EVALUATION OF INNOVATIVE PAVEMENT MARKINGS WITH APPLICATIONS IN WORK ZONES

MAY, 2003

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Acknowledgements:

The Office of Traffic, Security, and Operations (OTSO) would like to thank the 3M Traffic Materials Division for donating all of the pavement marking tape that was used in this study, as well as for allowing Mn/DOT to use their test center complex for preliminary material testing.

OTSO would also like to thank Mn/DOT's District 6 Rochester and District 7 Mankato staff for their participation in field testing.

Additionally, OTSO would like to thank Mn/DOT's Office of Construction for their extensive participation in preliminary testing, field testing, and report preparation.

Finally, OTSO would like to thank the many others who participated in this study by providing traffic control, materials installation, data collection, or report review.

EXECUTIVE SUMMARY

Concept Introduction

Work zones on the highway often present unexpected conditions to the driver and thus can create unsafe conditions. Of particular concern are drivers who wait too long to merge in advance of a closed lane in a work zone and drivers who do not slow down to a safe speed when entering a work zone. One way to potentially influence driver behavior is through the use of pavement markings. In the summer of 2000, together with 3M, the offices of Traffic, Security, and Operations (OTSO) and Construction (OC) within the Minnesota Department of Transportation (Mn/DOT) began a research project to determine whether or not innovative pavement markings could be used in work zones to help address these problems.

Preliminary testing was conducted in the summer of 2000 at the 3M Transportation Safety Research Center located in Cottage Grove, MN. All pavement markings that were used as part of this study were durable tape products and were supplied to Mn/DOT at no cost by 3M. As a result of preliminary testing, three pavement marking designs were finalized for field testing. The following is a brief description of each:

1. “Tiger Tails” (for speed reduction): Tiger Tails, a phrase coined by the researchers, are broken chevrons that would be placed within the lane and should create the illusion of faster travel, thus encouraging the motorist to reduce their speed. See Figure EX-1.

2. “Shark’s Teeth” (for early merge): Shark’s Teeth, a phrase also coined by the researchers, are triangular shaped pavement markings that would be placed with a point of the triangle pointing towards the lane into which vehicles must merge. See Figure EX-2.

3. Lane Arrows (for early merge): lane arrows were not specifically tested during the initial phase since these markings have been used in the past in the field. The initial design called for a length of 12 feet and a placement angle of approximately 30 degrees off the roadway edgeline.

Figure EX-1
Tiger Tail Marking

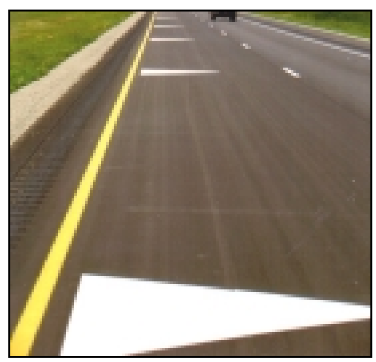


Figure EX-2
Shark’s Tooth Marking

This study included three years worth of data collection and analysis. Three separate field testing locations were chosen based on roadway design, observability of the location by the researchers, and relatively low average daily traffic (ADT). Site 1 was chosen and researched. Based on those results, site 2 was chosen as a follow-up study. Site 3 was then chosen for result verification. The following work zones were used for sites 1-3:

- Site 1: I-90, east of I-35, near Albert Lea, MN. Left lane closure on a freeway. Field testing occurred during summer of 2000.
- Site 2: TH 14, near Mankato, MN. Right lane closure on an expressway. Field testing occurred during the summer of 2001.
- Site 3: I-35, north of I-90, again near Albert Lea, MN. Right lane closure on a freeway. Field testing occurred during the summer of 2002.

Tiger Tails and Speed Reduction

Tiger Tail research only occurred at site 1. Baseline speed data was collected at site 1 for both daytime and nighttime operations. The Tiger Tail pavement markings were placed in advance of a lane shift sign. Speed data was again collected during daytime and nighttime conditions. The results of the speed study showed no meaningful reductions in speed during daytime conditions. Speed reductions were realized during nighttime conditions, though these were merely spot reductions – that is, immediately after the motorist crossed the Tiger Tails and slowed, they began to increase their speed again. This would suggest that Tiger Tail pavement markings might be effective in poorly lit rural work zones.

Because the results of this research were not promising, further testing was not pursued.

Lane Arrows / Shark's Teeth and Early Merge

Lane Arrow research occurred at all three sites, while Shark's Teeth were examined at only sites 1 and 2. In order to document the lateral placement of merging drivers, the study area was broken up into three zones: A, B, and C. At each site, zones A and B were of equal length and spanned from the merge sign to the beginning of the lane taper (A+B = 1,200' at sites 1 & 3, A+B = 900' at site 2). Zone C was the section of roadway where the lane taper occurred. For comparative purposes, baseline merging characteristics were recorded at all three sites.

The results of Shark's Teeth at site 1 were very promising, although the installation process presented some challenges. For example, the size of each Shark's Tooth precluded its ability to be installed in one piece – each Shark's Tooth had two strips of tape that had to be manually matched, installed, and rolled in the field. However, because the results were so promising, Shark's Teeth were included in the research for site 2. Site 2 results were similar to those at site 1; however, because the performance of the Lane Arrow improved significantly (and ease of installation was greater), the concept of the Shark's Teeth was abandoned at site 3.

