Figure 1. Test site on the Bluegrass Parkway in Woodford County.

Figure 2. Test site with plywood used to simulate rumble strips.

boards at speeds of 20, 30, 40, 50, and 60 mph (8.9, 13.4, 17.9, 22.4, and 26.8 m/s). Noise levels are presented in Table 2. Plots of noise level versus vehicle speed at the various spacings are presented in Figure 3. A spacing of 10 feet (3.0 m) gave a response that was most linear and therefore most desirable. That is, noise increased linearly with increased vehicle speed at this spacing. It can be seen from Table 2 and Figure 3 that the spacings of 1, 2, and 3 feet (0.3, 0.6, and 0.9 m) produce erratic and, therefore, unsuitable noise levels. The spacing of 5 feet (1.5 m) produced fairly linear noise levels approximately 2 dBA higher than the 10-foot (3.0-m) spacing. At the more hazardous locations, it may be appropriate to specify a spacing of 5 feet (1.5 m) rather than 10 feet (3.0 m).

A height of 1/2 inch (13 mm) was the optimum for strips in a rumble-strip pattern. Rumble strips higher than 1/2 inch (13 mm) produced a vibration which was uncomfortable and irritating to the driver. Drumming occurs when the tire impacts the ridge. A width of 4 inches (102 mm) was the optimum. A minimum width was desired so that an automobile tire could ride upon the strip and then drop off the other side. The 4-inch (102-mm) width was sufficient

Table 2. Noise Levels (dBA) from Spacing Tests.

Spacing (feet)	Vehicle Speed in mph 20	30	40	50	60
Ambient	57	61.3	62.8	64.5	66.9
1	73.6	72.9	72.4	75	77.9
2	71	69	70	71.5	77.3
3	64	69.5	71.1	72.4	74.4
4	64	65	71	71.1	75.9
5	66.2	68	70.2	73.7	76.5
5.5	66	66.2	68.5	69	74
7	62	66	71	72	73.5
7.5	60	64	69.5	69.5	72.2
8	61	64	69.2	70	72
9	63	67	68	72	74
9.5	63.3	67	67.7	70	72.7
10	64.5	66.6	68.2	71.3	74
10.5	66.6	69	70	70.9	71.1
11.5	63	65	71	73	74
12.5			66	66	73
14.5			63.5	69.1	71.5
15			70.5	71	73.5

Note: 1 foot = 0.3048 m; 1 mph = 1.609 m/s

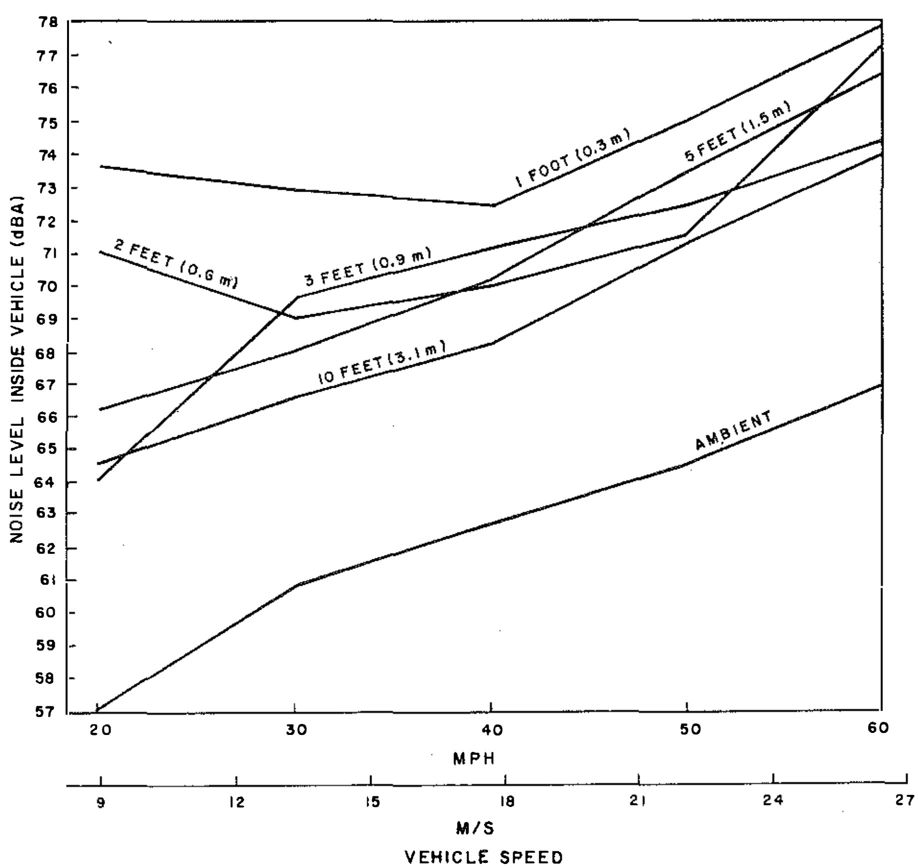


Figure 3. Noise level inside vehicle versus vehicle speed at various distances.

to cause the tire to leave the pavement and produce an adequate bump.

A factor controlling the number of elements in a rumble strip pattern is the amount of rumble time desired. From the tests of constant-spaced patterns on the Bluegrass Parkway, more than 3/4 second of continuous rumble may be irritating. A time constraint will restrict the number of strips which can be used in each set. For example, at 55 mph (24.6 m/s), a vehicle would travel 61 feet (18.6 m) in 3/4 second. This would allow the engineer to specify six rumble strips in a set at spacings of 10 feet (3.0 m). At slower approach speeds, fewer strips should be used to stay within the limit of 3/4 second of rumble.

Wheel-hop frequency is given by $f_n = 3.13 \sqrt{d}$, in which d is the static deflection of the tire; the distance between bounces is $\lambda = V/f_n$. If d = 0.5 in. and f_n = 4.43 H_z, then λ = 19.9 ft at 60 mph and 9.9 ft at 30 mph. At some speed during deceleration, the wheel-hop may be in resonance with the spacings on the pavement, and violent shaking may arise while passing through a range in speed. Otherwise, articles loose in a car and in the glove compartment may rattle.

Geometrics at the site will mandate the spacing of sets; however, in no case should the set of rumble strips nearest the hazard be closer than the stopping sight distance. The number of sets at a location would be dependent on geometric conditions. Unlimited use of rumble strips at many locations has resulted in cases of "overkill," and observations have shown that three sets of strips will probably produce optimum results.

Recommendations for changes in the specifications (Standard Drawing RPM-140) for constant-spaced design of rumble strips are presented in APPENDIX A.

Field Installation of Rumble Strips

The site selected for field installation of constant-spaced and variable-spaced rumble strips was the intersection of US 150 and US 127 (Danville Bypass) in Boyle County. Rumble strips were installed on both the northbound and southbound approaches of the Danville Bypass. The bypass had an AADT of 4,390 vehicles per day and a speed limit of 55 mph (24.6 m/s). The intersection had a history of "run the stop sign" accidents. Flashing beacons and oversized stop signs had been installed on both approaches. Rumble strips were located on both approaches but had been worn beyond effectiveness on the southbound approach for sometime. Rumble strips on the northbound approach were removed before the new design was installed.

CONSTANT-SPACED RUMBLE STRIPS

A constant-spaced design was used on the southbound approach (Figure 4). A sketch of the spacing of strips used on the southbound approach is shown in

