Elevated-Risk Work Zone Evaluation of Temporary Rumble Strips

Carlos Sun*, Ph.D., P.E., E2509 Lafferre Hall, University of Missouri-Columbia, Missouri 65201, csun@missouri.edu, Tel: 573-884-6330, Fax: 573-882-4784

Praveen Edara, Ph.D., E3502 Lafferre Hall, University of Missouri-Columbia, Missouri 65201 edarap@missouri.edu, Tel: 573-882-1900, Fax: 573-882-4784

Kyle Ervin, Rhythm Engineering, 12351 West 96th Terrace, Lenexa, Kansas 66215 kyle@rhythmtraffic.com, Phone (913)-227-0603, Fax (913)-227-0674

Keywords: Temporary Rumble Strip, Work Zone, Speed Study, Road Safety

*Corresponding Author: Carlos Sun

A paper submitted for publication in the Journal of Transportation Safety and Security

ABSTRACT

A field study was conducted on a Missouri low volume road to examine if temporary rumble strips could improve safety in elevated risk work zones. This study complements previous studies by addressing several new issues: vehicles that cross over a lane to bypass strips, physical displacement of strips and deployment of strips at an angle. An objective was to measure performance in a challenging and non-idealized site, thus the site contained geometric challenges such as curves, a bridge approach, and a pavement transition.

The study found an increase of over 10% in the number of vehicles that braked due to rumble strips, an average speed decrease of up to 6 kph (3.7 mph), and an increase in speed compliance of 2.9% for the braking vehicles. But the number of lane crossovers increased by 8.79%. The study also compared rumble strips deployed perpendicularly and at an angle, and found no significant differences in braking and speed reductions but found an increase in lane crossovers. In terms of vertical movement, perpendicular strips did not move while angled strips...
moved up to 3.73 cm per 100 wheel impacts. Taking into account all study measures, the rumble strips provided a net improvement in safety.

1. INTRODUCTION

Temporary rumble strips are designed to alert drivers of construction zones, short term work zones, temporary lane closures, and law enforcement checkpoints by providing vibratory and auditory feedback. The goal of the study is to measure the effectiveness of the rumble strip in improving safety near a work zone and to consider any effects related to its deployment. The study differs from some previous studies in that actual and not controlled vehicles are driven over the rumble strips in a highway work zone. The temporary rumble strip also differs from rumble strips evaluated in previous studies. Here, the rumble strips are not glued or screwed onto the surface of the road but remain in place because of weight and friction.

According to the manufacturer of the temporary rumble strip tested in this study, the Roadquake is an all-weather portable temporary rumble strip (PTRS) made from engineered polymer material (PSS 2009). A single strip measures 11 feet in length, 12 inches in width and 13/16 inch in thickness. The rumble strip is designed to span an entire driving lane. At a weight of 105 lbs., they can be moved by a crew of two workers and is heavy enough to remain deployed. No fasteners or adhesives are required for installation. Figure 1 shows a person deploying the system by unrolling a single strip.

1.1 Review of Temporary Rumble Strips

The New York State Department of Transportation (NYSDOT) studied temporary rumble strips as part of an investigation into different work zone intrusion countermeasures (Morgan 2003). NYSDOT investigated the following: 8 to 10 mm thick tape, glued-on 6 inch by 4-6 feet
long plastic bumps (the Rumbler), recycled tire tread strip, raised asphalt, traffic count tube, and screwed down reinforced rubber belt. The Rumbler was also evaluated by the Smart Work Zone deployment initiative (Horowitz 2002). NYSDOT used a controlled vehicle to drive over each rumble strip several times. NYSDOT concluded that the use of temporary rumble strips at work zones is effective in alerting drivers and should be continued. For the adhesive strips, NYSDOT reported that there were some problems such as tearing, shoving, and poor adhesion. For the screwed down strips, there were some problems with loose screws and strips pulled free from the pavement. NYSDOT also mentioned the Speedblocker rumble strip which is a 18 cm by 21.6 cm long fabric and metal reinforced rubber mat fastened by screws and weighing 190 kg. NYSDOT did not evaluate the Speedblocker. NYSDOT surveyed and found the following eleven states have tested or used rumble strips in work zones: California, Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Mexico, Ohio, Pennsylvania and South Dakota.