The results of the Lane Arrows were poor at site 1. Because of this, the initial design was modified. The size of the arrows was increased from 12 feet to 19 feet. As a result, site 2 and 3 merge characteristics were extremely impressive. Motorists merged earlier and in a more desirable manner.

Conclusions & Recommendations

As a result of this research, the following conclusions and recommendations can be made:

- Tiger Tails do not appear to be effective in reducing motorists' speeds in a meaningful way. However, there may be an application for Tiger Tails in rural, poorly lit work zones.
- Shark's Teeth were effective in promoting early merges, however because the Lane Arrows equaled or outperformed them at sites 2 and 3, they are not recommended for further field implementation.
- Lane Arrows appear to be the clear winner for promoting early merging, and thus show the most promise for widespread field implementation. Therefore, it is recommended that Mn/DOT consider the use of Lane Arrows in construction or maintenance work zones with an ADT of less than 15,000 where a lane must be closed (and remain closed) as part of a long term work zone. The 19 foot design should be used, which is a standard stock inventory size that can be ordered off the shelf.

INTRODUCTION

Work zones on the highway often present unexpected conditions to the driver. When driver expectations are not met, drivers may react by making poor decisions that can endanger themselves, other drivers, and the people working in the area. Of particular concern are drivers who wait too long to merge in advance of a closed lane in a work zone. Late merging disrupts traffic flow, thus increasing the potential for a crash.

Drivers exceeding the speed limit increase the potential for unsafe work zone conditions. In order for drivers to safely stop, merge, or maneuver they must be able to react in the required time frame. As drivers increase their speed, the distance they need to stop, merge, or maneuver increases. Therefore, safety is compromised as a result of drivers not having enough distance to react to unexpected or unique circumstances present in the work zone.

Many factors may contribute to the driver's speed or how they merge in a work zone. One way to potentially influence driver behavior is through the use of pavement markings. Innovative pavement markings such as the chevron and lane arrows have been recently used in various locations throughout the world. The chevron has been used to encourage drivers to reduce speed and the lane arrow has been used to encourage drivers to merge earlier. One problem with adopting the use of these pavement markings is the lack of available data regarding their use. For this reason, the Minnesota Department of Transportation (Mn/DOT) decided to perform further research.

PRELIMINARY TESTING

To more thoroughly research innovative pavement markings, Mn/DOT partnered with 3M to conduct a study. The 3M Transportation Safety Research Center in Cottage Grove, MN, is an isolated testing area for field research. 3M agreed to grant Mn/DOT use of this site for testing purposes. 3M also provided all of Series 620 removable pavement marking tape, manufactured by 3M, necessary to create numerous pavement marking designs.

Figure 1
Shark's Tooth Marking

Initial testing took place in May, 2000. The test consisted of Mn/DOT personnel from different disciplines driving on a merge test area. Triangular pavement markings, referred to as "Shark's Teeth" by the researchers, were placed in the test area with varying sizes and spacings. Figure 1 illustrates an example of the Shark's Tooth pavement markings. Variations in design included the spacing, size, and dimensions of the Shark's Teeth. Upon completing the course Mn/DOT personnel reported their opinions on the new pavement markings and refinements were then discussed.

Figure 2
Tiger Tail Marking

The first test was encouraging in that the participants agreed that the Shark's Teeth showed promise in effectively encouraging drivers to merge, but some changes to the design were necessary. First, the Shark's Teeth were difficult to see as the motorist approaches the work area. The markings needed to be enlarged and spaced more aggressively to increase conspicuity. The shape of the Shark's Teeth also needed modification. The longitudinal lengths of the Shark's Teeth were disproportionately small compared to the transverse lengths, and therefore simply increasing the size would not solve the problem. The pattern needed to be enlarged in the longitudinal direction in order to improve the visibility of the markings.

After considering the findings from the first test, a second test was conducted in July, 2000, using broken chevrons, referred to as "Tiger Tail" markings by the researchers. Figure 2 illustrates an example of the Tiger Tail pavement markings. Again 3M provided the materials and site to perform the testing.

Similar to the first evaluation, Mn/DOT personnel drove the merge test area marked with Tiger Tails and reported their opinions. Participants driving at the 3M road course felt that the Tiger Tails could effectively encourage drivers to reduce speed. Similar to the first evaluation, it was determined that the markings needed to be enlarged and spaced more aggressively.

CHOOSING A STUDY SITE

As a result of preliminary testing, a design for Shark's Teeth and Tiger Tail had been developed and was ready for field testing in a work zone. The following criteria were *required* in choosing a study site:

- 4-lane divided freeway/highway (55 mph minimum speed limit under normal conditions),
- Ability to observe and record data at the site without causing passing motorists to focus attention on the researcher.
- Long term work zone for adequate researching opportunities

The following criteria were *preferred* in choosing a site:

- Relatively low traffic volumes
- Relatively high percentage of non-local traffic
- Location within 100 miles of Minneapolis/St. Paul

Traffic volumes with an average daily traffic (ADT) of less than approximately 15,000 allow the driver to choose when and how they merge based on traffic control measures. As traffic volumes increase, the driver's point of merge is increasingly influenced by congestion and adequate gap selection rather than traffic control measures.