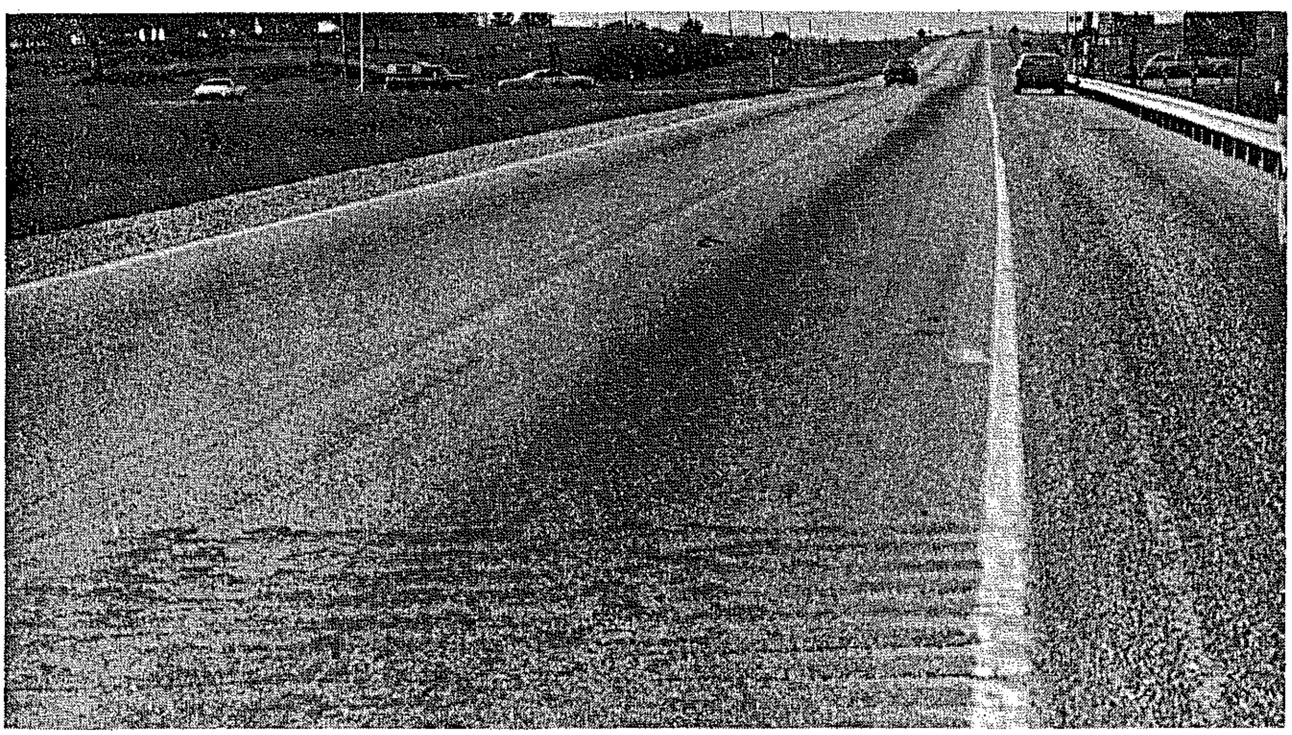


Figure 4. Southbound approach of US 127 at the intersection of US 150 in Boyle County.

Figure 5. The constant-spaced design started 1,000 feet (305 m) from the stopbar, and two sets of six rumble strips were used at 10-foot (3.1-m) spacings. The 600-foot (183-m) spacing from the last set of strips to the stopbar exceeds the stopping sight distance for 55 mph (24.6 m/s). Dimensions of the strips were 10 feet (3.1 m) long by 4 inches (102 mm) wide by 0.375 inches (9.5 mm) high.

The rumble strips made of polyvinyl chloride material were applied to the pavement using a two-part epoxy. In Figures 6 and 7, respectively, are photographs of application of epoxy to the polyvinyl strips

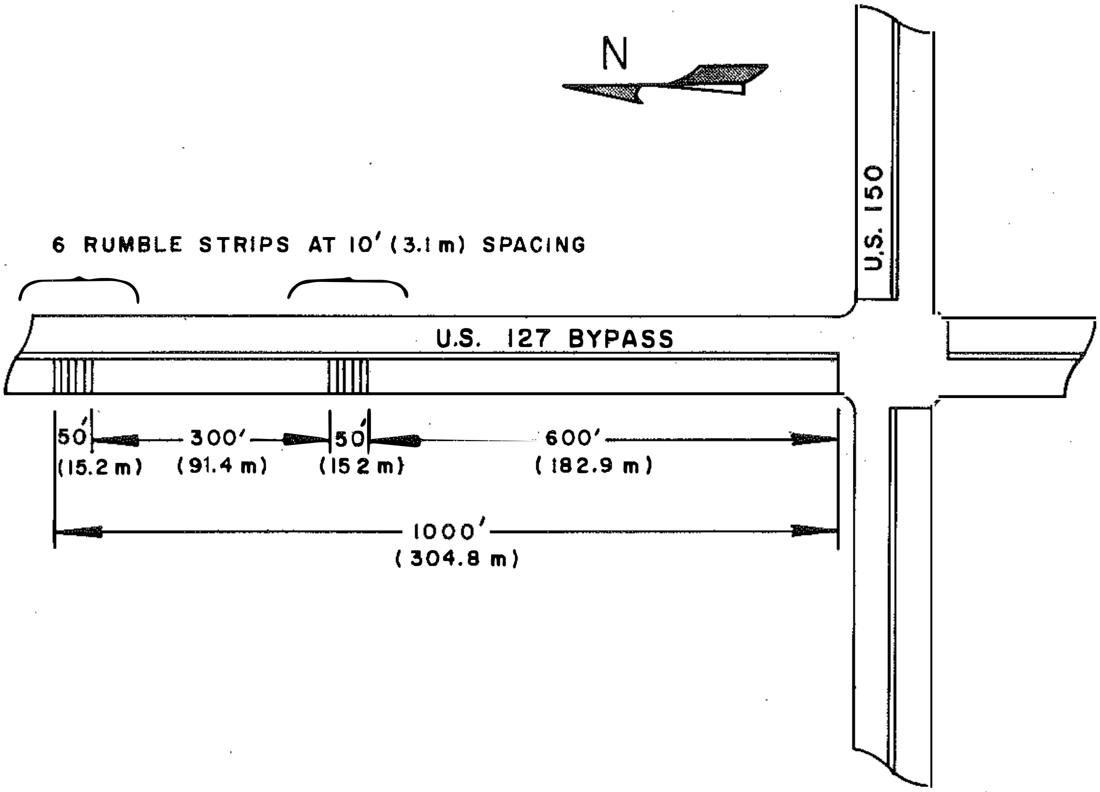


Figure 5. Constant-spaced pattern of rumble strips used on the southbound approach at the intersection of US 127 and US 150.

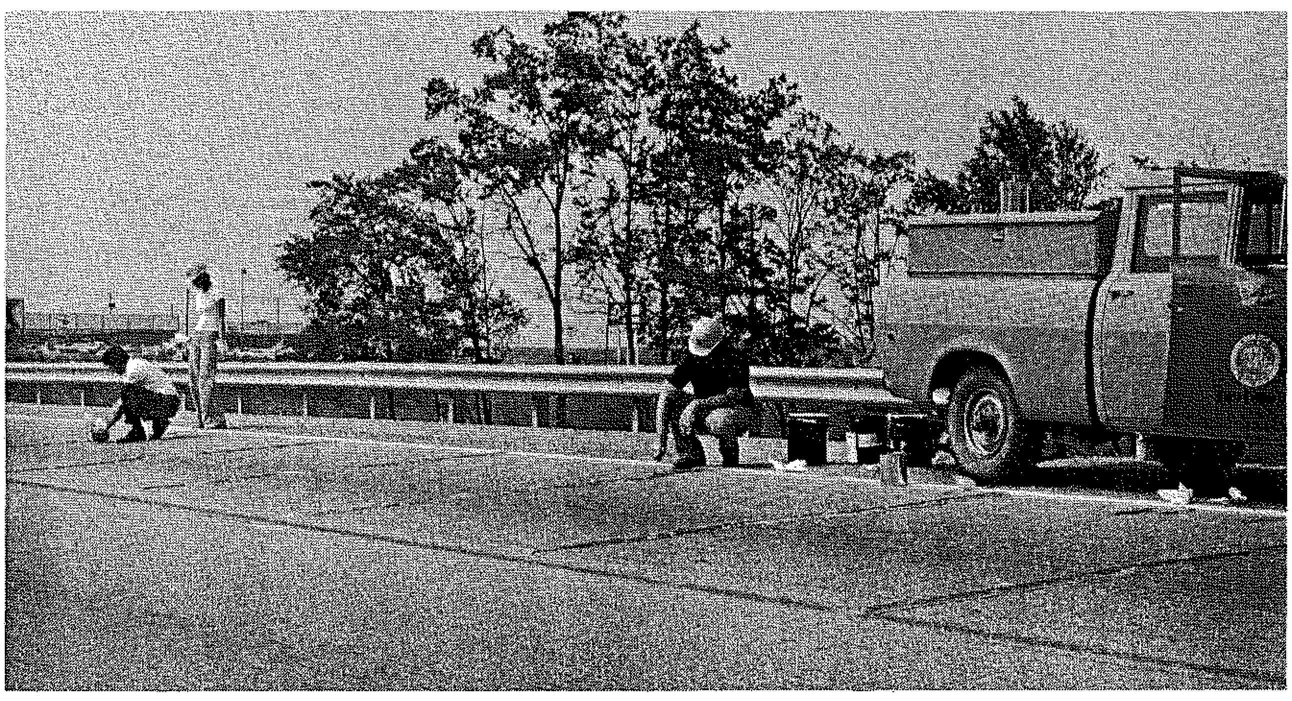


Figure 6. Application of epoxy to polyvinyl rumble strips on southbound approach.

Figure 7. Polyvinyl rumble strips after installation on southbound approach at the intersection of US 127 and US 150.

and the strips after installation. The first installation on the southbound approach was made in July 1977, and problems were experienced with adherence of the polyvinyl strip to the pavement. After a few months, the bond between the polyvinyl strips and the epoxy failed; and all of the strips were removed. Modifications, such as drilling holes and making striations on the back of the strip, were tried in an attempt to provide a more suitable surface for adherence. With the modified strips and three new types of adhesives obtained from the B. F. Goodrich Company, other installations were made in the summer of 1978. Failure of these adhesives occurred within a few days after installation.