Kansas Department of Transportation (KDOT) evaluated the Advanced Traffic Markings (ATM) which is a 3.175 mm (0.125 inch) thick and 100 mm (4 inch) wide raised plastic strip with polymeric tapes and adhesive. KDOT found ATM to significantly reduce the mean and 85% speed for both passenger cars and trucks (Meyer 2000).

Fontaine and Carlson (2001) evaluated the effectiveness of portable rumble strips at rural maintenance work zones in Texas. The dimensions of the rumble strips evaluated were different from the ones used in Kansas (Meyer 2000). The thickness of strips and spacing between them were greater than those used in the Kansas study. The rumble strips caused a slight decrease of 3.2 kph in average passenger car speeds and a decrease of 3.2 to 11.3 kph in average truck speeds. Also, the speed limit compliance increased between 1% and 7% for passenger cars.
Schrock et al (2010) measured the vibration and sound generating capabilities of two different types of portable rumble strips and compared them with those of permanent rumble strips. The portable plastic rumble strips (PPRS) and adhesive rubberized polymer rumble strips (ARPRS) were tested. The closed-course tests found that the PPRS were more effective at generating in-vehicle vibration and sound in passenger cars than trucks. The PPRS performance matched the performance of permanent rumble strips better than the ARPRS. Also, Heaslip et al (2010) measured the lateral movement of the fourth generation PPRS and steel-based rumble strips and found that the PPRS outperformed all the other types. The investigators then conducted field evaluations of these PPRS at rural short-term maintenance work zones in Kansas (Wang et al. 2011). They found that the speed reduction due to PPRS was more significant for cars than trucks. They found 30% to 80% of trucks applied brakes as they approached the PPRS and about 5% of all vehicles swerved around the PPRS.

In summary, previous evaluations of temporary rumble strips demonstrated that temporary rumble strips generated a significant audible and vibratory alert so as to improve the safety of road construction workers, drivers, and pedestrians. However, there were reported problems with loss of adhesion, loose screws, or tearing. The studies also reported decrease in average vehicle speeds, increase in speed limit compliance, and braking. The current study examined the additional issues of vehicle crossovers, angled deployment, and rumble strip displacement.

2. FIELD DATA COLLECTION

2.1 Field Site

One common challenge of empirical studies in work zones is the acquisition of a good field study site. Since road work typically reduces existing capacity, agencies are not willing to
artificially reduce capacity for the sake of a traffic study. For this study, a non-idealized site was sought in order to investigate how temporary rumble strips perform in an elevated risk setting. Thus the Missouri Department of Transportation (MoDOT) wanted to deploy such an additional safety tool at a complicated site involving vertical and horizontal curves, a pavement transition, and a bridge approach.

For this study, the field site was a MUTCD (Manual of Uniform Traffic Control Devices) Typical Application (TA) 12 work zone (FHWA, 2004). TA-12 is a one-lane two-way operation controlled by a temporary traffic signal. Because of the safety concerns with a two-way operation, it was a good location for the deployment of temporary rumble strips. The work zone was a bridge replacement project located on Route 17 near Lexington Road in Waynesville, Missouri. Route 17 had a speed limit of 80 kph (50 mph) that was reduced to 64.4 kph (40 mph) for the work zone. Some sections of Route 17 were 88.5 kph (55 mph).

Similar to other field study sites, this particular site had advantages and disadvantages. One challenge in using this site was that additional traffic control devices were deployed, since it was a one-lane two-way operation in curvy terrain. The devices were more than usual for a typical TA-12. The large number of devices could have masked the impact of the rumble strips. The layout of the site along with the deployed devices, as shown in Figure 2, included the typical road work ahead and speed limit reduction signs, a radar speed trailer, a “bump sign” warning of a pavement transition, and cones separating the new bridge and rumble strips. Another challenge was that there was a horizontal curve, a vertical curve, and a pavement transition immediately upstream from the rumble strip location. These geometric features could have naturally slowed vehicles, once again masking the potential impact of the rumble strips. Another challenge was the narrow driving lanes on the bridge immediately downstream from the rumble strips. The ten
foot lanes and the bridge configuration could have caused vehicles to slow down or encroach on the opposing lane.

This site also had several advantages. First, the site reflected the complexities of a location with elevated safety risk. This site thus complemented other studies where rumble strips were deployed on a flat and straight roadway. Second, the eastbound direction involved a new bridge that was not yet opened. This provided a location where the researchers could park and where data collection equipment could be safely deployed. Third, traffic was light, thus minimizing the number of platoons. Platoons and congestion were undesirable since the goal of this project was to isolate the effect of the rumble strips on driver behavior. Fourth, there was an elevated vantage point just upstream of the rumble strip deployment that provided an excellent field-of-view of the entire site.