A high percentage of non-local traffic at the site was important because these drivers were probably unfamiliar with the work zone. Drivers who are unfamiliar with the work zone are more likely to be influenced by traffic control measures such as signs and pavement markings. Local drivers, who probably are familiar with the work zone, likely drive on auto-pilot, paying little attention to traffic control measures such as pavement markings.

Having the location within 100 miles of Minneapolis/St. Paul was desired for ease of researcher scheduling at the test site.

STUDY SITE 1: I-90

After considering all the criteria, I-90 near Albert Lea, MN was chosen as the site for the first pavement marking study. I-90 is a four lane divided freeway with a posted speed limit of 70 mph. The ADT is 8,800, of which 1,650 (18.75%) is commercial heavy truck traffic. There is a relatively high percentage of non-local traffic in the area.

Construction at the site involved pavement resurfacing and bridge deck rehabilitation. The construction on I-90 spanned from I-35 to approximately 3 miles east of the I-35/I-90 interchange. Construction, at the time of the study, had been underway for about eight weeks. A closure of the left (inside) lane on westbound I-90, at the east end of the work zone, provided the location to perform the merge study. A temporary speed limit of 55 mph was in place for the entire length of the construction site. All other traffic control devices were installed in accordance with standard construction specifications.

One drawback to the site was a detour present at I-35/I-90. All traffic desiring to travel westbound on I-90 from I-35 was detoured onto eastbound I-90. At the first available interchange, traffic exited and re-entered the interstate on westbound I-90. This detour had the potential to familiarize drivers to the work zone prior to entering the study area.

Procedure: I-90 Merge Study

In order to document the lateral placement of merging drivers, the study area was broken up into three zones, A, B, and C. Zone A was approximately 600 feet long and began at the merge sign. Zone B began at the end of Zone A, ended at the beginning of the lane taper, and also was approximately 600 feet long. Zone C was defined as the section of roadway where the lane taper occurred and was approximately 900 feet long. Figure 3 shows the relative size and location of each zone and includes Lane Arrows in Zone A.

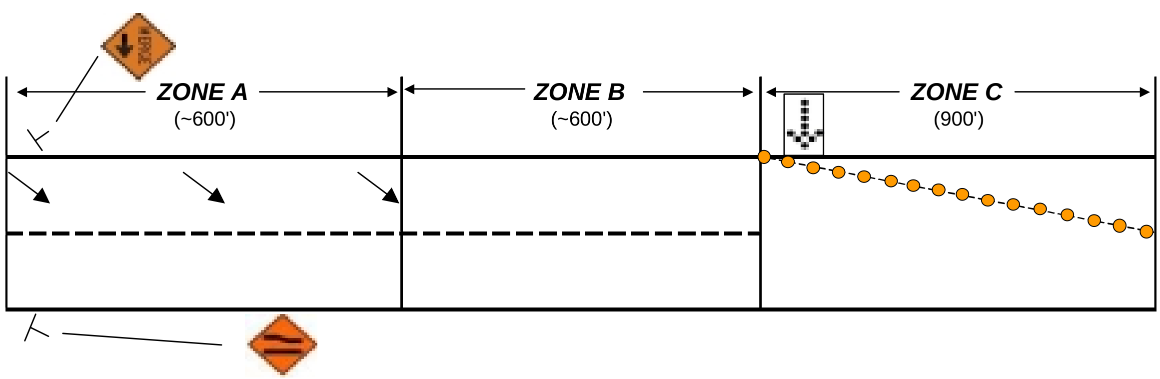


Figure 3
I-90 Zone Definition

For each of the merging studies, vehicles were documented as having merged in one of the three zones: A, B, or C. For each zone, the merging vehicle had to be at least halfway into the right (outside) lane to be considered merged. In addition, the characteristics of each merge were classified into one of four categories and recorded. The four categories were:

1. Decelerate to Merge – driver currently in lane that will end, decreases speed to merge into adjacent lane that will remain open

2. Normal Merge – driver currently in lane that will end, maintains speed while merging into adjacent lane that will remain open

3. Accelerate to Merge – driver currently in lane that will end, increases speed to merge into adjacent lane that will remain open

4. Begin to Pass – driver currently in lane that will remain open, changes lanes into lane that will close and begins a passing maneuver

Categorizing how a driver merged in the work zone was important because the act alone of merging early does not necessarily translate to a safe or positive behavior. Of the four categories, decelerate to merge and normal merge were considered positive behaviors, while accelerate to merge and begin to pass were considered negative behaviors.

On July 27, 2000, a base study was performed on traffic merging in the work zone on I-90. For a period of six hours, 9:00 a.m. to 3:00 p.m., 1247 vehicles passed through the study area. Approximately 82% of those vehicles were already in the outside lane prior to entering the study area. Observers recorded data for the remaining 18% of the vehicles.

I-90 Shark's Teeth Condition

Approximately one month later, on August 24, 2000, Shark's Teeth pavement markings were installed and studied on I-90. The Shark's Teeth had a transverse length of six feet and were placed every 75 feet from the merge sign up to the lane taper. Three more Shark's Teeth continued into the lane taper at the same spacing.

