INNOVATIVE SAFETY SOLUTIONS WITH PAVEMENT MARKINGS AND DELINEATION

AMERICAN TRAFFIC SAFETY SERVICES ASSOCIATION

ATSSA

SAFER ROADS SAVE LIVES

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Table of Contents

Overview

Pavement markings are a common and relatively low-cost treatment used by transportation agencies to delineate travel lanes, inform drivers of lane use restrictions and rules, and ultimately make roadways safer. This booklet presents several case studies that highlight innovative pavement markings that are intended to improve roadway safety by informing and warning drivers of certain aspects of the road, the road users, or the surrounding environment. These warnings are intended to promote positive driver behavior changes like slowing speeds, increasing awareness of other road users, correcting errant driver maneuvers, or operating a motor vehicle in an intended manner to improve safety. National standards on the use of pavement markings are provided in the Manual on Uniform Traffic Control Devices (MUTCD), and specific references to applicable sections of the MUTCD are included throughout this booklet. The MUTCD with the most up-to-date information is available at www.mutcd.fhwa.dot.gov.

The American Association of State Highway and Transportation Officials (AASHTO) has developed the Highway Safety Manual (HSM), which establishes a methodology for determining safety effects of treatments aimed at reducing crashes. Crash modification factors (CMFs), which express a numerical value reflecting the proportion of crashes that can be avoided using a particular treatment, are a common and easily understood measure of safety effects. As treatments are studied, CMFs are established and included in the HSM and the CMF Clearinghouse (www.cmfclearinghouse.org). CMFs can then be updated or expanded over time as more and better evaluations are performed for a certain treatment.

CMFs are rated according to quality based on their data sources, bias control, statistical rigor, and study design. The case studies presented in this booklet are intended to highlight innovative practices that may be newer or less commonly used compared with more traditional markings. As such, many of these treatments may not have been studied extensively to date, especially considering that comprehensive crash data of multiple years is required to establish high-quality evaluations and CMFs. Therefore, a consensus of high-quality CMFs for most of these treatments is not yet available, but readers are encouraged to consult the HSM and CFM Clearinghouse to obtain information on particular treatments and consider the evaluations performed in relation to their potential for use in future projects.

Certain properties of pavement markings pertain to all (or most) of the case studies. Marking durability, installation type, visibility, and friction considerations are therefore included in this section but may apply to the case studies that follow. Readers are encouraged to consider these overall aspects of pavement markings when considering the case studies.

Marking Durability

The durability of pavement markings is often thought of and defined by service life. The service life of a pavement marking reflects the amount of time that the marking will function and remain visible to drivers above some visibility thresholds. A number of studies have been conducted over the last few decades that establish service lives for different marking materials. Table 1 provides a summary of the different typical service lives as cited in the literature with snow-zone-specific values, high-traffic-specific values, and grooved-in-specific values (when available). The service life of a marking is highly dependent on the marking materials, traffic volumes, climate, winter maintenance activities, and installation practices. Therefore, the values established typically cover a range of circumstances. Typical values based on multiple studies may be the best indication of relative service lives between material types.

Table 1 also provides documented cost information from the literature (all converted to 2015 dollars using the National Highway Construction Cost Index). Material costs can vary significantly depending on the quantity installed, geographic region, and by the equipment and practices used, therefore a range is given in many of the references. Typical cost values based on multiple references may provide the best relative comparison between marking types.

Winter maintenance activities typically have a large effect on service life, and certain materials may be more susceptible than others to snowplowing. The practice of grooving-in pavement markings, while more expensive, can result in service life benefits that exceed the initial grinding cost.

More information on the practice of grooved-in markings is included in the next section, “Installation Type.” Higher traffic volumes will also typically result in shorter service lives. The pavement material of the road can affect marking service life, with certain markings lasting longer on asphalt than portland cement concrete .

Markings that last longer not only have reduced material costs, but also have benefits for agency personnel who must install and maintain these markings. It is inherently risky to have people on the roadway to install markings, therefore the less frequently this activity is necessary, the better.

Table 1: Typical Pavement Marking Service Lives and Costs From Literature

Type	Typical Service Life (years)		No. Ref.s	Typical Cost (per linear ft)	No. Ref.s
Epoxy	**All**	**1½–4**	8	$0.30–$0.45	6
	Snow Zone	*1½–3*	2		
	High Traffic	*3*	1		
Methyl Methacrylate (MMA)	**All**	**2–5**	5	$1.00–$2.00	6
	High Traffic	*5*	1		
Paint	**All**	**½–2**	12	$0.05–$0.10	9
	Snow Zone	*½–2*	3		
	High Traffic	*¼–½*	3		
	Grooved-In	*3+*	1	$0.80–$0.85	1
Polyester	**All**	**2–4**	3	$0.10–$0.20	3
Polyurea	**All**	**3–4**	5	$0.80–$1.20	6
	Snow Zone	*3*	1		
	High Traffic	*3*	1		
Tape	**All**	**2½–6**	12	$2.00–$3.00	9
	Snow Zone	*4–6*	3		
	High Traffic	*4*	1		
	Grooved-In	*4+*	3	$3.00–$3.75	4
Thermoplastic	**All**	**1–4**	14	$0.30–$0.80	10
	Snow Zone	*1½–4*	4		
	High Traffic	*1–3*	2		
	Grooved-In	*6+*	2	$1.00–$3.00	2
Urethane	**All**	**3–4**	2	$0.70–$1.00	2
	High Traffic	*3*	1		

Note: Certain references cite service lives for some of these materials to be much shorter or much longer than the values listed. The typical lives shown are the more common and conservative ranges cited without outliers.

Installation Type

Marking placement techniques can significantly change the durability of markings. Examples of marking installations besides traditional surface-applied markings include practices such as inlaid tape, which is marking tape inlaid into freshly placed pavement, grooved-in marking, which is the practice of grooving out a shallow strip to slightly recess the marking, and rumble stripes, which are rumble strips with longitudinal markings applied directly over the rumble pattern. These alternative practices can have a large influence on durability and cost-effectiveness of pavement markings. Pavement markings installed in grooves can increase the service life of the marking, especially in areas where snow removal is common. A few studies from the past decade have documented the practice of using grooved-in longitudinal markings as a cost-effective means to prolong the life of the markings.