### 2.2 Rumble Strip Configuration

Temporary rumble strips were deployed by MoDOT in two pairs of two strips each approximately three feet apart from center to center. When traveling eastbound on Route 17, one pair was upstream from the bridge and the other was downstream in the westbound direction. As shown in Figure 3, the strips were deployed at an angle to the direction of travel at approximately N60° E to the centerline of the road. Presumably the strips were deployed at this angle so that each wheel would hit them individually, thus the driver felt four impacts per strip as opposed to two simultaneous hits if the strips were perpendicular. After significant data was collected for the angled configuration, the researchers re-deployed the strips perpendicular to the road. When the strips were tested perpendicular to the road, they were placed approximately three feet apart from center to center. According to the manufacturer, the strips have been tested at 30.5 cm (12
in) and 91.4 cm (36 in) center to center spacing (PSS, 2009). The manufacturer showed pictures of sample deployments that consisted of at least four strips in succession that were deployed perpendicular to the direction of travel (1). Thus the deployment of two instead of four strips did not conform to the manufacturer’s specifications. The researchers did not have access to additional rumble strips.

2.3 Data Collection Setup

Two video cameras and one radar gun were used to capture traffic data as shown in Figure 4. One camera was located next to the lane of travel with a receding view so that the radar gun readout, lane crossovers, and brake lights could all be viewed within the same field-of-view. The other camera was placed at an elevation of approximately 6 m (20 ft) on a hill just north of the road. Data processing involved the derivation of the following:

- Time and frame at which the vehicle speed was taken and the number of vehicles
- Type of vehicle
- If the vehicle was part of a platoon
  - The speed upstream and downstream from the rumble strips
  - If brakes were applied
- Any partial or complete crossovers into the opposing lane

Unlike data collected from automated counters, this investigation involved the detailed review of video of individual vehicle movements. In contrast, automated counters are not able to identify brake lights, assess the extent of crossovers, recognize platoons or track speeds over distance. For every hour of field data, four hours were spent processing the data for traffic parameters and driver behavior.
Table 1 summarizes the data collection times and the corresponding traffic flows. Table 1 shows the flow rate was light during all the data collection periods. The data collection consisted of approximately 12 hours over two days and a total of 24 hours of video footage. The low flow during the weekend allowed for the examination of individual vehicles instead of platoons. The 24 hours of video footage was significant because of the amount of detail that was derived from each vehicle.

3. RESULTS

3.1 Effect of Temporary Rumble Strips

The MoDOT deployment of the rumble strip was compared against the control scenario without any rumble strip deployment. The overall volumes of the two configurations were similar, so it could be assumed that driving times and conditions did not vary much between configurations. The parameters examined included speeds upstream and downstream from the location of the strips, percentage of drivers applying brakes, and centerline crossovers. Table 2 shows the traffic characteristics for with and without rumble strip deployments. Note that the traffic characteristics of vehicles following in a platoon are not included. Row 3 shows the average speed difference between upstream (Row 1) and downstream (Row 2). Row 4 shows the percentage of drivers in which brake lights were observed. Row 5 shows the percentage of drivers who either completely crossed over (no contact made with the strips) or partially crossed over (at least one set of wheels contacted strips). Platoon in Row 6 is defined as vehicles that were constrained by the leading vehicle as determined visually from the video footage. Row 7 shows the number of platooned vehicles in parenthesis. The data from Column 1 is divided into vehicles with brakes applied (Column 2) and vehicles without brakes applied (Column 3). The
vehicles that encroached upon the adjacent lane (Column 4) are contrasted with those who stayed entirely in the lane (Column 5).

For the without rumble strip deployment scenario, Table 2 shows the average upstream and downstream speeds as 57.23 kph (35.56 mph) and 58.64 (36.44 mph). Thus there was an average speed increase of 1.42 kph (0.88 mph) downstream from where the rumble strips were deployed. The percentage of vehicles that braked was 12.33%. The percentage of vehicles that crossed over the centerline was 51.89%. The percentage of vehicles in platoons was 12.13%.