As in the base study, observers recorded how the drivers merged and the zone they merged in from a nearby bridge. Tube counters were used to record the number of vehicles that entered the study area. Over a period of six hours, 9:00 a.m. to 3:00 p.m., 895 vehicles were recorded. Of the 895 vehicles, 115 vehicles merged in the study area.

I-90 Lane Arrow Condition

On September 5, 2000, Shark's Teeth were removed and Lane Arrow pavement markings were installed and studied on I-90. The Lane Arrows were twelve feet long and directed at an angle of approximately 30 degrees from the roadway edgeline. A total of three Lane Arrows were placed, starting at the merge sign, and spaced every 400 feet thereafter.

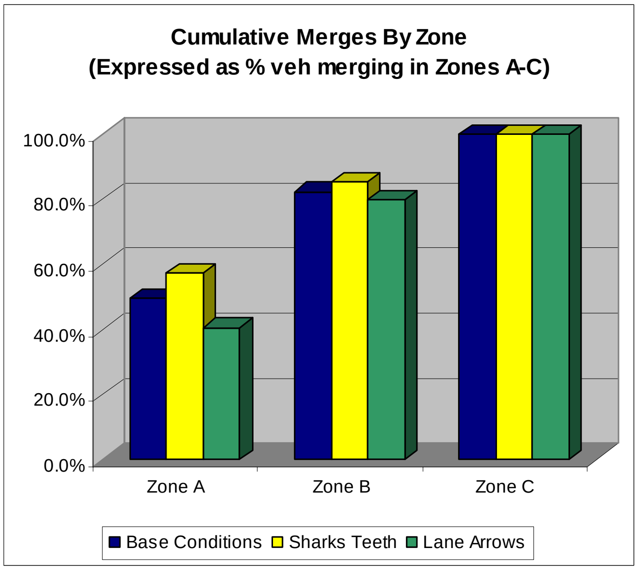
The same data was collected as in the two previous merge studies. Over a period of six hours, 9:00 a.m. to 3:00 p.m., 922 vehicles were recorded. Of the 922 vehicles, 138 vehicles merged in the study area.

Results: I-90 Merge Study

One of the objectives of the study was to encourage drivers to merge earlier prior to a lane closure. It was determined that the best way to quantify the effectiveness of both Shark's Teeth and Lane Arrows was to compare the cumulative percentage of vehicles that had merged by the end of each zone. Whether a larger percentage of drivers merged in Zone A versus Zone B was not as important as whether drivers had merged at some point in one of the two zones. Results for cumulative merges by zone as well as cumulative desirable merges by zone, for each of the three merge patterns, are shown in Figure 4. Desirable merges are defined as "decelerate to merge" and "normal merge".

Shark's Teeth recorded a larger percentage than the other two merge patterns for early merges. 57% of drivers merged in Zone A compared to 50% in the base condition study and over 85% of the drivers merged by the end of Zone B compared to 82% in the base study. The Lane Arrows showed no improvement over the base study.

For the case of Shark's Teeth pavement markings, 96% of all the merges were considered desirable compared to 83% in the base condition study. Again the Lane Arrows showed no improvement over the base condition.



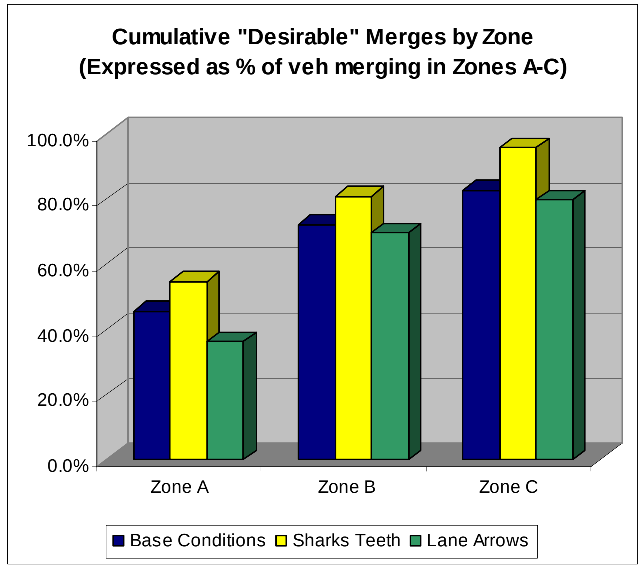


Figure 4
I-90 Cumulative Merges by Zone

Figure 4 shows that Shark's Teeth outperformed both the Lane Arrows and the base conditions. Shark's Teeth not only appear to have encouraged drivers to merge earlier, but driver behavior appears to have improved. Simply encouraging drivers to merge early will not necessarily result in safer work zone conditions. The fact that both the early merges and desirable early merges increased from the base condition validates the idea that innovative pavement markings can improve work zone safety.

After studying the early merge Shark's Teeth and Lane Arrows at this location, it was recommended to choose another site for study. Additional research was needed to support and validate the effectiveness of innovative pavement markings. For the next study site, it was recommended to pick a location that would provide a larger sample size. The relatively low sample size at the I-90 location could have had an affect on the results. The small sample size may also have been responsible for why the Lane Arrows showed little difference from the base conditions.

Procedure: I-90 Speed Reduction Study

The speed reduction study took place in the I-90 work zone, just east of I-35, as well. Using handheld laser devices, experienced personnel collected speeds of free-flow vehicles (minimum 7 sec. headway) at two points upstream of the reverse curve on the east end of the work zone. It should be noted that an advisory speed limit sign of 40 m.p.h was posted for the reverse curve.