Research was conducted on the practice of grooved-in lines for a section of snow-prone Interstate in Oregon. The work did not establish specific service-life benefits for the practice of grooved-in markings, but did establish some recommended grooving practices. Overall it was found that the quality and consistency of the groove is an important factor in the performance of the line marking. Clearing debris from the groove prior to marking is also emphasized, and the use of compressed air in addition to conventional sweeping machinery may be beneficial for marking adhesion. For the hot-poured thermoplastic and extruded MMA markings, a 200-mil groove depth filled with up to 150 mil of marking material was recommended from the testing performed.

Research on multiple marking materials, both grooved-in and placed on the road surface, was conducted on test decks in Tennessee and Alaska in the mid- to late 2000s. Many marking materials and application methods were used for the lines. The retroreflectivity levels of the markings (see "Marking Visibility and Retroreflectivity" section) were monitored over time to establish performance. In general grooved-in thermoplastic, MMA, polyurea, tape, and certain paint markings maintained their minimum retroreflectivity longer than their surface-applied counterparts. This research also produced a web-based Pavement Marking Selection Tool for informational purposes using the results of the evaluations. The tool can be found at www.ctre.iastate.edu/PMST.

Figure 1. Pavement marking line in a grooved strip (Photo courtesy of Neal Hawkins, Center for Transportation Research and Education, Iowa State University)

Researchers in Iowa have also documented the benefits of grooved-in line markings. The researchers evaluated water-based paint and high-build water-based paints with different retroreflective bead types on grooved and non-grooved surfaces. The practice of grooving the surface for painted lines was found to extend the life of the marking up to two years. The grooved-in lines are more durable, as they are somewhat protected from traffic and winter maintenance activities. Both the Iowa Department of Transportation (DOT) and the Minnesota DOT have changed their marking installation practices after learning of the benefits of the grooved-in lines. Figure 1 shows a longitudinal marking line in a grooved surface.

Marking Visibility and Retroreflectivity

Markings must be visible to be beneficial, and more and more agencies are making efforts to monitor and maintain markings as they wear to certain visibility thresholds. Nighttime visibility, as defined by the retroreflectivity of the marking, is typically used when determining minimum thresholds. Many agencies only specify certain retroreflectivity values to be achieved after installation, while an increasing number of agencies are embracing an approach that monitors retroreflectivity as markings wear in an effort to maintain certain minimums before requiring marking replacement. States currently use their own minimum retroreflectivity thresholds, as no federal guidance has been adopted (although some have been proposed). While more research is needed, preliminary studies tend to show that maintaining certain retroreflectivity thresholds may have safety benefits.

Researchers in Iowa have developed a geographic-information-system-based Iowa DOT Pavement Marking Management Tool, which allows the agency to track marking performance statewide. Using data from this system and statewide crash histories, the researchers established the safety effects of retroreflectivity levels of pavement markings. Higher retroreflectivity was associated with decreases in crashes. An increase in retroreflectivity from 50 to 200 millicandela (mcd) on two-lane rural roads resulted in a 2.5 percent decrease in overall crash probability. For more information on the benefits of providing nighttime visibility and marking retroreflectivity, readers are encouraged to visit the Federal Highway Administration (FHWA) Office of Safety Program website on nighttime visibility:
www.safety.fhwa.dot.gov/roadway_dept/night_visib/

Skid-Resistance Considerations

Certain pavement markings may extend across the entire lane, which can cause skid-resistance concerns especially for motorcyclists and bicyclists. With certain markings, it may be possible to allow for a tire gap in the marking pattern or allow for space to travel between the marking and lane line to allow cyclists an area of unmarked pavement as they pass through the marking. There may also be opportunities to use high-friction marking materials or install a colored high-friction surface treatment with certain marking strategies. If a marking will extend across the entire lane, it may also be favorable to place the marking on a flat tangent section of road where braking and the need to turn (and lean on a motorcycle) will be minimal. ■

CASE 1: Audible and Tactile Warning Pavement Markings

Audible and tactile warning pavement markings can be rolled or milled into the pavement or be in the form of profiled markings that give a tactile (i.e., vibration) alert to the driver that the vehicle is leaving the lane. Milled-in rumble strips are the most common type used today. Rumble strips and rumble stripes (i.e., rumble strips that have also been longitudinally marked) have been extensively studied and established as a cost-effective way to improve safety. Profiled markings installed with longitudinal lines are typically only used in warmer climates, as snow and ice removal methods tend to damage the markings. These longitudinal markings are used for edge lines, centerlines, and occasionally lane lanes and HOV lines in multilane highway situations. The MUTCD provides guidance for the use of rumble stripes in Section 3J-01.

Rumble stripes may also have some increased visibility benefits, especially in wet and dark conditions. Figure 4 shows a rumble stripe in dark, wet conditions after one winter season where snowplowing is common. This photo also shows a typical surface-applied marking line of the same material and age that was used in an evaluation setting that compared the marking practices.

Less evaluation has been completed for profiled markings compared with milled-in rumble strips and stripes, and these markings may be somewhat less effective than milled rumble strips, depending on the dimensions and amount of tactile or audible warning provided. Figure 5 shows an example of a profiled thermoplastic line.

Figure 2: Edge-line rumble stripe with bike gaps
(Photo courtesy of the FHWA)

Figure 4: Rumble stripes in dark, wet conditions after a winter season
(Photo courtesy of Michigan DOT)

Figure 3: Centerline rumble stripe (Photo courtesy of the FHWA)

Figure 5: Profiled marking (Photo courtesy of Seth Chalmers, Pima County, Arizona)

More research is necessary to fully evaluate the profiled markings and other possible raised audible markings for use as an alternative to milled-in rumble strips and rumble stripes, and multiple state transportation agencies appear to be interested in investigating this more thoroughly. Texas and Alabama have begun to experiment with raised audible markings to alert drivers leaving their lanes.

Rumble strips, rumble stripes, and certain raised audible markings produce noise when contacted by a vehicle, and the noise produced is occasionally a nuisance to nearby residents, therefore this should be considered with the placement of rumble strips near inhabited areas. Rumble strips also create challenges for bicyclists, and appropriate measures — including adequate shoulders and bike gaps in the rumble-strip pattern — can improve conditions for locations with bicycle users. Figure 2 shows a gap in a rumble-strip pattern for bicyclists.

Another form of audible marking is transverse rumble strips that are milled-in or raised markings that are installed in the roadway perpendicular to the travel direction and in the wheel paths of vehicles. These rumble strips are typically used to warn drivers to slow down for an unexpected intersection or curve. Evaluations showing the effectiveness of transverse rumble strips have been performed in Texas, Louisiana, and Minnesota. Overall speed reductions at intersections ranged from 1 mph to 5 mph, and crashes were reduced up to 29 percent. Section 3J-02 of the MUTCD provides guidance on the use of transverse rumble strips. Figure 6 shows examples of transverse rumble strips.