For the rumble strip deployment scenario, Table 2 shows the average upstream and downstream speeds as 56.6 kph (35.17 mph) and 57.04 kph (35.44 mph). Thus there was an average speed increase of 0.43 kph (0.27 mph) downstream from where the rumble strips were deployed. The percentage of vehicles that braked was 22.82%. The percentage of vehicles that crossed over the centerline was 60.48% (partial and complete crossovers) with the percentage of total crossovers being 5.38%. The percentage of vehicles observed in platoons was 10.76%.

Based on these comparisons, some possible trade-offs of rumble strip deployment could be identified. First, observed braking could be evidence of driver awareness of unusual road conditions. The percentage of drivers that braked was 22.82% for angled strips and 12.33% without any strips. An average speed reduction of 5.97 kph (3.71 mph) was observed for the vehicles that braked after traveling over the strips. In contrast, a speed reduction of only 0.98 kph (0.61 mph) was observed when no strips were deployed. This was possible evidence of the effectiveness of the rumble strips, because the number of braking vehicles almost doubled and the magnitude of speed decrease was much larger with the rumble strips deployed.

Second, the average speeds and speed distributions with and without rumble strips were compared. The average speeds decreased by 0.63 kph (0.39 mph) and 1.61 kph (1 mph) for the
upstream and downstream locations, respectively, when rumble strips were deployed. Figure 5 shows the distribution of speeds. Note that the end bins, 25 and 50, take on the remaining values so that the end bins contain enough samples for statistical testing. Focusing on the downstream speed compliance, Figure 5 shows the percentage of vehicles exceeding the speed limit of 64.4 kph (40 mph) was 22.2% without rumble strips and 19.3% with rumble strips. The upstream speed distributions for with and without strips were found to be similar. But for downstream, Figure 5 shows that the speed distribution was shifted toward the lower speeds for the rumble strip deployment. In other words, there were fewer vehicles in the high speed bins and more vehicles in the low speed bins. This again, is possible evidence of the effectiveness of rumble strips because speeds were reduced, and a greater number of vehicles complied with the speed limit. Despite the aforementioned differences in the average downstream speeds and speed distributions, the difference in speed distributions for with and without rumble strips was not statistically significant. Note that this does not mean that the speed distributions were the same; only that there was no statistical evidence for the distributions being different. Pearson’s Chi-Squared ($\chi^2$) test was used to test for statistical differences between the distributions. The Chi-Squared test statistic (NIST, 2006) is

$$\chi^2 = \sum_{i=1}^{n} \frac{O_i - E_i}{E_i}$$

where

- $O_i$ is the observed frequency of speeds for bin $i$
- $E_i$ is the expected frequency of speeds for bin $i$
- $i$ is an index representing the number of bins in the speed distribution
Here, observed represents ‘with rumble strips’ and expected represents ‘without rumble strips’. The p-value was 0.675 for the downstream speeds with 5 degrees of freedom. Typically, a p-value of less than 0.1 (90% confidence) or 0.05 (95% confidence) are considered to be significant.

Third, crossing the centerline (crossover) could be due to drivers wanting to avoid traveling over rumble strips or because of the narrow 10 foot lanes on the bridge. It might be reasonable to assume that complete crossovers are due entirely to the desire to avoid rumble strips, but partial crossovers could be due to both rumble strips and narrow lanes. Figure 4b shows an example of a partial crossover. The total percentage of crossovers was 60.68% for angled strips with 5.38% being complete crossovers, and total percentage was 51.89% without the rumble strips. The ideal scenario in a “before and after” study would be to first collect the data without any treatments. Then the treatment would be applied and a normalization period would follow to allow drivers to adjust to the treatment. Finally, the after data would be collected. Unfortunately, field situations are never ideal. Because the ‘without strips’ scenario was implemented after the strips were in place for some time, the percentage of crossovers for that scenario could be due to some drivers’ past knowledge that the strips have been deployed.