On July 27, 2000, from 9:30 a.m. to 11:00 a.m., speeds were collected during normal daytime traffic conditions at both locations. On July 31, 2000, from 9:30 p.m. to midnight, night time base conditions were collected.

On August 23, 2000 Tiger Tail pavement markings were installed on I-90. Tiger Tails were placed in advance of the reverse curve sign. The Tiger Tails were installed so that spacing was progressively decreased, thereby creating the perception of a vehicle traveling faster than it is in reality. If the pavement markings could create the illusion that the vehicle was traveling faster than it actually was, the driver would feel constrained and would consequently reduce their speed.

On the night of the installation of the Tiger Tails, speed data was collected from 9:15 p.m. to 11:00 p.m. at both locations. The following morning, speed data was again collected at those locations from 9:30 a.m. to 11:00 a.m.

Results: I-90 Speed Reduction Study

Table 1 lists spot speed data before and after the Tiger Tail pavement markings were installed. Speed data at both locations is listed during daytime and nighttime conditions. An additional column, highlighted in yellow, lists changes from the "before" to the "after" conditions.

Typical speed measurements of effectiveness (MOE) such as 85^{th} percentile speed, 50^{th} percentile speed, and mean speed showed very little change as a result of the Tiger Tails. All these values, at both speed check locations, fell within a one to three mile per hour window of the base condition. These changes are statistically significant, but in practical operation, these small changes are meaningless as an indicator of behavioral improvement in the work zone. However, specific behaviors within the data set indicate some improvements that can be used to determine further study projects for job specific applications.

One notable change is that most MOE's for the nighttime study showed a decrease in speed. The pavement markings were made with reflective white tape and placed on new bituminous pavement; therefore, the pavement markings were more pronounced at night.

The Tiger Tail pattern reduced the percentage of high-speed drivers at night, especially at the reverse curve warning sign. This would suggest that Tiger Tail pavement markings might be effective in poorly lit rural work zones.

Finally, drivers seemed to decrease speed most at the end of the first series of Tiger Tails. Unfortunately, it made minimal difference to the curve entry speed 750 feet away. The 750 feet gave drivers enough time to perform a secondary judgment about navigating the curve. Further research could determine if a better placement of warning signs and pavement treatments would improve speed characteristics.

Table 1
I-90 Spot Speed Study Results

		Daylight			Night		
		Before	After	Change	Before	After	Change
At Reverse Curve Sign	85th Percentile	64	63	-1	66	63	-3
	50th Percentile	59	57	-2	58	56	-2
	Mean Speed	59	57	-2	59	57	-2
	Mean Speed of top 15%	68	68	No Change	70	66	-4
	10 mph pace	53 - 62	53 - 62	No Change	53 - 62	51 - 60	-2
	Percent in 10 mph pace	66%	64%	-2%	64%	68%	4%
	Percent above 35 mph	100%	100%	No Change	100%	100%	No Change
	Percent above 45 mph	99%	97%	-2%	99%	99%	No Change
	Percent above 55 mph	75%	62%	-13%	71%	53%	-18%
	Percent above 65 mph	12%	11%	-1%	15%	9%	-6%
	Percent above 75 mph	2%	3%	1%	6%	1%	-5%
Entering Crossover	85th Percentile	57	57	No Change	57	55	-2
	50th Percentile	51	51	No Change	49	49	No Change
	Mean Speed	51	51	No Change	50	49	-1
	Mean Speed of top 15%	60	60	No Change	62	60	-2
	10 mph pace	47 - 56	45 - 54	-2	44 - 53	44 - 53	No Change
	Percent in 10 mph pace	59%	62%	3%	65%	59%	-6%
	Percent above 35 mph	99%	100%	1%	100%	98%	-2%
	Percent above 45 mph	83%	86%	3%	79%	70%	-9%
	Percent above 55 mph	24%	24%	No Change	19%	14%	-5%
	Percent above 65 mph	1%	0%	-1%	3%	2%	-1%
	Percent above 75 mph	0%	0%	No Change	0%	0%	No Change

STUDY SITE 2: TH 14

After performing the initial merge study on I-90 near Albert Lea, it was determined that the results warranted further study. It was important to find a location that would produce a larger sample size. The preferred method to obtain a larger sample size was to find a location with a right (outside) lane closure. Construction on TH 14 near Mankato involved a complete interchange rebuild and offered the opportunity to study traffic under a right lane closure.

TH 14 is a four lane divided highway with a posted speed limit of 55 mph. The ADT was 9500, of which 780 (8.2%) was commercial heavy truck traffic. A relatively low percentage of traffic in this location was non-local.

Procedure: TH 14 Merge Study

In order to document the lateral placement of merging drivers, the study area was broken up into three zones, A, B, and C. Zone A was approximately 450 feet long and began at the merge sign. Zone B began at the end of Zone A, ended at the beginning of the lane taper, and was approximately 450 feet long. Zone C was defined as the section of roadway where the lane taper occurred and was approximately 700 feet long. Figure 5 shows the relative size and location of each zone and includes Lane Arrows in Zones A and B.