As with longitudinal raised markings, these raised transverse audible markings may be limited to warmer climates, as winter maintenance activities may damage raised markings. ■

Figure 6: Transverse rumble strip marking
(Photo courtesy of Texas A&M Transportation Institute)

CASE 2: Bike and Pedestrian Markings

There are many bike and pedestrian signing and marking strategies that can make motorists more aware of these alternate modes of transportation while providing guidance for bicyclists and pedestrians near roadways. Chapter 9C of the MUTCD provides some markings used for bicycle facilities, and pedestrian considerations are scattered throughout the manual. Much of the guidance related to bikes and pedestrians in the MUTCD is focused on signing and considerations at traffic signals. Other marking strategies for bikes and pedestrians exist, especially in urban settings, but are outside of the direct guidance included in the MUTCD. As such, the FHWA has published a memorandum expressing support for taking a flexible approach to designing bicycle and pedestrian facilities. This memo specifically supports using other references from AASHTO, the National Association of City Transportation Officials (NACTO), and the Institute of Transportation Engineers (ITE).

These references include:

- AASHTO Guide for the Planning, Design, and Operation of Pedestrian Facilities,
- AASHTO Guide for the Development of Bicycle Facilities,
- NACTO Urban Bikeway Design Guide, and
- ITE Guide: Designing Walkable Urban Thoroughfares: A Context Sensitive Approach.

Strategies provided in these guides may still require experimental status or interim approval in accordance with the MUTCD, but do provide more marking treatment strategies for bicyclists and pedestrians especially in urban environments. It may be beneficial for agencies to provide public education and outreach on the use of some of the bike and pedestrian markings, as they can be different from marking typically encountered by unfamiliar drivers.

Figure 7: Sharrow (Photo courtesy of National Association of City **Transportation Officials**)

One bike marking included in the MUTCD is the shared-lane marking, or sharrow, as shown in Figure 7. These markings are intended to alert motorists and bicyclists that they are sharing the roadway. These markings can be placed on roads with speed limits under 35 mph and should be placed 11 feet (to the center) from the curb face or the edge of the pavement on roads with on-street parallel parking and at least 4 feet from the edge of the road on streets with no on-street parking and a lane width less than 14 feet. The markings and placement are intended to prevent dooring crashes in situations with on-street parking, assist bicyclists with lateral placement in lanes too narrow to allow a vehicle to pass, alert drivers of the presence and position of bicyclists, encourage safe passing of bicyclists, and reduce wrong-way biking.

Researchers from the University of North Carolina have evaluated the use of these shared-lane markings in four different urban areas in recent years. Some of the benefits of sharrows found during the evaluations include increases in operating space for bicyclists (vehicles traveling farther from on-street parked vehicles), decreases in percentage of bicyclists riding in the dooring zone, and decreases in bicyclists riding on sidewalks.

Another use of pavement markings intended to improve safety and operations for bicyclists are the use of colored pavements and markings at intersections. These colored bike lanes and bike boxes are not explicitly included in the MUTCD but are detailed in the additional FHWA flexible-design-memo-referenced guides. Figure 8 shows a colored bike box, and Figure 9 shows a colored cycle track through an intersection.

The use of bike boxes and colored cycle tracks, especially near intersections, has been evaluated to some extent in the past decade. In general, these treatments have been found to improve conditions for bicyclists by making road users aware of bikes and their expected locations and movements.

Figure 8: Bike box (Photo courtesy of National Association of City **Transportation Officials**)

Figure 9: Intersection cycle track (Photo courtesy of National **Association of City Transportation Officials**)

In-roadway warning lights are a type of marking that can improve safety for pedestrians. These in-roadway lights for use at crosswalks are detailed in section 4N-02 of the MUTCD. These lights are embedded in the pavement and are activated when a pedestrian crosses the road either by a push button or passive pedestrian detection. Figure 10 shows an installation of in-roadway warning lights.

General studies have shown these lights to be beneficial for pedestrian safety by increasing the awareness of drivers to the presence of pedestrians crossing the road, especially in dark conditions.

Collectively there are many pavement marking strategies aimed at making a safer environment for pedestrians and bicyclists. Many innovative bike and pedestrian markings like those highlighted in this section show promise and may benefit from further evaluation and analysis. ■

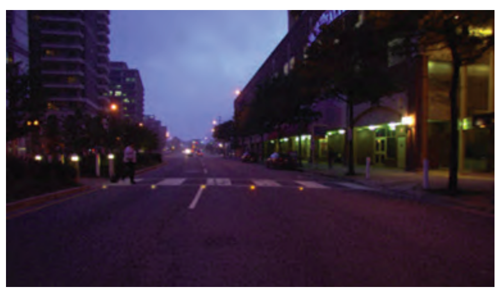

Figure 10: In-roadway warning lights (Ref. Public Roads Jan/Feb 2004)

CASE 3: In-Lane Curve Warnings

Pavement markings that are installed directly in the driver's lane are perhaps more noticeable than signs on the roadside, as the majority of the time spent driving the driver's eyes are on the road ahead. Horizontal curves are a common location for crashes, and vehicles traveling too fast for the conditions or drivers who are distracted may run off the road at the location of curves. These factors have led to a few innovative uses of in-lane pavement markings to warn drivers of curves ahead.

The in-lane pavement curve warnings aim to inform the driver that a curve is ahead, thereby increasing the driver's awareness and possibly reducing speeds to keep vehicles on the road and in their lanes, and thus avoid crashes. The Pennsylvania DOT has installed in-lane curve warnings with the word "SLOW" as shown in Figure 11.

Figure 11: In-lane curve warning (Photo courtesy of the FHWA)

Detailed documentation or a rigorous evaluation could not be found, but results from the pilot tests of "a few hundred locations" showed "significant reductions in crashes initially." Another document reported 6 percent to 7 percent speed reductions for the treatments. Further, the results of a preliminary investigation of this treatment suggested that an "estimated 25 percent reduction in curve-related deaths at each of the locations" could be possible.

The same in-lane curve warning as depicted in the Pennsylvania example was more recently evaluated at two locations in Iowa. The markings were thermoplastic, and speed data was collected before, one month after, and 12 months after installation. In general, the treatments were moderately effective, with one location showing mixed results on speeds and speeding behavior and the other location showing speed reductions up to 2 mph and significant reductions in most speeding behaviors. This evaluation led researchers to conclude that the treatment showed promise, especially considering the low-cost nature of the treatment, but more investigation is likely warranted.