After failure of the new adhesives, a third installation was made on the southbound approach. A reflective marking tape (Stamark), manufactured by the 3M Company, was placed on the roadway using a bonding adhesive. To simulate a rumble strip, two layers of the tape were used, one on top of the other for a total thickness of 120 mils (3.1 mm). The bonding adhesive was also used between the two layers of tape. Photographs of the Stamark tape installation during daytime and nighttime conditions are shown in Figure 8 and 9, respectively. The durability of the Stamark tape has been satisfactory during one year of service.

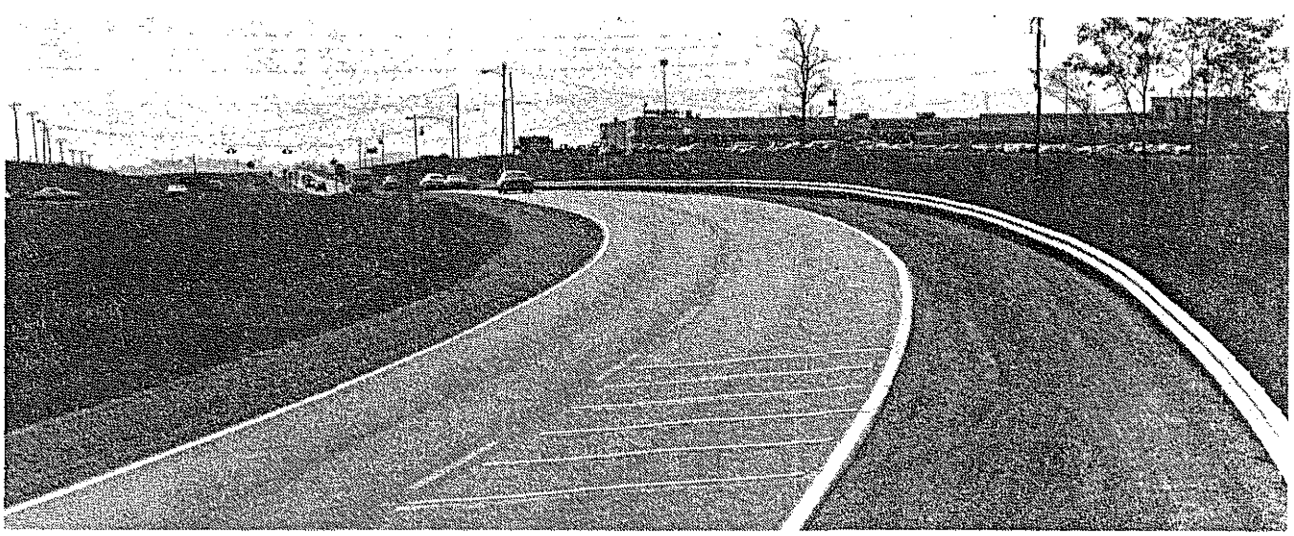


Figure 8. Reflective tape on southbound approach at the intersection of US 127 and US 150 (two layers of Stamark tape).

VARIABLE-SPACED RUMBLE STRIPS

A variable-spaced design was used on the northbound approach (Figure 10). Variable-spacing is based on the assumption that a motorist will slow down over the pattern at an acceptable deceleration rate, and the elements in the pattern will be struck at a constant rate. If the motorist fails to slow down while traveling over the strips, he will strike the elements at an increasing rate. The following equation was used to determine the spacing between elements in the pattern:

$$D = (V_1^2 - V_2^2)/2d$$

in which
- D = distance between elements,
- d = deceleration rate,
- V_1 = vehicle speed at first element, and
- V_2 = vehicle speed at second element.

Given that d = 3 ft/sec^2 (0.92 m/sec^2) (deceleration due to engine braking only) and an entering speed of 55 mph or 81 fps (24.6 m/s), the pattern selected for installation on the northbound approach is illustrated in Figure 11. This pattern was based on the assumption that a vehicle would decelerate throughout the pattern while striking one rumble strip per second. As can be seen from the diagram, the distance from the last element to the stopbar was significantly less than the distance on the southbound approach. The 600-foot (183-m) spacing seemed to be too far. Also the anticipated speed at 400 feet (91 m) from the stop bar should be 42 feet per second (12.8 m/s) or about 30 mph (13.4 m/s), and a long stopping distance is not required.

Figure 9. Reflective tape on southbound approach at the intersection of US 127 and US 150 at night.

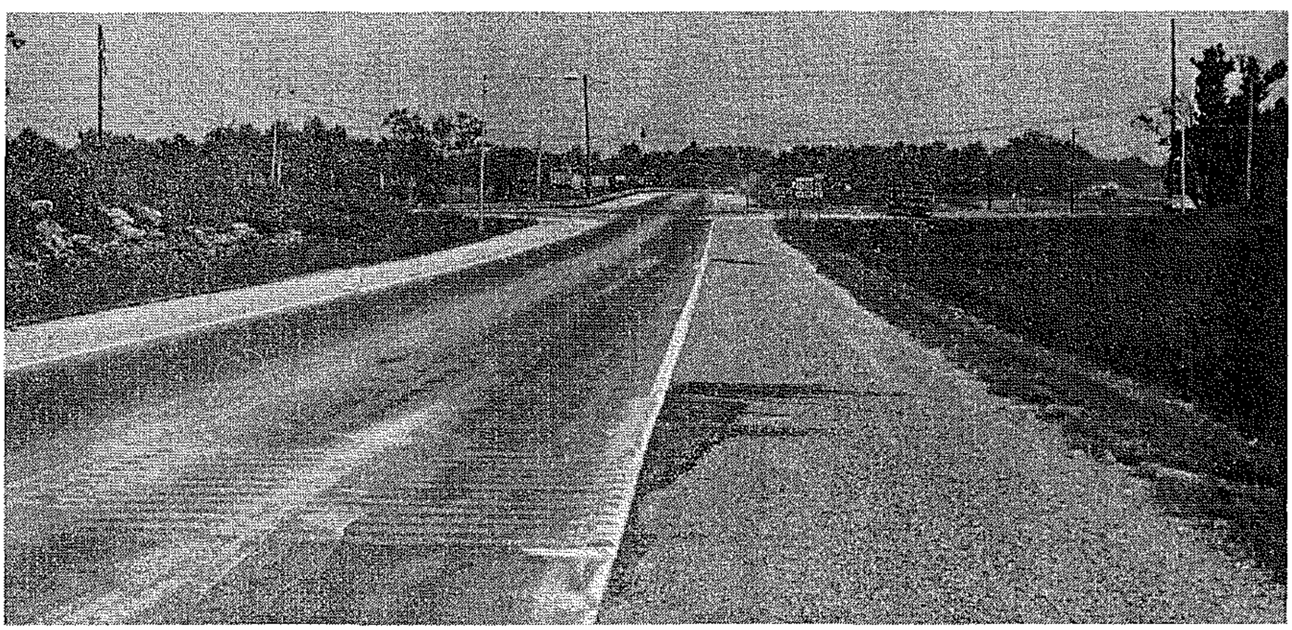


Figure 10. Northbound approach of US 127 at the intersection of US 150 in Boyle County.

The polyvinyl strips were used for the first six strips. The last eight strips were formed by a reflective pavement-marking tape (Stamark) which was 60 mils (1.5 mm) thick. It was thought that the reflective tape would provide a slight rumble effect and at the same time provide visual delineation of the approach at night. Adherence problems were also experienced with the polyvinyl strips on the northbound approach. This approach is shown in Figures 12 and 13.