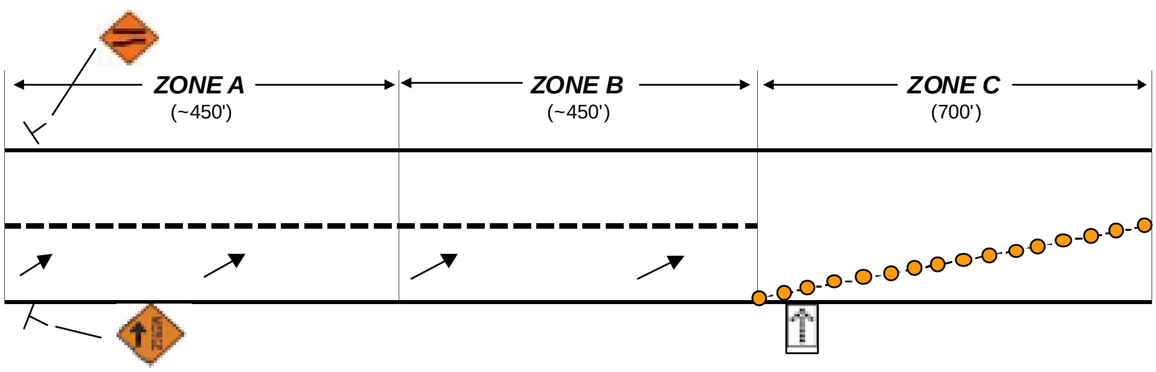


Figure 5
TH 14 Zone Definition

On August 28, 2001, a base study was performed on traffic merging in the work zone on TH 14. Data was recorded for 452 drivers.

On September 11, 2001, Shark's Teeth pavement markings were installed and studied on TH 14. Twelve Shark's Teeth, each with a transverse length of six feet, were placed at intervals of 75 feet beginning at the merge sign. Observers then recorded the merges and behavior of 382 vehicles entering the study area. Figure 6 is a picture of a Shark's Tooth from the TH 14 project area.

Figure 6
TH 14 Shark's Tooth with Black Outlining Tape

On September 25, 2001, the Shark's Teeth were removed and Lane Arrows were installed and studied on

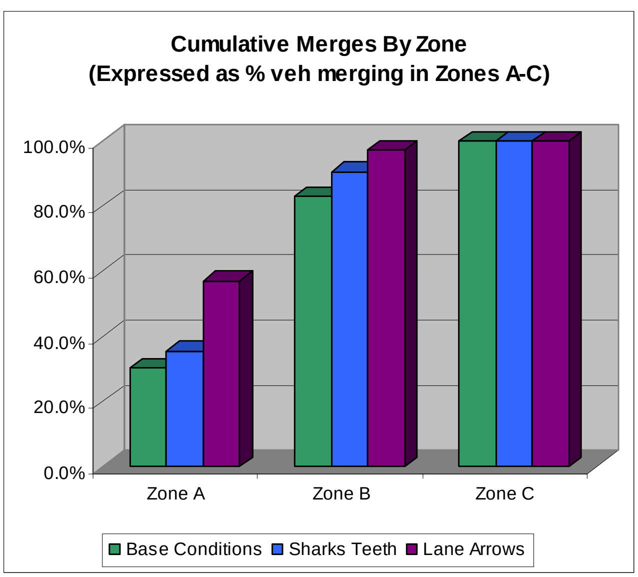
Figure 7
TH 14 Lane Arrows with Black Outlining Tape

TH 14. Four Lane Arrows, each with a length of 19 feet, were installed at intervals of 200 feet beginning at the merge sign. Observers then recorded the merges and behavior of 434 vehicles in the study area. Figure 7 is a picture of a Lane Arrow from the TH 14 study project area.

One notable difference in the installation of the Shark's Teeth and Lane Arrows on TH 14 as compared to I-90, was the use of black outlining tape. TH 14 is concrete pavement, so in order to create the desired contrast between the pavement markings and the roadway surface, black tape was used around the white tape of the Shark's Teeth and Lane Arrows. Black outlining tape can be seen in both Figure 6 and 7.

Results: TH 14 Merge Study

Results for cumulative merges by zone as well as cumulative desirable merges by zone, for each of the three merge conditions, are shown in Figure 8. Desirable merges are defined as "decelerate to merge" and "normal merge". Results are displayed as a percentage of the vehicles merging in Zones A-C. Both Shark's Teeth and Lane Arrows had a larger percentage of early merges and desirable early merges than the base conditions. Lane Arrows had the largest percentage of early merges, over 57% in Zone A, compared to 36% and 30% for the Shark's Teeth and base conditions, respectively. With the Lane Arrow pavement markings, over 97% of drivers merged prior to Zone C, of which, 1% were considered undesirable merges. This was a 7% and 14% increase in desirable early merges from the Shark's Teeth and base conditions respectively.