A more recent and different in-lane curve warning treatment has been tried in Kansas and Wisconsin. This marking is an elongated version of a post-mounted sign as shown in Figure 12.

These curve warning markings are recreations of MUTCD W1-2 curve warnings signs. Kansas installed them using thermoplastic at two sites, and Wisconsin used a pavement marking tape to install it at one site. Before-and-after speed data was collected to evaluate the sign's effect on drivers' chosen speeds. The sites in Kansas both showed statistically significant speed reductions, with the mean reduction ranging from 2 mph to 4 mph at the location of the treatment. The speeds at the Wisconsin treatment location were not statistically significant and showed increase in the mean speed of 0.7 mph. Similar patterns were found when considering the proportion of vehicles exceeding the advisory speed by 10 mph or more. Both Kansas locations showed improvements in the excessive-speed behavior, while the Wisconsin location showed little change. It was noted that the Wisconsin DOT installed a "Traffic Paint Test Area" sign with flags upstream of the treatment, which may have influenced drivers' behavior through the test site.

These two innovative in-lane curve warning markings show promise as potential means of slowing vehicles entering curves and making drivers more attentive to the presence of curves. With only limited studies having been performed, it is likely that more evaluations of these and similar treatments may be warranted.

Both of the in-lane pavement markings shown in this section are not directly included in the MUTCD and were both granted experimental status in order to evaluate their performance. ■

Figure 12: Elongated sign marking for in-lane curve warning (Photos courtesy of Douglas County, Kansas Public Works)

CASE 4: In-Lane Intersection Warnings

In-lane pavement markings can be used to warn motorists of an intersection ahead. Section 3B.20 of the MUTCD covers the use of these types of intersection pavement warnings. Figure 13 shows a "Stop Ahead" intersection warning, and Figure 14 shows a "Signal Ahead" intersection warning.

The FHWA led an effort to evaluate low-cost safety strategies in many states, and one of the safety efforts that was evaluated was the Stop Ahead marking. An empirical Bayes before-after safety analysis was conducted using sites from Arkansas, Maryland, and Minnesota. The analysis included an average of 6.6 years to 9.8 years of before data and 2.2 years to 3.4 years of after data (from the late 1990s through 2000s) on a total of 175 sites. Overall there were statistically significant reductions in total crash rates and many crash types following the installation of Stop Ahead markings. A conservative crash-reduction estimate for total crashes of approximately 15 percent is suggested from the research, but significant results for a combination of Arkansas and Maryland data and Arkansas data alone showed total crash reductions of 31 percent and 52 percent, respectively. The results also show that the treatment may be most effective on three-legged intersections (although it was also found effective on four-legged intersections). Similarly, the treatment may be most effective on all-way stop-controlled intersections.

Another pavement marking used for in-lane intersection warning is the Signal Ahead marking. An evaluation of this marking as a means to reduce red-light-running behavior was conducted in Florida and published in 2010. This marking was designed as defined in the MUTCD, but was placed at a distance equal to the stopping sight distance upstream of the intersection. The marking placement is intended to be a visual cue to help drivers determine whether to stop or go when the traffic signal turns yellow. Drivers upstream of the marking when the signal turns yellow would need to stop in order to avoid running the red light.

The evaluation of the marking was performed near Orlando, Fla. An untreated intersection was also used that did not receive the treatment but was monitored as a control. Both intersections were on the same three-lane highway with the same geometries and speed limits. A media campaign that was intended to inform the public about the use of the markings was performed four months after the installation. This media campaign was focused on how the marking was supposed to function in helping drivers decide to stop or go at the changing signal. The media campaign included public TV coverage, newspaper articles, and content published

Figure 13: In-lane intersection warning (Photo courtesy of Ennis-Flint)

Figure 14: In-lane intersection warning (Photo courtesy of University of Central Florida)

on the Internet. The test location is near a university, and numerous campus-specific media efforts were also performed, including campus newspapers, university websites, and emails to students and faculty.

Red-light-running rates were reduced approximately 26 percent after the installation of the marking and prior to the media campaign. Red-light-running rates were reduced another 46 percent following the media campaign at the test intersection. No significant changes in red-light-running behavior were observed at the control intersection during the evaluation. While this treatment should be evaluated at more locations in the future, it appears to show promise as a means to reduce red-light running and may improve overall safety at treated intersections. ■

CASE 5: In-Lane Speed Limit Markings

In-lane pavement markings can be used to inform drivers of the speed limit. These markings have traditionally been white numerical speed limits as described in the MUTCD in section 3B.20 and as shown in Figure 15.

More recently, other experimental speed limit markings have been implemented, including elongated sign markings and ones that use color to grab the driver's attention.

Colored pavements and markings that use large portions of color to grab the driver's attention have been used to a limited extent in the United States and more so internationally. Examples of these colored pavements include colored shoulders and colored bike and pedestrian lanes to highlight the separation between vehicle space and nonvehicle space. Intersection color and texture differences have also been used in more urban settings, and large colored markings (often with speed limit signs or on-pavement speed legends) have been tried as gateway treatments to communities

Transition zones at entrances to towns and small communities are often plagued by speeding vehicles that fail to slow from the higher speeds found outside communities to the lower speeds necessary when approaching more developed areas. Gateway treatments include signs and markings that are intended to capture the driver's attention and inform them that they are entering an area with houses and other community development requiring slower speeds.

Colored gateway installation evaluations have been performed in Iowa. The Iowa colored-gateway evaluations were performed as part of larger projects, one of which concluded in 2007 and another concluded in 2013. Examples of the colored gateway treatments used are shown in Figure 16.

Colored gateways with 35-mph speed limit markings were installed on the entrances to a small community in Iowa in an effort to slow vehicles entering the town from the 55 mph speed limit outside of town. Speeds were measured before the treatments and one month, three months, nine months, and 12 months after. Overall the treatments were effective in reducing speeds, with statistically significant reductions in mean speed ranging from 1 mph to 7 mph and reductions in 85th-percentile speed ranging from 1 mph to 9 mph. Reductions in the percentage of vehicles exceeding the speed limit by 5 or more mph were also evident.