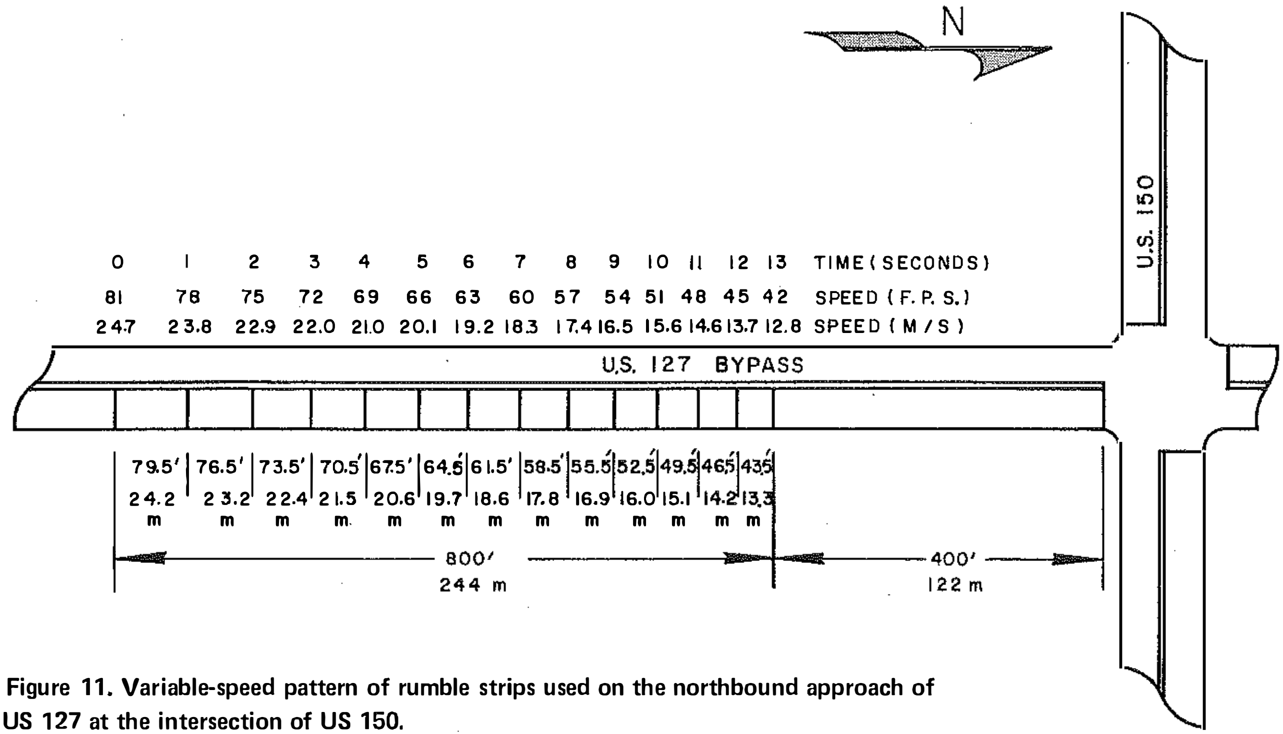


Figure 11. Variable-speed pattern of rumble strips used on the northbound approach of US 127 at the intersection of US 150.

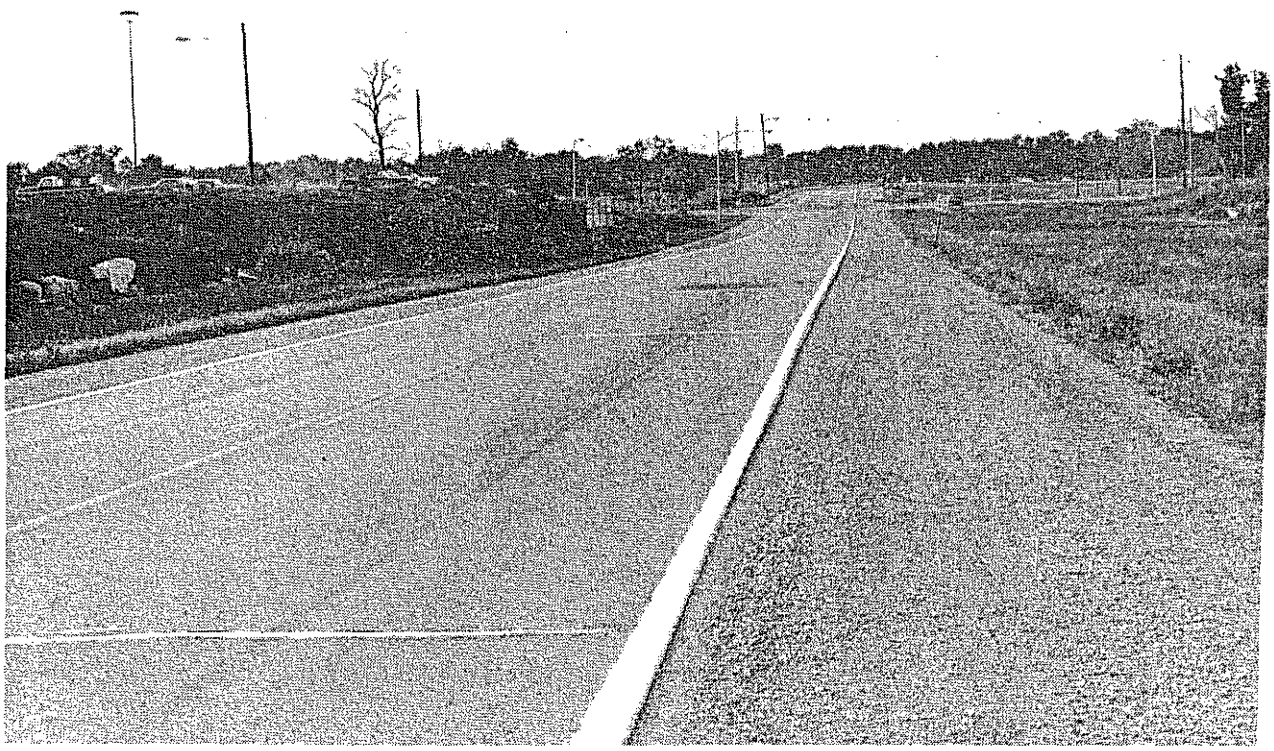


Figure 12. Reflective tape on the northbound approach of US 127 at the intersection of US 150 during daytime.

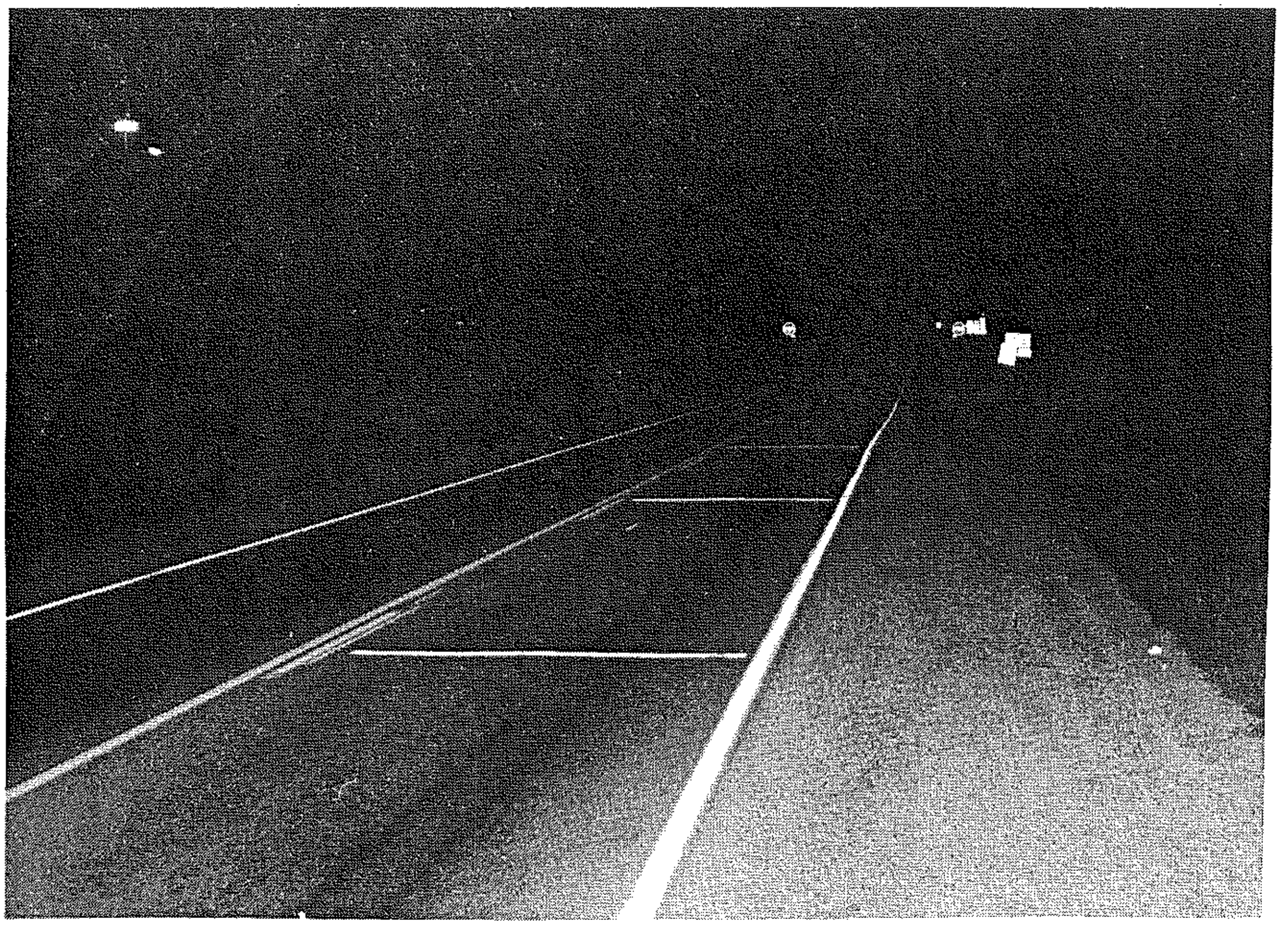


Figure 13. Reflective tape on the northbound approach of US 127 at the intersection of US 150 at night.