In terms of the significance of crossovers, on the one hand the 8.79% increase in crossovers for rumble strips reveals a possible undesirable effect of rumble strips. On the other, crossovers are possible evidence that rumble strips are effective in generating significant sound and vibration thus alerting drivers of the work zone.
3.2 Comparison of Angled vs. Perpendicular Rumble Strips

A comparison of the angled versus perpendicular deployment was made since the manufacturer recommended deployment of the rumble strips perpendicular to the direction of travel. Table 2 shows the traffic characteristics of the perpendicular rumble strips in contrast to the angled rumble strips. There were similarities in the results between the two rumble strip configurations. The percentage of drivers who braked was similar being 22.82% for angled and 21.25% for perpendicular or a 1.57% difference. The difference between upstream and downstream speeds was similar being 0.43 kph (0.27 mph) for angled and 0.45 kph (0.28 mph) for perpendicular. When vehicles braked downstream, the speed was reduced similarly for the angled (4.07 kph/2.53 mph) and the perpendicular (4.92 kph/3.06 mph) deployments.

There are also some notable differences. Both the total percentage of crossovers and the percentage of complete crossovers were higher for perpendicular deployment. The total percentage was higher by 11.31% and the percentage of complete crossovers was higher by 1.21%. One possible reason for the higher percentages for perpendicular strips was that perpendicular strips moved much less than angled strips. Thus the perpendicular strip covered the entire travel lane while the angled strips slowly moved towards the shoulder. The movement of rumble strips is discussed in more detail in the next section. Despite the fact that crossovers could be undesirable from a safety standpoint, they were an indication that drivers were alerted of the rumble strips.

Figure 6 shows that the speed distributions for angled and perpendicular were different for both upstream and downstream. The angled strips speed distribution is more desirable because it had fewer number of vehicles in the high speed bins and greater number of vehicles in the low speed bins. The Chi-Squared test produced p-values of 0.0362 and 0.0363 respectively.
for upstream and downstream. The degrees of freedom were 5 for both. The Chi-Squared test showed the differences in speed distributions were statistically significant. One possible reason for the differences was that the angled strips produced four separate rumble strip hits while the perpendicular produced two hits. This could mean that in order to maximize effectiveness, perpendicular strips should be deployed in greater numbers. Another possible reason was that the traffic that traveled over the perpendicular strips had different characteristics than the traffic that traveled over the angled strips. One support for this reason was that the upstream distribution showed a similar difference as the downstream. This was in contrast to the comparison between angled strips and no strips where the upstream distribution was similar but the downstream distribution was somewhat different. Thus the upstream distribution could be viewed as a control.

3.3 Analysis of Deflection or Rumble Strip Movement

To measure the amount of deflection, the rumble strips were outlined with pavement chalk before the start of each data collection period. Then after a significant amount of time had elapsed, the amount of rumble strip movement or deflection was measured. Photographs were taken of the measurement as shown in Figure 7. Because of the non-slip texture and the weight of the rumble strip, the assumption was made that any movement would be due to wheel contact or impact and not environmental factors such as wind.

Table 3 summarizes the results of the deflection data. The vertical deflection is the amount of movement from the original outline of the top of the strip, and the horizontal deflection is the amount of movement from the outline of the side of the strip. The symbol Δ was used in Table 3 as a short-hand for deflection. Because traffic flow varied throughout the data collection period, the rate of Δ/100 wheel impacts was used to control for exposure. The
number of wheel impacts was used since only one wheel per axle contacted the rumble strip for partial crossovers.

In analyzing the deflection results, one should note that part of the rumble strip was on the adjoining grass as the lanes were only ten feet wide. Comparing the vertical deflections, the angled strips moved at a rate of 1.70 cm (0.67 in) and 3.73 cm (1.47 in) per 100 impacts for strips one and two respectively, while the perpendicular strips had negligible movement. It was unclear why there were differences in the deflection between the two strips in a rumble strip series. After 1,204 impacts, the maximum vertical deflections were 11.43 and 24.13 cm (4.5 in and 9.5 in) for angled strips; and after 361 impacts, there was no noticeable deflection for the perpendicular strips. Comparing the horizontal deflections, the angled strips moved at a rate of 0.41 cm and 0.81 cm (0.16 in and 0.32 in) per 100 impacts for strips one and two respectively; while the perpendicular strips moved at a rate of 0.36 cm and 0.71 cm (0.14 in and 0.28 in) per 100 impacts. After 1,204 impacts, the maximum horizontal deflections were 5.72 cm and 11.43 cm (2.25 in and 4.5 in) for angled strips one and two respectively; and after 361 impacts, the maximum horizontal deflections were 1.27 cm and 2.54 cm (0.5 inch and 1 inch) for perpendicular strips. The horizontal movement of the rumble strips was in the opposite direction for angled and perpendicular deployments. For angled strips, the strips moved backwards as shown in Figure 7. For perpendicular strips, the strips moved forward. In summary, the deflection of the angled strips was much greater than the perpendicular strips, thus making the angled deployment less desirable.