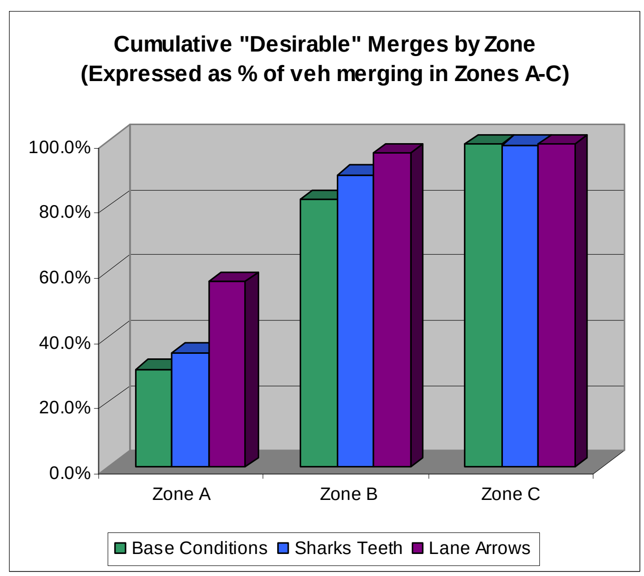


Figure 8
TH 14 Cumulative Merges by Zone

Figure 8 shows that the Lane Arrows performed the best. Shark's Teeth did not perform as well as Lane Arrows, but did show an improvement over the base conditions. Lane Arrows had a larger percentage of cumulative merges and desirable cumulative merges for each zone.

Although the Lane Arrows performed very well on TH 14, further research is needed. The design and placement of the Lane Arrows and Shark's Teeth were different than the I-90 study. These design changes could be responsible for the change in driver behavior. It's also possible that the switch from a left (inside) lane closure to a right (outside) lane closure is responsible for the change in behavior. Drivers in the left lane might be more aggressive in nature and therefore a left lane closure may have a larger number of drivers exhibiting undesirable behavior.

After studying the early merge Shark's Teeth and Lane Arrows at this location, it was recommended to choose another site for study. Again, additional research was needed to support and validate the effectiveness of innovative pavement markings; however, this time the use of Lane Arrows resulted in significantly better results than the Shark's Teeth. For the next study site, only Lane Arrows were to be tested. The third study was needed to further validate that Lane Arrows work well in promoting early merges.

STUDY SITE 3: I-35

Lane Arrows were chosen as the focus of the study on I-35 for two main reasons. First, the Lane Arrows showed a lot of promise as a result of the TH 14 study. They produced much better results over the Shark's Teeth. Second, the installation of the Lane Arrows involves significantly less labor. Three or four Lane Arrows could be placed in a much shorter period of time than ten or more Shark's Teeth.

A section of I-35 near Albert Lea was chosen as the site for the third merge study. I-35 is a four lane divided freeway with a posted speed limit of 70 mph. The ADT at the time was 17,500, of which 2,800 (16%) was commercial heavy truck traffic. A relatively moderate percentage of traffic in this location was non-local.

Construction at the site spanned almost 14 miles and involved paving, lighting, and bridge repair. A left (inside) lane closure on northbound I-35 provided the location for the study.

Procedure: I-35 Merge Study

In order to document the lateral placement of merging drivers, the study area was broken up into three zones, A, B, and C. Zone A was approximately 600 feet long and began at the merge sign. Zone B began at the end of Zone A, ended at the beginning of the lane taper, and was approximately 600 feet long. Zone C was defined as the section of roadway where the lane taper occurred and was approximately 900 feet long. Figure 9 shows the relative size and location of each zone and includes Lane Arrows in Zone A.

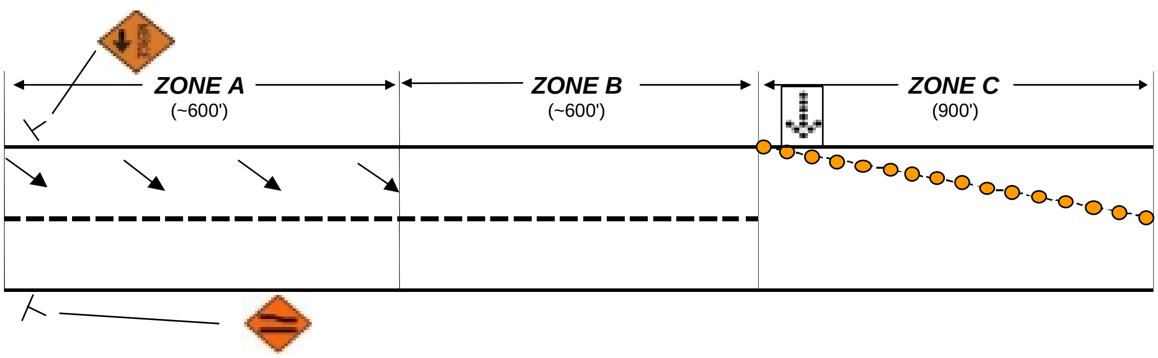


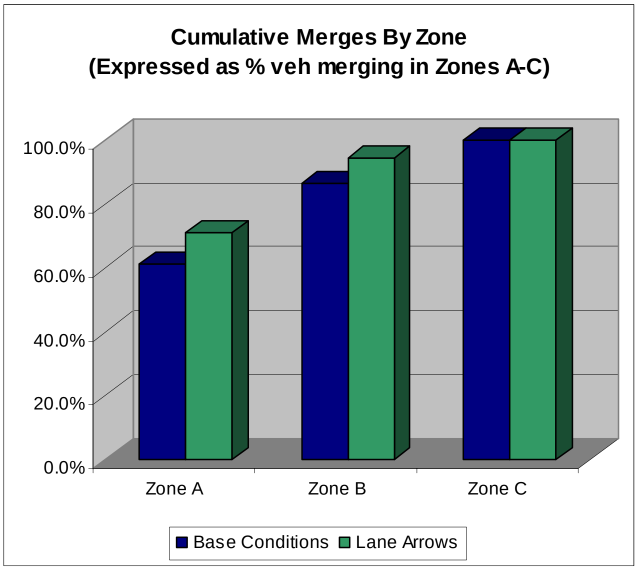
Figure 9
I-90 Zone Definition

On August 5, 2002, base conditions were recorded for merging traffic in the I-35 work zone. Merge data was collected for the 139 vehicles that performed a merge maneuver within the study area over a period of almost four hours (4:15 p.m. to 8:00 p.m.).