DATA COLLECTION

Speed data were taken on both the northbound and southbound approaches of the intersection where rumble strips were installed. Two radar meters were used to track individual vehicles through successive points of the approach. The radar meters were used at the following distances approaching the stop bar: 1400 and 900 feet (427 and 274 m), 900 and 700 feet (274 and 213 m), 700 and 500 feet (213 and 152 m), and 500 and 200 feet (152 and 61 m). Brakelight data were taken to determine the average distance from the stopbar at which drivers began to decelerate their vehicles.

Results of Field Installations

The primary means for evaluating the effectiveness of polyvinyl rumble strips was before-and-after speed and deceleration data. As stated before, data were collected at several sets of distances in advance of the intersection. A summary of the speed and deceleration data is presented in Table 3. Statistical tests to determine whether the differences in speeds were significant between the before and after conditions are presented in APPENDIX D. Data showing the distance from the intersection at which brakelights were applied are also presented for both the northbound and southbound approaches.

CONSTANT-SPACED DESIGN

Somewhat better results were achieved with the constant-spaced design on the southbound approach as compared to the variable-spaced pattern on the northbound approach. Before data on the southbound approach showed that the greatest deceleration occurred between 500 and 200 feet (152 and 61 m). After installation of the constant-spaced rumble strips, the deceleration rates were practically the same between 500 and 200 feet (152 and 61 m) and between 900 and 700 feet (274 and 213 m). An indication of the success of the constant-spaced design was the

Table 3. Before and After Speed and Deceleration Data.

		Before				After			
Distance		Speed		Deceleration		Speed		Deceleration	
ft	m	mph	m/s	ft/sec^2	m/sec^2	mph	m/s	ft/sec^2	m/sec^2
Southbound									
1,400	427	50.8	22.7			50.8	22.7		
				0.77	0.23			0.87	0.27
900	274	47.1	21.1			46.6	20.8		
				1.89	0.58			2.02	0.62
700	213	43.2	19.3			42.4	19.0		
				1.90	0.58			1.94	0.59
500	152	38.9	17.4			37.9	16.9		
				2.12	0.65			2.03	0.62
200	61	30.4	13.6			29.5	13.2		
Overall Deceleration 1,400 ft (427 m) to 200 ft (61 m):				Before: 1.49 ft/sec^2 (0.45 m/s^2)					
				After: 1.53 ft/sec^2 (0.47 m/s^2)					
Northbound									
1,400	427	49.8	22.3			50.3	22.5		
				0.82	0.25			0.67	0.20
900	274	45.8	20.5			47.1	21.1		
				1.15	0.35			1.99	0.61
700	213	43.4	19.4			43.0	19.2		
				1.87	0.57			1.64	0.50
500	152	39.2	17.5			39.3	17.6		
				2.17	0.66			2.09	0.64
200	61	30.5	13.6			31.0	13.9		
Overall Deceleration 1,400 ft (427 m) to 200 ft (61 m):				Before: 1.39 ft/sec^2 (0.42 m/s^2)					
				After: 1.41 ft/sec^2 (0.43 m/s^2)					

overall increase in the deceleration rate after installation of the rumble strips -- 1.49 ft/sec^2 (0.45 m/sec^2) before compared to 1.53 ft/sec^2 (0.47 m/sec^2) after. Statistical tests comparing speeds before and after installation of rumble strips at each of the monitoring sites (APPENDIX D) indicate that none of the differences in speeds was significant on the southbound approach. Data show that the distance from the intersection at which brakelights were applied increased from 405 feet (123 m) before to 427 feet (130 m) after installation.

VARIABLE-SPACED DESIGN

Deceleration rates were somewhat similar before and after installation of rumble strips on the northbound approach. Little deceleration occurred from 1,400 to 900 feet (427 to 274 m) in either before or after conditions; however, a high rate of deceleration occurred from 500 to 200 feet (152 to 61 m). Overall deceleration on the northbound approach was slightly less before installation of the rumble strips -- 1.39 ft/sec^2 (0.42 m/sec^2) before compared to 1.41 ft/sec^2 (0.43 m/sec^2) after. Similar to the constant-spaced pattern, differences in speeds for the variable-spaced design on the northbound approach were not statistically significant at any of the monitoring sites.

The distance from the intersection at which brakelights were applied did show a greater increase for the variable-spaced design as compared to the constant-spaced design. The increase was from 410 feet (125 m) before to 470 feet (143 m) after. Part of the increase in brakelight distance with the variable-speed design could be attributed to the greater total distance from the intersection at which the rumble strips were installed (1,200 feet (366 m) for the variable-spaced design and 1,000 feet (305 m) for the constant-spaced design).

Because of failure to find an adhesive suitable for adhering the polyvinyl strips to the pavement, it appears that traditional bituminous rumble strips should continue to be used. Some consideration should be given to the use of an epoxy-aggregate rumble strip at locations where a bituminous rumble strip cannot withstand large volumes of heavy vehicles. A form could be used to mold the epoxy into a desired shape and 1/2-inch (12.7-mm) aggregate could be dropped on and rolled into the epoxy. The use of reflective tape has some advantages because of ease of application and because of reflectivity; however, the thickness is not sufficient to provide an adequate rumble.

Even though grooved rumble strips were not evaluated in this study, they appear to be practical for portland cement concrete pavements. Grooved strips should not be used on bituminous concrete pavements because of a tendency for the material to flow.

Summary

Rumble strips have been or are being used by at least 33 states. This was not unexpected because rumble strips have been observed in general use as a traffic control device where other traditional methods of warning have failed. However, only five states have warrants for their usage. To determine whether rumble strips should be installed, specific analysis and specialized engineering judgment are required. The primary purpose of rumble strips has been as a device for warning of an impending hazardous condition.

Two types of rumble-strip design for rural intersections were evaluated -- one with constant spacing between elements and one with variable spacing between elements. For the purpose of determining optimum dimensions and spacings, the constant-spaced pattern produced the better results. Simulated tests of rumble-strip patterns were made using plywood strips nailed in wheelpaths.

Results from the evaluation show that the optimum spacing for rumble strips is 10 feet (3.0 m). At more hazardous locations, it may be appropriate to specify a spacing of 5 feet (1.5 m) when higher noise levels are desired. A width of 4 inches (102 mm) and a height of 1/2 inch (13 mm) produced the best results. Rumble strips lower than 1/2 inch (13 mm) did not produce sufficient vibration, and those higher than 1/2 inch (13 mm) created so much vibration that they were uncomfortable and irritating to the driver. The 4-inch (102-mm) width was the minimum necessary for the tire to leave the pavement and produce an adequate bump.

The controlling factor for the number of elements in a rumble-strip pattern is the amount of rumble time desired. Using the constant-spaced pattern, more than 3/4 second of continuous rumble may be irritating. This time constraint will restrict the number of strips in a set to six (at spacings of 10 feet (3.0 m)) when approaching a hazard at 55 mph (24.6 m/s). A smaller number of strips should be used in a set when approaching the hazard at slower speeds (calculate distance traveled when velocity and time are known).

The spacing of rumble-strip sets will be dependent upon geometric conditions; however, the set of strips nearest the hazard should not be closer than the stopping sight distance. Unlimited use of rumble strips at many locations has resulted in cases of "overkill," and observations have shown that three sets of strips will probably produce optimum results.

The field installation of rumble strips was made at the intersection of US 150 and US 127 in Boyle County. Two installations of polyvinyl strips were made on the southbound approach, and failure of the bond between adhesive and strip occurred in both cases. Two layers of reflective marking tape were installed to simulate a rumble strip, and the durability was satisfactory. A combination of polyvinyl strips and reflective tape was used on the northbound approach, and similar adherence problems were experienced with the polyvinyl strips.

Somewhat greater increases in deceleration rates were achieved with the constant-spaced design on the southbound approach as compared to the variable-spaced pattern on the northbound approach. Since the differences in speeds were not statistically significant at any of the sites for either the constant-spaced pattern or variable-spaced pattern, it appears that the constant-spaced pattern should continue to be used (Standard Drawing RPM-140 in APPENDIX A). APPENDIX A contains some recommended changes in the specifications for constant-spaced designs of rumble strips. Grooved strips should be spaced according to the same requirements as for raised strips. Depths of grooved strips should correspond to the height dimensions for raised strips. Some merit may be associated with the variable-spaced pattern because of its characteristic of giving motorists an impression of increasing speed if the motorists fail to slow down.

Because of failure to find an adhesive suitable for adhering the polyvinyl strips to the pavement, it was recommended to continue using traditional rumble strips (bituminous material). Use of an epoxy-aggregate rumble strip at locations where the bituminous strip cannot withstand large volumes of heavy vehicles should be considered. Use of reflective tape has some advantages because of ease of application and reflectivity; however, the thickness is not sufficient to provide adequate rumble.