4. CONCLUSIONS

A primary goal of the temporary rumble strips is to improve road safety by alerting drivers of unusual road conditions. Another goal is for the strips to remain in place without the
use of adhesives or screws. This study used several parameters to assess the effectiveness of the temporary rumble strips. The parameters and the results are summarized as follows:

- Percentage of braking vehicles: average increase of up to 10.49% (statistically significant, p=0.000)
- Speed of braking vehicles: average decrease of up to 5.97 kph/3.71 mph (statistically significant, p=0.000)
- Speed compliance: average increase of 2.9% (statistically significant, p=0.000)
- Speed distribution: shift towards lower speeds (not statistically significant, p=0.675)
- Number of crossovers: increase of 8.79% (statistically significant, p=0.000)
- Vertical deflection: up to 3.73 cm/1.47 in per 100 impacts for angled strips
- Vertical deflection: 0 cm/0 in per 100 impacts for perpendicular strips
- Horizontal deflection: up to 0.81 cm/0.32 in per 100 impacts for angled strips
- Horizontal deflection: 0.71 cm/0.28 in per 100 impacts for perpendicular strips

The increase in braking, decrease in speed of braking vehicles, and increase in speed compliance are all evidence of the effectiveness of rumble strips for increasing safety. The deflection of perpendicular strips is not very significant, but the deflection of angled strips is very significant and undesirable. As a result, the researchers agree with manufacturer’s suggested perpendicular deployment and in greater numbers than just two.

The increase in lane crossovers could be undesirable depending on the opposite lane volumes, but the crossovers could be mitigated by the deployment of rumble strips across both lanes of traffic. Traffic that is heading in the opposite direction would not be dramatically affected as they are traveling at a slow speed while leaving the work zone. The striping allowed
for passing, so the crossovers were not forbidden. A better solution would be to deploy more than two strips in a series as recommended by the manufacturer. The greater number of strips would potentially make it undesirable to cross over to the opposite lane. Another possible solution is to reduce the vibration and sound produced by the rumble strip, but that could also reduce the effectiveness.

The observed increase in speed compliance of 2.9% was within the range of 1% to 7% reported by Fontaine and Carlson (2001) in their Texas study. A slight decrease in the mean speed and a shift in the speed distribution towards lower speeds were observed but were not statistically significant. Previous research reported slightly higher reductions in the mean speeds due to rumble strips. However, it was not possible to directly compare their results with the current study results since the previous studies did not report the effect on all vehicles (they treated cars and trucks separately). Also, the effect of rumble strips on different vehicle types was not consistent across studies. For example, Fontaine and Carlson (2001) stated, “The rumble strips did not appear to significantly affect the speeds of passenger cars.” And, they reported a greater speed reduction in truck speeds ranging between 2 mph and 7 mph. On the other hand, Wang et al. (2011) found portable rumble strips to be more effective in reducing speeds of cars than trucks. However, the type of rumble strips evaluated by Wang et al. (2011) were different than the adhesive-based rumble strips tested by Fontaine and Carlson (2001). Even though the results of the current study cannot be directly compared with past studies due to differences in site characteristics and in some performance measures, they complement existing studies by providing data for sites with elevated risk.

The study site presented several challenges. First, narrow 3 m (10 ft) lanes caused vehicles to cross over to the opposite lane and resulted in a section of the 3.35 m (11 ft) strip to
overhang the pavement edge which negatively impacted the strips’ resistance to movement.

Second, the complex nature of the site involving one-lane two-way operation, pavement transitions, bridge closure, geometric curves and the resulting saturation of traffic control devices could have masked the impact of the rumble strips. It was unclear if drivers were already alert and careful due to the complexities of the site. Third, no data was collected before the rumble strips were deployed. Rumble strips were later removed to investigate the no strips scenario. Frequent travelers of the road might be used to the rumble strips and react as if they were still deployed. Because of these challenges, this study describes the realistic benefits and consequences that could result in work zones with elevated risk.

ACKNOWLEDGEMENT

The authors would like to acknowledge the kind assistance by the following individuals. Dan Smith and Michael Shea from the MoDOT Traffic Division coordinated the search for an appropriate site for this study. Victoria Woods was the Resident Engineer for the project and gave the researchers permission to study at the project site. Tim Cox from Plastic Safety Systems helped to define the need for the study and gave insights into the characteristics and performance of the rumble strips. Jordan Freborg assisted with data processing and reduction.