Two additional Iowa communities installed treatments during the more recent project, one with markings to slow vehicles from 55 mph to 35 mph and one to slow vehicles from 55 mph to 25 mph on the edges of the communities. During this evaluation, speeds were collected before, one month after, and 12 months after installation. Again mean

Figure 15: Traditional in-lane markings by Hot Springs, Arkansas Public Works (Photo courtesy of Mark A. Toth, Whittington Valley Neighborhood Association)

Figure 16: Colored gateway markings with speed limits (Photo courtesy of the Center for Transportation Research and Education at Iowa State University)

and 85th-percentile speeds were reduced after installing the colored gateway treatments. In general, moderate speed reductions of 1 mph to 2 mph were found following installation, but the proportion of vehicles exceeding the speed limit by 5 mph or more was greatly reduced. The proportion of vehicles going 40 mph or greater at the 35-mph treatment zone was reduced 30 percent to 49 percent. These reductions increased over time at one location and decreased slightly at the other location. The proportion of vehicles going 30 mph or greater in the 25-mph treatment zone was reduced by 30 percent one month after installation and 15 percent one year after installation.

The pavement markings used during the earlier Iowa project were painted on the pavement, but they were subject to significant fading during the evaluation phase of the study. Therefore, the markings were repainted between the ninth month and 12th month of the post-installation monitoring period. It was also mentioned that thermoplastic marking may be a better option for this treatment in the future. The more recent Iowa project did use high-friction thermoplastic markings and glass beads, presumably in response to the wearing issue and to provide increased visibility and skid resistance. No wearing or fading issues were raised during the second project evaluation.

The MUTCD does provide guidance on the use of word, symbol, and arrow markings in section 3B.20, which covers the standard use of white markings to indicate speed limit in the lane. However, the MUTCD does not include guidance on the use of the colored gateway warning accompanying the speed limit. Therefore the process to request and obtain experimentation status for the treatments used in Iowa was completed.

These experimental markings were used in a rural targeted situation and may not be suited for widespread use, considering the color scheme used and possible difficulties with maintenance and skid resistance. Alternative means of pavement coloring, including the use of colored high-friction surface treatment may provide similar benefits with reduced maintenance and friction concerns.

Another experimental speed limit pavement marking was installed and evaluated at sites in Kansas, Missouri, and Wisconsin. These markings were elongated recreations of regulatory speed limit signs (MUTCD R2-1) as shown in Figure 17.

A before-and-after speed study found that these elongated speed limit sign markings reduced speeds at three of the four locations. In general the mean and 85th-percentile speed reductions ranged from 2 mph to 5 mph. These elongated speed limit pavement markings are not directly included in the MUTCD, but were granted experimental status in order to evaluate their performance.

Both the colored gateway treatment and the elongated-sign marking treatment are experimental, but do show promise for reducing speeds in certain situations. Additional investigation into their use in the future may help to establish them as viable lower-cost speed-reduction safety treatments. ■

Figure 17: Elongated Speed Limit Sign Markings (Photo courtesy of Sedgwick County, Kansas City Public Works)

CASE 6: Lane Narrowing

Typically, wider lanes are desired for the majority of roadway conditions and are thought to be safer than narrower lanes, especially for higher-speed facilities. There are however, instances of intentional lane narrowing that can be used to improve safety in certain applications. Using pavement markings to narrow lanes has been implemented at intersections on two-lane roads and in or near small communities to slow speeds. Pavement markings can increase the shoulder width or introduce a shoulder in the road cross section to narrow the effective lane width while also allowing for additional room for pedestrians and bicyclists, as shown in Figure 18. Painted median islands can also be used to create narrower lanes on either side of a larger median strip. The wider median does not allow more room for pedestrians and bicyclists, but it may provide a benefit by increasing the distance available between opposing traffic streams.

It is common for vehicles to be traveling faster than the desired speed when approaching intersections on high-speed facilities like those often found on two-lane roads. Lane narrowing confines the vehicle to a narrower path, demanding more attention from the driver and influencing drivers to slow down as they enter the treated area. This reduction in speed can result in fewer crashes and safer roads in certain situations.

The FHWA led an effort in 2008 to investigate the lane-narrowing concept at nine rural intersection locations around the United States on two-lane roads, with two-way stop control on the minor approaches. Sites from Florida, Kentucky, Missouri, and Pennsylvania were included in the evaluation. Sites with known speed issues or intersections that might be unexpected as drivers travel along the major road were chosen for the lane-narrowing treatment. The

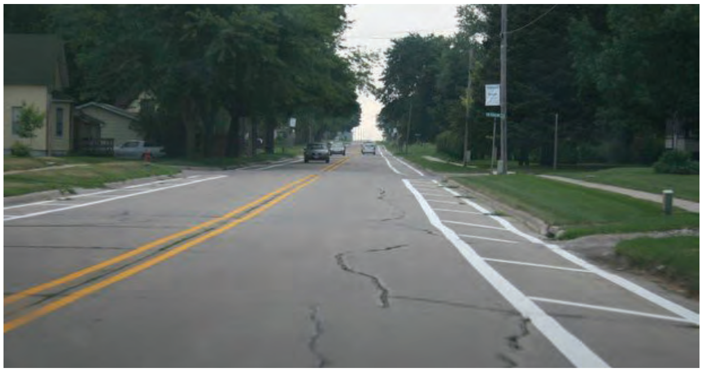
Figure 18: Lane narrowing via shoulder widening (Photo courtesy of the Center for Transportation Research and Education at Iowa State University)

lanes on the major approaches are tapered and narrowed using pavement markings to create a painted median. Rumble strips were also installed in the painted median and on the shoulder near the intersections. The view along a major route entering the lane-narrowed portion approaching an intersection is shown in Figure 19.

Driver behavior and speed data were collected before and after the lane-narrowing treatments at the nine locations. In general, the narrowed lanes reduced driver's chosen speeds by 3.5 mph (mean speed reductions) and 4.5 mph (85th-percentile speed reductions) for all vehicles, with both reductions found to be statistically significant results. The speed reductions were greater for large trucks, which slowed 4.4 mph (mean speed) and 4.8 mph (85th-percentile speed).

Simple before-after crash analyses were also completed for the study sites to gauge an initial indication of potential crash-reduction safety effects using the limited data available, which were not enough to perform the more detailed empirical-Bayes methods at the time. Four to seven years of before data and one to two years of after data were used for the safety analyses at the different sites. Overall, the combined crash rate, expressed as crashes per million entering vehicles (MEV), was reduced from 1.85 to 1.27, a reduction of approximately 31 percent.