References

1. Bellis, W. R.; *Development of an Effective Rumble Strip Pattern*, Traffic Engineering, April 1969.
2. Franke, K. A.; *Evaluation of Rumble Strips*, Virginia Highway and Transportation Research Council, November 1974.
3. *Rumble Strips Used as a Traffic Control Device -- An Engineering Analysis*, North Dakota Highway Department, Traffic Engineering Division, September 1974.
4. Enustun, Nejad; *Three Experiments with Transverse Pavement Stripes and Rumble Bars,* Michigan Department of State Highways, October 1972.
5. *Rumble Strips Used as a Traffic Control Device -- An Engineering Analysis,* Illinois Department of Public Works and Buildings, Division of Highways, April 1970.

Appendix A.

KENTUCKY GUIDELINES AND STANDARD
DRAWING FOR RUMBLE STRIPS

Division of Design
Guidance Manual

Chapter 61-08

61-08.1000 RUMBLE STRIPS

Rumble strips fall in the category of traffic control devices and should be applied in situations to warn the motorists of temporary or very unusual hazardous driving conditions. In order for the public to maintain this connotation, they must be applied at various selected locations and then with the acknowledgement, consent, and approval of the Traffic Engineer. Except for very limited cases, the rumble strip is a temporary device, and definite plans should be made to eliminate the hazard. An example of a permanent installation is at toll collection booths which are in themselves rather permanent installations.

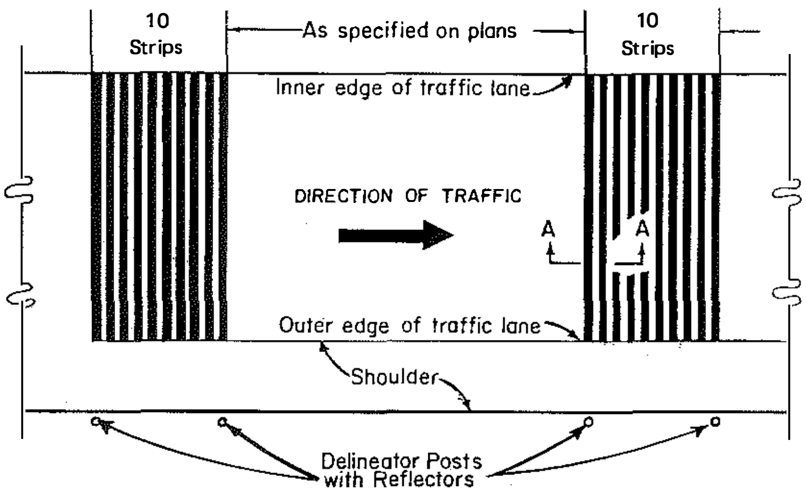
When used, rumble strips should be located so as to supplement conventional traffic control devices such as warning signs, stop signs, signals, flashers, etc. They should be located so as to call attention to warning signs or to other devices which will identify the particular hazard in question. Warning signs should normally be placed some distance beyond the particular group of rumble strips and not right adjacent to the strips themselves. The idea is that the rumble strips should be far enough in advance of the sign that the sign can be read after traversing the rumble strips.

Rumble strips should not be used in areas of super elevation or within close proximity to stop signs. In these areas tire contact with the pavement surface is extremely important. Rumble strips in these areas tend to break tire contact and contribute to hazards rather than being an effective warning device. Drainage of the pavement can be adversely affected by the application of rumble strips; therefore, extreme care should be taken by the designer to properly locate the strips both as a warning device and from the standpoint of tire contact areas and drainage.

Rumble strips are applied to correct or prevent certain high accident locations; however, their applications should be held to a minimum. They tend to lose their effectiveness when overexposed. In general, hazardous conditions should not be designed into a project but should be eliminated through the use of higher type design technique.

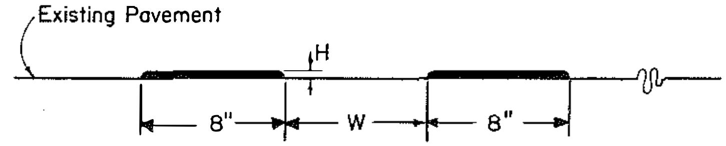
Details for materials and method of pay are to be found in the plans or Standard Drawings.

July 10, 1975



PLAN VIEW

TYPE	M.P.H.	H	W
1	0 - 45	1/4" – 3/8"	12"
2	OVER 45	3/8" – 1/2"	24"



PART-SECTION A-A

MATERIAL REQUIREMENTS

Approximate quantities required for one 10 strip 8' long unit.
- 0.08 Ton for 1/4" Bituminous Concrete Mix
- 0.12 Ton for 3/8" Bituminous Concrete Mix
- 0.15 Ton for 1/2" Bituminous Concrete Mix
- 0.60 Gal of Tack Coat

The Bituminous Material shall be either Class I Surface or Sand Asphalt Surface except that all the aggregate retained on the No. 4 sieve shall be removed prior to mixing the material. No. 11 stone may be used in Class I Surface for coarse aggregate in lieu of No. 8 Stone.

Two Delineator Posts shall be installed at each location. The reflective liquid will not be required on the top 4" of the post.

Two-3 3/8" diameter Type IIIA Silver White delineator units shall be installed at the top of each delineator post.

CONSTRUCTION REQUIREMENTS

The pavement shall be cleaned and the strips shall be constructed uniformly at right angles to the center line of the roadway.

The Tack Coat shall be applied full strength with a liberal brush coat.

Side forms or other approved methods shall be used to accomplish the desired 10 unit strip system. A sufficient amount of Bituminous mixture shall be placed in the forms and compacted with a light roller so as to provide a compacted thickness of 1/4" to 1/2" as applicable.

METHOD OF MEASUREMENT AND BASIS OF PAYMENT

The contract unit price Rumble Strips Type 1 or 2 for each ten (10) strip unit shall include all labor, forming, materials, delineator posts, delineator units and all other incidentals necessary to complete the one unit installation.

KENTUCKY
BUREAU OF HIGHWAYS

RUMBLE STRIPS

STANDARD DRAWING No. RPM-140
SUBMITTED [illegible] DIRECTOR DIVISION OF TRAFFIC [illegible] DATE
APPROVED [illegible] STATE HIGHWAY ENGINEER 2-23-25 DATE

Figure A1. Standard drawing for rumble strips.

Recommended Changes in Standard Drawing RPM-140

1. Under Material Requirements, quantities for rumble-strip heights other than 1/2 inch (13 mm) should be omitted.

2. The view showing PART -- SECTION A-A and the short table with dimensions based on speeds should be omitted and replaced with the following information.

   a. Width -- 4 inches (102 mm)
   b. Height -- 1/2 inch (13 mm)
   c. Spacing of strips -- 10 feet (3.0 m)
   d. Number of Strips in Set --
      Not to exceed 3/4 second of rumble time; calculate distance traveled when velocity and time are known. (For example, at 55 mph (24.6 m/s), a vehicle would travel 61 feet (18.6 m) in 3/4 second).
   e. Spacing of Sets --
      Dependent upon geometric conditions; however, the set of strips nearest the hazard should not be closer than the stopping sight distance.
   f. Total Number of Sets --
      Not more than three sets

Appendix B.

SUMMARY OF RUMBLE STRIP USAGE
IN KENTUCKY

Summary of Rumble Strip Usage in Kentucky.

County	Route	Milepoint	Location	Associated Hazard	Type	Design
Bath	I 64	121.2	Exit ramps of I 64 and KY 36 interchange	T-intersection	Grooved	3 sets on westbound ramp and 4 sets on eastbound ramp
Bath	I 64	123.0	Eastbound exit ramp at the I 64 US 60 interchange	T-intersection	Grooved	3 sets on eastbound ramp
Bell	US 119	0.0	US 25E at US 119	T-intersection	Raised	3 sets; 12 strips, 12" spacing (7" wide; 1/4-1/2" high)
Caldwell	Western KY Parkway	9.9	Princeton Toll Plaza	Toll booth approach	Grooved	3 sets
Christian	KY 1682	0.0	KY 1682 at US 68	Stop condition	Grooved	2 sets
Christian	KY 91	0.7	KY 91 at KY 1682	Stop condition	Grooved	2 sets
Christian	KY 109	12.1	KY 109 at KY 1682	Stop condition	Grooved	2 sets
Christian	Pennyrile Parkway	12.0	Hopkinsville Toll Plaza	Toll booth approach	Raised	3 sets of 1; 1 set of 30
Clay	Daniel Boone Parkway	34.2	Daniel Boone Parkway at KY 66	Toll booth approach	Raised	1 set; 10 strips, 16" spacing (6" wide, 1/4-1/2" high)
Daviess	US 60 Bypass	10.2	US 60 Bypass at US 60	T-intersection	Grooved	3 sets
Daviess	Green River Parkway	70.2	Green River Parkway at US 60 Bypass	End of parkway	Grooved	3 sets
Estill	KY 1571	0.0	KY 52	T-intersection	Raised	3 sets; 8 strips per set and 2' between strips (8" wide, 1/2" high)
Fleming	KY 11	0.0	KY 11 at KY 1325	T-intersection	Grooved	3 sets at 12' spacings
Graves	Jackson Purchase Parkway	13.7	Wingo Toll Plaza	Toll booth approach	Grooved	
Grayson	Western KY Parkway	107.0	Leitchfield Toll Plaza	Tool booth approach	Raised	8" spacing in groups of 12, each group spaced from 500 to 750' 8" wide, 1/4" high
Harlan	US 119	13.1	US 119 at US 421	T-intersection	Raised	4 sets; 10 strips, 16" spacing (7" wide, 1/4-1/2" high)
Henderson	Audubon Parkway	3.2	Hebbardsbille Toll Plaza	Toll booth approach	Grooved	3 sets
Hopkins	US 41A	0.0	US 41A - US 41	Stop condition	Grooved	3 sets
Hopkins	KY 70	23.2	KY 70 at KY 85	Stop condition	Grooved	2 sets
Hopkins	Western KY Parkway	24.4	Dawson Springs Toll Plaza	Toll booth approach	Grooved	3 sets