On August 22, 2002, Lane Arrows were installed and studied on I-35. Four Lane Arrows, 19 feet long, were installed at intervals of 200 feet, starting at the merge sign. Similar to TH 14, eight inch black outlining tape was used around the markings to create a stronger contrast between the concrete pavement and the Lane Arrows. Observers recorded the merges and behavior of the 137 drivers that merged in the study area.

Results: I-35 Merge Study

Results for cumulative merges by zone as well as cumulative desirable merges by zone, for both the Lane Arrows and base conditions, are shown in Figure 10. Desirable merges are defined as "decelerate to merge" and "normal merge". Results are displayed as a percentage of the vehicles merging in Zones A-C. Lane Arrows showed a larger percentage of both early merges and early desirable merges than the base conditions. With Lane Arrows, over 70% of the vehicles sampled merged in Zone A and 94% of the vehicles had merged by the end of Zone B, compared to 61% and 86% respectively for the base conditions. Less than 4% of all merges for the Lane Arrow condition were considered undesirable, compared to 8% for the base condition.



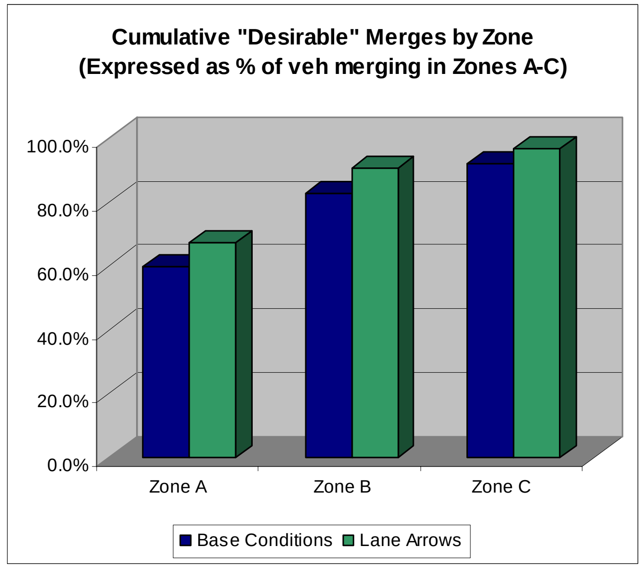


Figure 10
I-35 Cumulative Merges by Zone

Figure 10 shows that the Lane Arrows again outperformed the base conditions, although not to the degree they did on TH 14. It's important to note that although the design and placement of the Lane Arrows were almost the same as they were on TH 14, a few of the site characteristics were slightly different, which could have impacted the results. First, traffic volumes increased from previous studies. Second, visual observations showed that a larger than expected percentage of traffic had already merged prior to entering the study area because of extended sight distance. Third, the site at I-35 was a left (inside) lane closure.

The fact that Lane Arrows showed improvement from the base conditions at a second site strongly supports the belief that they do promote early merges, and more importantly, early desirable merges.

CONCLUSIONS / RECOMMENDATIONS

Three summer's worth of work went into developing the most effective design and pattern of Shark's Teeth and Lane Arrows for promoting early merges in advance of rural highway work zones. After performing merge studies at three separate sites over three consecutive summers, it is concluded that Lane Arrows show the most promise for widespread field implementation in construction or maintenance work zones. This is because (1) the Lane Arrow pattern requires very few arrows (~4) which results in an inexpensive and quick installation, and (2) the final Lane Arrow design produced the best results. For these reasons, it is recommended that Mn/DOT consider the use of Lane Arrows in construction or maintenance work zones with an ADT of less than 15,000 where a lane must be closed (and remain closed) as part of a long term work zone. The nineteen foot design that was used at the I-35 site should be used for future applications, which is a standard stock inventory size that can be ordered off the shelf.

As a result of this research, no field implementation is recommended for Tiger Tail pavement markings. They were not effective enough in speed reduction to warrant installation recommendations. However, results were somewhat mixed. There was virtually no speed reduction during the daytime "after" condition. The speed reductions were more pronounced at night, but even then, it was only a spot speed reduction. As the motorist traveled over the pavement markings, speeds dropped, but as soon as the motorist passed the markings, speeds returned to levels recorded under baseline conditions. Conversely, the Tiger Tail pattern did reduce the percentage of high-speed drivers at night, especially at the reverse curve warning sign. This would suggest that Tiger Tail pavement markings might be effective in poorly lit rural work zones during night time operations. Further research may be warranted to further explore the possible applications of Tiger Tails for spot speed reductions or for use during night time operations in poorly lit rural locations.