The use of hatch markings on shoulders and medians (between opposing traffic streams) is included in section 3B.24 of the MUTCD. ■

Figure 19: Lane narrowing via painted median (Photo courtesy of the FHWA – Turner-Fairbank Highway Research Center)

CASE 7: Lane Selection and Guidance Markings

Freeway interchanges with multiple lanes and the potential for lane drops are common areas where drivers may become confused and perform erratic maneuvers and late lane merges. An innovative pavement marking strategy to assist drivers in these situations is guidance markings in the form of route-number symbols applied directly to the pavement as shown in Figure 20. Section 3B-20 of the MUTCD provides some guidance on the use of these symbol markings.

In 2009 researchers completed field evaluations of these types of markings at two interchange sites in Texas. One site received the symbol marking in addition to the appropriate cardinal direction where directional arrows and "ONLY" markings were already present. The other site received the symbol markings where no other in-lane markings were present. The researchers evaluated the markings by quantifying the number of lane changes in the study area before and after the treatments using video recordings.

Figure 20: Route guidance markings (Photo courtesy of Ennis-Flint)

Total lane changes, late lane changes, and unnecessary lane changes were tracked whenever possible using the video data at the two sites. Statistical checks were made to ensure that before-and-after traffic volumes were not significantly different at the sites, and only those periods with no statistical difference were used for comparison. Overall the symbol markings resulted in better utilization of the optional lane (indicating that drivers better understood the possible lane uses), lane changes taking place further upstream, and fewer unnecessary lane changes. These changes in lane use and lane-changing behavior improve operations overall and therefore could potentially improve safety with fewer late lane changes and erratic maneuvers.

While these markings do help drivers, the costs associated with installing and maintaining these markings in high-traffic-volume areas and the risks to agency personnel installing these should be considered. Therefore these markings may be best suited for locations with a documented history of driver confusion, late lane merges or erratic driving maneuvers related to lane selection. ■

CASE 8: Lighted Raised Pavement Markers for Delineation

Raised pavement markers (RPM) have been used successfully for road delineation over the past few decades. More recently, lighted RPMs have begun to be used to enhance visibility of the delineation. Sections 3B-11 through 3B-14 provide guidance on the use of RPMs and lighted RPMs. Lighted RPMs can be powered a variety of ways, including hard-wired and solar-powered.

A recent study investigated the use of lighted RPMs for turning-lane delineation in a multilane-turning situation at a traffic signal. Figure 21 shows the lighted RPMs used in the study during nighttime conditions.

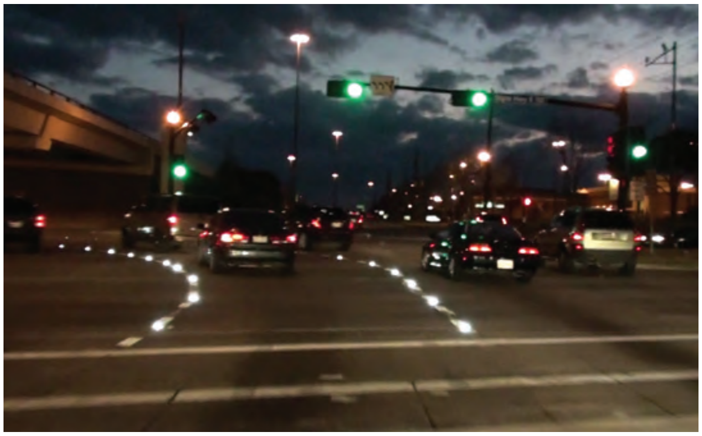

Figure 21: Lighted RPMs for turning lane delineation (Photo courtesy of Texas A&M Transportation Institute)

The study focuses on a triple left turn intersection movement in Sugar Land, Texas. There are three lanes dedicated for left-turn movements and lighted RPMs are installed between the three lanes. The RPMS are illuminated at the start of the green signal phase until the start of the red signal phase. Before-and-after video recording data were used to evaluate the effects of the lighted RPMs. Overall, the lighted RPMs were reported to reduce the number of lane-keeping violations that occurred when a turning vehicle encroached into an adjacent lane. This lane-keeping improvement may help to improve safety by reducing the number of crashes at this location.

Another lighted-RPM installation was documented in the literature but without a formal evaluation. This implementation was used in a lane-merge situation in New Jersey. The lighted RPMs were used to delineate the lanes involved in the merge and to create an in-lane arrow pattern. This system was not formally evaluated, but DOT personnel considered it to be effective. Figure 22 shows the New Jersey merge-area installation.

Lighted RPMs may be slightly recessed into the pavement in certain applications or made to be snowplow-able in an effort to improve their durability. The color of lighted RPMs is typically achieved using light-emitting diode (LED) technology, and care should be taken to ensure the correct light color as defined in the applicable MUTCD sections dependent upon their intended use. ■

Figure 22: Lighted RPMs for a merge area (Photo courtesy of Nick Hutchins, HIL-Tech Ltd.)

CASE 9: Road Diets

A Road diet is a way to use pavement markings to reconfigure a roadway and improve safety. The traditional example of a road diet involves converting a four-lane, undivided roadway into a three-lane roadway with a two-way left-turn lane. This reduction from four through lanes to three allows for increased room in the road cross section for bike lanes, pedestrian facilities, or parking. In general, road diets are good candidates for use on facilities up to 15,000 to 20,000 AADT and will not typically cause congestion on facilities with traffic below these levels. Special considerations for legal passing opportunities may be warranted if a longer corridor has a considerable number of slow-moving or frequently stopping vehicles. Figure 23 shows a before-and-after view of a road diet conversion in Reston, Va.

Road diets can have substantial safety and operational benefits in addition to the livability improvements made possible by overall bike and pedestrian enhancements. Safety and operational benefits that are possible as a result of road diets include:

- reduced vehicle conflicts, especially rear-end, left-turn, and side-swipe,
- reduced speed differential and associated higher-speed weaving maneuvers,
- separated left-turn lane that may reduce certain delays,
- improved side-street crossings or entrances with fewer lanes to cross and fewer lanes of traffic to decipher, and
- improved pedestrian crossings with fewer lanes to cross and less time exposed to moving traffic.

A detailed empirical-Bayes, before-after safety analysis of road diets was conducted by the FHWA in 2010. This investigation used data from 30 treatment sites and 51 reference sites in California and Washington and another 15 treatment sites and 296 reference sites in Iowa. All treatment sites were essentially the same traditional road diet example of a four-lane roadway being reduced to a three-lane with a two-way left-turn lane. The California and Washington treatment sites were typically in suburban areas surrounding larger cities, while the Iowa sites were U.S. and state routes in small urban areas. The traffic volumes on the Iowa sample ranged from approximately 3,700 to 14,000 AADT, while the California and Washington samples ranged from 5,500 to 26,000 AADT.