Summary of Rumble Strip Usage in Kentucky. *(Continued).*

County	Route	Milepoint	Location	Associated Hazard	Type	Design
Hopkins	KY 1751	1.4	KY 1751 at US 41 SB	Stop condition	Grooved	2 sets
Jefferson	I 71	6.0	Ramp from I 71 SB to I 65 SB	Hazardous curve	Raised	2 sets
Kenton	I 71-I 75	184-186	I 71-I 75	Construction detour	Raised	2 sets; 10 strips, 8" long units placed 8" apart for speeds of -45 mph, 16" apart for 45 mph
Laurel	Daniel Boone Parkway	0.0	Daniel Boone Parkway at US 25	Intersection	Grooved	1 set; 12 strips, 6" spacing (6" wide)
Laurel	Daniel Boone Parkway	7.2	Daniel Boone Parkway	Toll booth approach	Grooved	1 set; 12 strips, 6" spacing (6" wide)
Leslie	KY 118	44.2	Hyden Spur at US 421	T-intersection	Raised	5 sets; 14,14,19,20,21 strips; 16" spacing (6" wide, 1/2" high)
Leslie	Daniel Boone Parkway	44.2	Daniel Boone Parkway at Hyden Spur	Toll booth approach	Raised	2 sets; 10 strips, 16" spacing (6" wide, 1/4-1/2" high)
Lyon	Western KY Parkway	3.7	Western termini in advance of ramp at US 62	Slow condition	Grooved	
Magoffin	Mountain Parkway	69.0	Gullett Toll Plaza	Toll booth approach	Raised	3 sets; 8 strips per set and 2' spacing (8" wide, 1/2" high)
Marshall	Jackson Purchase Parkway	42.6	Benton Toll Plaza	Toll booth approach	Grooved	
Marshall	Jackson Purchase Parkway	52.3	Where eastern termini junctions with US 62	Stop condition	Grooved	7 sets; 300,400,500,750,1000,1500, 2500' from stop bar, length of set: 12-18'
McCracken	KY 286	2.3	Eastbound lane of KY 286 at US 62	Stop condition	Raised	
McCracken	US 68	0.0	Westbound lane of US 68 at US 62	Stop condition	Grooved	
Muhlenberg	Western KY Parkway	57.2	Central City Toll Plaza	Toll booth approach	Raised	3 sets
Nelson	Bluegrass Parkway	10.0	Boston Toll Plaza	Toll booth approach	Raised	8" spacing in groups of 12, each group spaced from 500 to 750' 8" wide, 1/4" high
Nelson	Bluegrass Parkway	33.3	Bloomfield Toll Plaza	Toll booth approach	Raised	Same as above
Ohio	Green River Parkway		Hartford Toll Plaza	Toll booth approach	Grooved	3 sets
Perry	Daniel Boone Parkway	59.0	KY 15	Unexpected stop condition at T-intersection	Raised	3 sets; 8 strips per set, 2' between strips, 8" wide, 3/8" high

Summary of Rumble Strip Usage in Kentucky. *(Continued).*

County	Route	Milepoint	Location	Associated Hazard	Type	Design
Powell	Mountain Parkway	14.8	Toll Plaza	Toll booth approach	Grooved	3 sets; 2' between each strip, 8 strips per set, 8" wide, 1/2" high
Powell	Mountain Parkway	32.8	Toll Plaza	Toll booth approach	Grooved	3 sets; 2' between each strip, 8 strips per set, 8" wide, 1/2" high
Powell	KY 15	4.2	KY 82	T-intersection	Grooved	5 sets; 2' between each strip, 8 strips per set, 8" wide, 1/2" high
Taylor	KY 55	10.0	Northbound on KY 55 at US 68	Intersection stop condition	Raised	4 sets; 12 strips, all 8" wide spacing: first two sets 24", third set 18", fourth set 12", all compacted depth - 3/8"
Webster	Pennyrile Parkway	62.6	Sebree Toll Plaza	Toll booth approach	Raised	3 sets
Wolfe	Mountain Parkway	46.2	Toll Plaza	Toll booth approach	Raised	3 sets, 8 strips per set, 2' between each strip, 8" wide, 1/2" high

Appendix C.

QUESTIONNAIRE AND SUMMARY OF
RUMBLE STRIP USAGE IN OTHER STATES

Rumble Strip Usage in Other States

ALABAMA

Good experience has been reported with rumble strip installations. The only drawback was noise to nearby residences. Criteria for rumble strip installation include:

1. When an intersection is hidden from view by either a horizontal or vertical curve.
2. When an intersection has a history of accidents caused by failure to observe the traffic control device.
3. When the traffic control device is not expected following an extremely long tangent.

It was also noted that rumble strips should be considered as temporary corrective measures and installation should coincide with recognition that the existing facility is inadequate in design.

ARKANSAS

Use of rumble strips has been limited even though they are considered to have a positive effect on alerting the motorists to an impending condition. Design is based on research by the New Jersey DOT (published in the April 1969 issue of Traffic Engineering).

CALIFORNIA

No specific warrants or design specifications for the installation of rumble strips are used. A very limited number of rumble strips have been installed.

COLORADO

Rumble-strip installations are based solely on engineering judgment, and no warrants have been established. Raised types are preferred because freezing and thawing makes use of the grooved types unsatisfactory. Grooved strips lose their effectiveness because of chipping, cracking, and general enlarging of the groove.

CONNECTICUT

Some installations were made, but most were eliminated soon after placement as a result of complaints registered by drivers concerned with noise and damage to their vehicles.

DELAWARE

Rumble-strip installations have been used successfully at rural stop approaches and at sharp curves. It has been concluded that rumble strips are useful to prevent accidents when other methods are not completely effective.

GEORGIA

No specific warrants are used; however, rumble strips are generally installed on approaches to stop signs where accident experience indicates that inadequate observation of the stop condition is a substantial problem. Because of noise, they are not recommended for use in residental areas unless all other methods have failed.

HAWAII

Raised pavement markers have been used as rumble strips at two locations. One installation was at a rural intersection and the other was at a temporary freeway-end exit with a very unusual alignment.

IDAHO

Variable results have been reported with the use of rumble strips. Snowplowing operations generally nullify the benefit from rumble strips in one snow season. Chip sealing served the purpose of surface sealing requirements and also provided a random rumble strip. Installation of random chip sealing on a section of interstate did decrease accidents in one direction but had no significant effect in the other direction.

ILLINOIS

Warrants have been developed which specify rumble strips in advance of stop signs at intersections where the number of accidents exceeds 3.0 for the past 2 years and where at least 50 percent of the accidents have been right-angle collisions. In addition, rumble strips are used at the termination of a freeway facility when the number of lanes has been reduced to one. Either grooved strips or a continuous overlay of aggregate has been used.

INDIANA

Rumble strips have been used where results show that other traffic control devices have been ineffective in controlling undesirable occurrences. The use of rumble strips has declined over the past several years because of maintenance problems and some indications that rumble strips may cause erratic and undesirable vehicle behavior. The use of grooved strips appear to hold more promise than the raised strip.

IOWA

Both grooved and raised strips have been used; however, a decision has been made to use only the grooved strip because it provides better noise and causes less disturbance to the vehicle and driver. Wide-

H.3.75

Dear Mr. ______________:

The Kentucky Bureau of Highways is conducting a study with the objective of developing standards for the design and application of rumble strips. We are surveying other states to determine what policies have been developed in this area. Your response to the following questions concerning your state's official policy on rumble strips would be greatly appreciated:

1. Does your state have specific warrants for the installation of rumble strips? If so, what are the warrants? If not, what procedure is used?
2. What design specifications does your state use concerning the following aspects of rumble strips: strip width, strip height, spacing between strips, the number of strips in each group, spacing between groups, and the number of groups in each set?
3. What effect does speed have on the design criteria? What effect does varying the grouping of strips have on the design criteria?
4. What comparisons have you drawn between raised and grooved strips?
5. How have drivers reacted to the audible and physical stimuli produced by contact with the rumble strips? What effects have you found rumble strips to have on different types of vehicles?