REFERENCES


Presentation at the American Traffic Safety Services Association (ATSSA) 39th Annual Convention and Traffic Expo, San Jose, California, February 1-5.


<table>
<thead>
<tr>
<th>Configuration</th>
<th>Date</th>
<th>Start Time</th>
<th>End Time</th>
<th>Time (hr)</th>
<th>Vehs.</th>
<th>Flow (vph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angled</td>
<td>10/3/09 (Sat.)</td>
<td>11:17:10</td>
<td>15:43:23</td>
<td>4.43</td>
<td>297</td>
<td>67.0</td>
</tr>
<tr>
<td>No strip</td>
<td>10/3/09 (Sat.)</td>
<td>15:44:33</td>
<td>18:53:53</td>
<td>3.15</td>
<td>206</td>
<td>65.4</td>
</tr>
<tr>
<td>Perpendicular</td>
<td>10/4/09 (Sun.)</td>
<td>7:44:14</td>
<td>10:46:01</td>
<td>3.03</td>
<td>292</td>
<td>96.3</td>
</tr>
<tr>
<td>No strip</td>
<td>10/4/09 (Sun.)</td>
<td>10:48:46</td>
<td>11:53:51</td>
<td>1.08</td>
<td>55</td>
<td>50.7</td>
</tr>
</tbody>
</table>
### TABLE 2 Before and After Traffic Characteristics

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Avg. Speed Upstream (kph)</td>
<td>57.23</td>
<td>57.76</td>
<td>57.15</td>
<td>57.58</td>
<td>56.78</td>
</tr>
<tr>
<td>2. Avg. Speed Downstream (kph)</td>
<td>58.64</td>
<td>57.81</td>
<td>58.79</td>
<td>58.92</td>
<td>58.29</td>
</tr>
<tr>
<td>3. Avg. Speed Difference (kph)</td>
<td>1.42</td>
<td>0.05</td>
<td>1.64</td>
<td>1.32</td>
<td>1.53</td>
</tr>
<tr>
<td>4. % Brakes</td>
<td>12.33%</td>
<td>100.00%</td>
<td>0.00%</td>
<td>12.64%</td>
<td>12.03%</td>
</tr>
<tr>
<td>5. % Lane X-Over</td>
<td>51.89%</td>
<td>53.23%</td>
<td>51.84%</td>
<td>100.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>6. % Platoons</td>
<td>12.13%</td>
<td>0.00%</td>
<td>0.26%</td>
<td>11.49%</td>
<td>12.86%</td>
</tr>
<tr>
<td>7. Total Vehicles</td>
<td>442 (503)</td>
<td>62</td>
<td>380</td>
<td>261</td>
<td>241</td>
</tr>
</tbody>
</table>

### Angled Strips Data

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Avg. Speed Upstream (kph)</td>
<td>56.60</td>
<td>54.75</td>
<td>57.73</td>
<td>57.07</td>
<td>57.61</td>
</tr>
<tr>
<td>2. Avg. Speed Downstream (kph)</td>
<td>57.04</td>
<td>52.96</td>
<td>58.93</td>
<td>56.79</td>
<td>58.26</td>
</tr>
<tr>
<td>3. Avg. Speed Difference (kph)</td>
<td>0.43</td>
<td>-1.79</td>
<td>1.21</td>
<td>-0.29</td>
<td>0.64</td>
</tr>
<tr>
<td>4. % Brakes</td>
<td>22.82%</td>
<td>100.00%</td>
<td>0.00%</td>
<td>27.59%</td>
<td>20.20%</td>
</tr>
<tr>
<td>5a. % Complete X-Over</td>
<td>5.38%</td>
<td>6.50%</td>
<td>5.35%</td>
<td>100.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>5b. % Partial X-Over</td>
<td>55.10%</td>
<td>48.78%</td>
<td>57.46%</td>
<td>0.00%</td>
<td>100.00%</td>
</tr>
<tr>
<td>6. % Platoons</td>
<td>10.76%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>3.45%</td>
<td>10.77%</td>
</tr>
<tr>
<td>7. Total Vehicles</td>
<td>478 (539)</td>
<td>123</td>
<td>355</td>
<td>29</td>
<td>297</td>
</tr>
</tbody>
</table>