Statistically significant reductions in total crashes were found for each sample individually and for all sites combined. The Iowa sample showed a 47 percent reduction in total crashes; the California and Washington samples showed a 19 percent reduction in total crashes, and the combined sample showed a 29 percent reduction in total crashes. Based on the analysis results, the researchers suggest using crash reduction factors in accordance with the different treatment environments and traffic volumes present in the two sample types. Roads in higher-population settings (with potentially higher traffic volumes) may expect crash reductions more in line with the 19 percent result, while roads in smaller cities (like the Iowa sites) may expect greater reductions of up to 47 percent. ■

Figure 23: Road diet, before (left) and after (right) (Photos courtesy of Virginia DOT)

CASE 10: Transverse Speed Markings

Optical speed-bar markings intended to give drivers the perception that they are increasing speed have been implemented and evaluated a number of times across the United States. These markings have been used in attempts to reduce speeds on both two-lane and multilane roads. These markings are typically used on approaches to curves and other potentially unexpected changes in road character, including at entrances to small communities. The MUTCD provides guidelines on the use of these types of markings in Section 3B.22.

Various patterns have been tried, including bars across the entire lane, bars only near the edge of the lane, and broken bars across most of the lane with clear wheel paths. Retroreflective elements have also been used in creating these markings to increase visibility in dark conditions. The MUTCD recommended use is for bars that extend no more than 18 inches into the lane on both sides of a lane. Figure 24 shows optical speed bars used in the MUTCD recommended style in Virginia.

Considering all the evaluations documented, optical speed bars do produce benefits and tend to result in minor reductions in speed and speeding behavior. Some studies showed that the speed-reduction effects dissipated over time, as is the case with many new treatments, but other studies showed lasting effects. The potential for reduced effectiveness over time is likely why the MUTCD suggests avoiding their use in areas with many local and familiar drivers.

The converging chevron marking is another transverse marking similar to optical speed bars that has been installed in an attempt to reduce speeds. Converging chevrons have been installed and evaluated in Iowa, Minnesota, Wisconsin, Ohio, Texas, and Georgia. The converging chevron marking has been used on multilane highways, suburban local roads, and entrances to small communities. Figure 25 shows converging chevron markings on a multilane highway, and Figure 26 shows them on a two-lane two-way road.

Similar to optical speed bars, the combined evaluation results of converging chevrons show promising results, with some studies showing diminishing results over time and others showing lasting speed reduction effects. The use of converging chevron markings is not covered in the MUTCD and likely requires experimental approval. ■

Figure 24: Optical speed bars (Photo courtesy of Virginia DOT)

Figure 25: Converging chevrons (Photo courtesy of Texas A&M Transportation Institute)

Figure 26: Converging chevrons (Photo courtesy of the Center for Transportation Research and Education at Iowa State University)

CASE 11: Wider Markings

A normal lane marking, according to the MUTCD, is 4 to 6 inches wide. Traditionally a 4-inch line has been used by most transportation agencies, but more recently agencies have begun to use wider lines as their safety benefits continue to be established and documented. Figure 27 shows the difference of wider edge-line markings on a two-lane, two-way road.

A study that concluded in 2013 used data from Illinois, Kansas, and Michigan to compare the safety effects of wider lines used in those states. Two-lane and multilane highways were studied, with two-lane highways showing the largest safety benefits from wider edge-lines. Some of the highways considered were used to compare 5-inch with 4-inch markings, while others were used to compare 6-inch with 4-inch markings. Extensive controls and bias-removal efforts were completed to ensure the best possible comparisons between line widths in this study. Overall the highways with lines wider than 4 inches experienced fewer crashes than those with 4-inch-wide lines. Total crash rates were 15 percent to 30 percent lower on the highways with wider edge lines. Some of the largest crash rate differences were evident during wet and wet nighttime conditions, with wider lines experiencing up to 67 percent fewer wet crashes and up to 79 percent fewer wet nighttime crashes.

Another study published in 2011 evaluated the results of wider lines as part of a larger program including overall striping and delineation improvements in Missouri. The program installed wider, 6-inch lines in place of the traditional 4-inch lines on more than 1,000 miles of roadway. In general the wider markings reduced fatal and disabling injury crashes by:

- 21 percent on rural freeways,
- 34 percent on rural multilane divided highways,
- 46 percent on rural multiline undivided highways, and
- 38 percent on urban two-lane highways.

The study also considered the costs of the treatments in order to establish benefit-cost relationships for using wider lines. Considering the costs of wider lines and crash reduction benefits, the following benefit-to-cost ratios were established:

- 9.3 for rural freeways,
- 12.0 for rural multilane divided highways,
- 145.9 for rural multiline undivided highways, and
- 117.6 for urban two-lane highways. ■

Figure 27: Wider edge-line markings (Photos courtesy of the Pennsylvania Transportation Institute, Pennsylvania State University)

CASE 12: Wrong-Way-Driving Prevention

Wrong-way driving can result in serious crashes and cause severe injuries and fatalities. Many strategies, including signing, marking, illumination, retroreflective products, channelization, and intelligent transportation systems, have been used to prevent wrong-way driving. Some of these countermeasures are focused on preventing drivers from entering the wrong lane, and some are aimed at alerting drivers to stop after they have already entered the wrong lane. Two traditional markings intended to prevent drivers from driving in the wrong direction are covered in the MUTCD section 3B.20 and include white arrow markings in the correct direction of travel and arrow patterns comprising RPMs that reflect red in the wrong direction of travel.

Wrong-way-driving crashes often involve drunken drivers with impaired sign- and marking-recognition abilities. This has led to several enhanced signing and marking efforts to reduce wrong-way driving. Few formal evaluations of innovative wrong-way-driving prevention markings have been conducted, but some enhanced marking and delineation treatments have been documented, including improved RPM patterns and additional lane markings and channelization to ensure proper lane selection.

Research demonstrating the effectiveness of the RPM arrow with red reflectors in the wrong direction of travel dates back to the 1970s. Most recently, researchers in Texas have documented maintenance challenges with these arrows and have proposed an alternative arrow that may require less maintenance while achieving the same benefits. The research team compared the traditional RPM arrow pattern with a narrower experimental pattern. The narrower pattern may have fewer marker failures, because the narrower pattern will not experience as many wheel hits as the wider pattern. The narrower pattern, shown in Figure 28 (right), was found to be as recognizable as the traditional pattern (left), leading the researchers to recommend using the new pattern at all locations when replacing the traditional patterns.