Again, we would appreciate any information you can provide concerning rumble-strip design and application. If requested, we will supply you with the summary of our survey when it is concluded.

Thank you for your cooperation.

Sincerely yours,

Jerry G. Pigman
Research Engineer Chief

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spread use would diminish the value of the device and would be objectionable to the public. Presently, rumble strips are used only in advance of a stop condition.

KANSAS

Warrants have not been developed, but installations are generally guided by average accident experience for the type of intersection under study. For rural locations with an entering ADT less than 5,000, the average is eight accidents per ten million entering vehicles. Raised rumble strips made of hot-mixed, bituminous material are normally used and some installations with a 1-inch (25-mm) thickness have created considerable adverse reactions from the public.

LOUISIANA

Rumble strips as generally defined are not used; however, raised pavement markers are placed on the shoulder lane of bridges to prevent usage as a driving lane.

MASSACHUSETTS

Peastone seal applications and granite rumble blocks are used within the area separating a ramp entrance from the through roadway.

MICHIGAN

Installation of rumble strips is based on engineering judgment, accident rates, evidence of conflicts, or high potential for accidents. A polyvinyl chloride, raised rumble strip has been used successfully at several sites.

MINNESOTA

Rumble strips currently in use are raised strips located only in the wheel paths. Grooved strips in bituminous pavements have not been durable or effective.

MISSISSIPPI

Rumble strips have been used as an alerting device on approaches to stop conditions at hidden intersections. A height of the strip above 1/2 inch (12 mm) increases the physical discomfort to the point where motorists attempt to dodge the installations. The general opinion is that rumble strips should be used sparingly and only as a last resort where other traffic control measures have failed.

MISSOURI

Rumble strips have been used at a few trial locations; and based on that experience, no plans have been made for standardized design or usage.

NEBRASKA

Rumble strips have been used satisfactorily for many years in front of STOP AHEAD signs where two or three "ran the STOP sign" accidents have occurred. Grooved strips are being tested as a possibility of replacing raised strips made of epoxy binder and aggregate. The epoxy bar is effective for approximately 4 years.

NEW JERSEY

Rumble strips are used only where it is felt that conventional methods are inadequate for warning motorists of an unusual situation. Some research has been conducted; however, specific warrants for the use of rumble strips have not been developed.

NEW MEXICO

Experience with rumble strips indicates that accidents can be reduced at high-accident "T" intersections. The opinion was expressed that speed should determine the grouping of strips. As speed decreases, the strips should be placed closer together.

NORTH CAROLINA

Rumble strips have been used when other traffic control devices, such as signs and flashers, failed to create an awareness in motorists of an upcoming condition. Raised strips are damaged or torn away by snowplows and their jarring effect has caused adverse reactions from the public.

NORTH DAKOTA

Warrants for rumble strips require three or more accidents over a 5-year period at an intersection. Grooved strips were found to be preferable to the raised type because of lower cost and generally equal performance. The 4-inch (101-mm) groove at 8-inch (202-mm) spacings was preferable to the 6-inch (152-mm) groove.

OKLAHOMA

Even though a few rumble strips have been installed where standard treatments have failed, they are not recognized as an effective traffic control device.

PENNSYLVANIA

Rumble strips are only installed as a remedial treatment after other traffic engineering measures have been tried and found unsuccessful. Grooved strips are preferred over raised strips since frequent snowplowing destroys the raised rumble strip. Warrants for rumble strips include: (1) intersections having a history of four or more accidents per year, (2) intersections where a stop-sign observance study reveals poor adherence, and (3) other locations with high-accident experience where signing has proven inadequate and a reduction in speed is desirable.

jiggle bars are used as rumble strips.

RHODE ISLAND

Precast concrete, reflectorized gore markers have been used at freeway ramp tenninals.

SOUTH CAROLINA

Rumble strips have been used at stop approaches to rural intersections. Spacings between the raised rumble strip are graduated, attempting to provide a constant time element between strips if motorists decelerate in a normal fashion.

TENNESSEE

Varying results have been achieved with rumble strips used as an audible warning to accentuate the "STOP AHEAD," "JUNCTION," and "STOP" signs. Accident experience shows a decrease in "ran stop" and "rear-end" collisions; however, accident rates at intersections controlled by two-way stops have not been reduced. Rumble strips are viewed as having little or no value as a permanent installation and should never be considered as part of normal highway design.

TEXAS

Rumble strips are recommended for use only across areas which are not intended for vehicular travel, such as emergency parking lanes on bridges and the triangular area between throughway and ramps. They are not recommended for use on full control-of-access highways. They are not recommended for use, except as a last resort, across the traveled lanes of any conventional highway. Reflectorized ceramic or plastic jiggle bars are used as rumble strips.

UTAH

Because of problems encountered with snow removal, rumble strips have been installed on some projects only because of requirements of the Federal Highway Administration.

VIRGINIA

Rumble strips are used at stopping or exaggerated decelerating situations where motorists tend to run off the road. Spacings of 2 feet (0.61 m) or less caused wheel hop or did not allow tires to touch the pavement between raised rumble strips. Spacings of 10 feet (3 m) between sets were found to be best for stopping situations and five feet spacing best for shoulders.

WISCONSIN

Rumble strips are used only at known high-accident locations; use at potential hazardous locations is not recommended because of the probability of overexposure. On bituminous pavements, it was noted that grooved strips have a significantly longer effective life than raised strips.

WYOMING

Installations of rumble strips on a section of interstate were not successful in reducing the number of accidents. Opinion was expressed that rumble strips would be more useful at locations such as "T" intersections, where a motorist must stop.

Appendix D.

STATISTICAL TESTS

Statistical Tests

The normal approximation was used to evaluate the significance between the changes in average speed at the measurement sites *(D1)*. When using this method, it is assumed that there is no significant difference in the before and after means and that they are representative of the same population. The accuracy of this assumption is then examined.

If the sample size is sufficiently large (n has a value of at least 30), both X_1 and X_2 (sample means from the before and after studies) are mean values of samples from a population and have the same distribution (no significant difference in before or after population), the value $(X_1 - X_2)$ approaches a mean of 0 and a standard deviation of σ_D. The value σ_D is given by

$$\sigma_D = \sqrt{(S_1^2/n_1) + (S_2^2/n_2)}$$

in which S = standard deviation and n = sample size.

Given that $(X_1 - X_2)$ is greater than 3.09 σ_D, it is at most 0.1-percent probable that this difference occurred by chance, if the two samples are representative of the same distribution. The assumption that X_1 and X_2 are from the same distribution is, therefore, rejected; and the difference observed is taken as significant (P = 0.999). This high level of significance was chosen because of the small speed reduction necessary to be statistically significant at lower levels of significance. The following table is a summary of statistical tests to determine whether the differences in speeds were significant between the before and after conditions.

Table D1. Statistical Tests For Speeds Before and After Rumble Strip Installations.

APPROACH	DISTANCE IN FEET (M) FROM INTERSECTION	N_1	X_1	σ_1	N_2	X_2	σ_2	σ_D	3.09 σ_D	$X_1 - X_2$	SIGNIFICANT
Southbound	1,400 (427)	63	50.8	4.90	65	50.8	4.58	0.84	2.59	0	No
Southbound	900 (274)	109	47.1	6.26	135	46.6	5.34	0.75	2.33	0.5	No
Southbound	700 (213)	113	43.2	6.23	94	42.4	5.03	0.78	2.41	0.8	No
Southbound	500 (152)	115	38.9	4.64	130	37.9	5.51	0.65	2.01	1.0	No
Southbound	200 (61)	80	30.4	3.80	66	29.5	4.84	0.73	2.26	0.9	No
Northbound	1,400 (427)	32	49.8	4.00	38	50.3	4.42	1.00	3.09	-0.5	No
Northbound	900 (274)	75	45.8	5.14	87	47.1	4.52	0.76	2.35	-1.3	No
Northbound	700 (213)	93	43.4	4.40	89	43.0	4.56	0.66	2.04	0.4	No
Northbound	500 (152)	114	39.2	4.82	85	39.3	3.18	0.57	1.76	-0.1	No
Northbound	200 (61)	73	30.5	3.18	43	31.0	3.30	0.62	1.92	-0.5	No

N_1 -- Number of observations before installation
X_1 -- Mean value of speeds before installation
σ_1 -- Standard deviation of speeds before installation
N_2 -- Number of observations after installation
X_2 -- Mean value of speeds after installation
σ_2 -- Standard deviation of speeds after installation

REFERENCE

D1. Pignataro, L.J.; **Traffic Engineering Theory and Practice**, Prentice Hall, Inc., 1973.