### Perpendicular Strip Data

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Avg. Speed Upstream (kph)</td>
<td>59.95</td>
<td>57.58</td>
<td>60.59</td>
<td>58.47</td>
<td>61.04</td>
</tr>
<tr>
<td>2. Avg. Speed Downstream (kph)</td>
<td>60.40</td>
<td>55.47</td>
<td>61.73</td>
<td>58.39</td>
<td>61.57</td>
</tr>
<tr>
<td>3. Avg. Speed Difference (kph)</td>
<td>0.45</td>
<td>-2.11</td>
<td>1.14</td>
<td>-0.10</td>
<td>0.53</td>
</tr>
<tr>
<td>4. %Brakes</td>
<td>21.25%</td>
<td>100.00%</td>
<td>0.00%</td>
<td>27.78%</td>
<td>16.29%</td>
</tr>
<tr>
<td>5a. % Complete X-Over</td>
<td>6.59%</td>
<td>8.62%</td>
<td>6.02%</td>
<td>100.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>5b. % Partial X-Over</td>
<td>65.20%</td>
<td>50.00%</td>
<td>63.89%</td>
<td>0.00%</td>
<td>100.00%</td>
</tr>
<tr>
<td>6. % Platoons</td>
<td>5.86%</td>
<td>0.00%</td>
<td>0.46%</td>
<td>0.00%</td>
<td>6.18%</td>
</tr>
<tr>
<td>7. Total Vehicles</td>
<td>274(290)</td>
<td>58</td>
<td>216</td>
<td>18</td>
<td>178</td>
</tr>
</tbody>
</table>

21
<table>
<thead>
<tr>
<th>Approx. Cumul. Wheel Impacts</th>
<th>Strip 1 Vert. Δ cm</th>
<th>Δ/100 impacts</th>
<th>Strip 1 Hor. Δ cm</th>
<th>Δ/100 impacts</th>
<th>Strip 2 Vert. Δ cm</th>
<th>Δ/100 impacts</th>
<th>Strip 2 Hor. Δ cm</th>
<th>Δ/100 impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>501</td>
<td>8.89</td>
<td>1.78</td>
<td>Minimal</td>
<td>0.00</td>
<td>20.32</td>
<td>4.06</td>
<td>Minimal</td>
<td>0.00</td>
</tr>
<tr>
<td>703</td>
<td>11.43</td>
<td>1.63</td>
<td>5.72</td>
<td>0.81</td>
<td>24.13</td>
<td>3.43</td>
<td>11.43</td>
<td>1.63</td>
</tr>
<tr>
<td>Average Δ/100</td>
<td>1.70</td>
<td>Average Δ/100</td>
<td>0.41</td>
<td>Average Δ/100</td>
<td>3.73</td>
<td>Average Δ/100</td>
<td>0.81</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Approx. Cumul. Wheel Impacts</th>
<th>Strip 1 Vert. Δ cm</th>
<th>Δ/100 impacts</th>
<th>Strip 1 Hor. Δ cm</th>
<th>Δ/100 impacts</th>
<th>Strip 2 Vert. Δ cm</th>
<th>Δ/100 impacts</th>
<th>Strip 2 Hor. Δ cm</th>
<th>Δ/100 impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>361</td>
<td>Minimal</td>
<td>0.00</td>
<td>1.27</td>
<td>0.36</td>
<td>Minimal</td>
<td>0.00</td>
<td>2.54</td>
<td>0.28</td>
</tr>
<tr>
<td>Average Δ/100</td>
<td>0.00</td>
<td>Average Δ/100</td>
<td>0.36</td>
<td>Average Δ/100</td>
<td>0.00</td>
<td>Average Δ/100</td>
<td>0.28</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 3 Rumble Strip Movement**
FIGURE 1 Rumble strip deployment (1).

FIGURE 2 Field site temporary traffic control.
FIGURE 3 Angled rumble strips deployment by MoDOT.
FIGURE 4a. Elevated view.

FIGURE 4b. Ground level view.

FIGURE 4. Video surveillance fields-of-view.
FIGURE 5 Speed distributions upstream and downstream of the rumble strip location.
FIGURE 6 Speed distributions upstream and downstream of the rumble strip location.
FIGURE 7 Example of horizontal deflection measurement of an angled strip.