Certain road and interchange geometries may be more susceptible to wrong-way driving due to their layout. One freeway interchange, the partial cloverleaf, can experience wrong-way driving with drivers entering an exit ramp from an adjacent intersection. This situation, and similar ones, can be improved through pavement markings delineating the correct turning movement to avoid entering an approach the wrong way. Figure 29 shows a yellow pavement marking used for left-turning vehicles at the intersection to avoid wrong-way drivers entering the exit ramp of a partial cloverleaf interchange.

Figure 28: RPM wrong-way arrow standard (left) and narrower (right) (Photos courtesy of Texas A&M Transportation Institute)

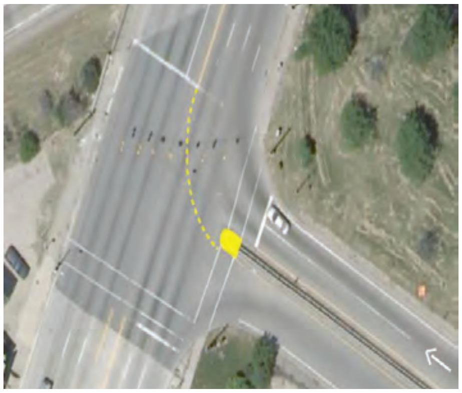

Figure 29: Pavement marking extensions for left-turn movement from crossroad (Photo courtesy of Michigan DOT)

Another situation with the potential for wrong-way driving was studied in Texas. In this case, a two-way frontage road immediately following a freeway exit was treated using white arrow markings indicating the appropriate two directions of travel on the two-lane frontage road. This location in particular was chosen as other nearby freeways exit to one-way frontage roads that look similar to this two-way frontage road. Figure 30 shows the wrong-way driver situation (left) that occurred before treatment and correct movement with arrow markings (right) intended after implementation.

Overall, there was a 91 percent reduction in incorrect maneuvers following installation of the white arrow markings.

Research is currently under way at Southern Illinois University and Auburn University to develop a directional rumble strip to reduce wrong-way freeway entries. Field tests of multiple rumble patterns will be completed to determine a solution that will "generate elevated noise and vibration for wrong-way driving and normal noise and vibration for right-way driving." This work is scheduled to be completed in summer 2015, but no published materials were found at the time of this writing.

A National Cooperative Highway Research Program (NCHRP) project is currently under way that will eventually propose new and updated wrong-way control measures and related information for potential adoption in the MUTCD. Readers are encouraged to look for any new information stemming from that work (NCHRP Project 03-117), which will conclude in 2017. ■

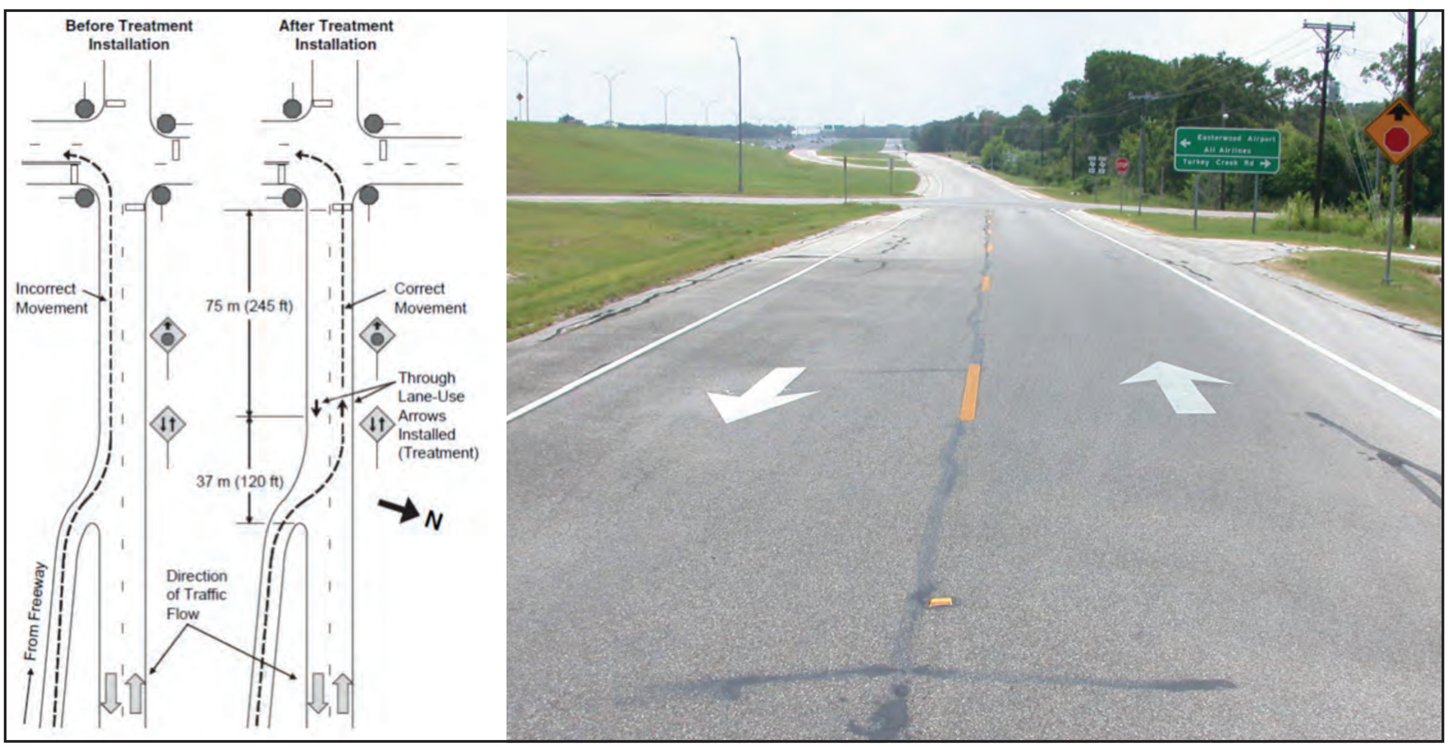

Figure 30: Arrows to prevent wrong-way driving on frontage road (Photos courtesy of Texas A&M Transportation Institute)

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