System-wide Safety Treatments and Design Guidance for J-Turns

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16. Abstract

In an effort Toward Zero Deaths (TZD) the Missouri Department of Transportation (MoDOT) initiated this research project to develop guidance on treatments that can reduce crashes and fatalities. The project first synthesized the literature and state of practice on system-wide safety treatments and documented their effectiveness. In particular, the objective was to examine those treatments that have not been already implemented in Missouri. The safety effectiveness, implementation guidelines, limitations, costs, and concerns of the treatments were documented. The identified safety treatments work in conjunction with the 'Necessary Nine' strategies identified in the Missouri's Blueprint. Accordingly, the synthesis covered three areas: 1) Horizontal curves, 2) Intersections, and 3) Wrong way crashes. The reviewed treatments included signing, geometric and access management, ITS, pavement markings, and signal control enhancements to improve safety. In the last few years, MoDOT has replaced several high crash intersections on rural highways in the state with J-turns. Given their safety effectiveness and low cost the J-turn has become a preferred alternative to replace high crash two-way stop-controlled intersections on high speed highways. Unfortunately, national guidance on the design of J-turns is very limited. This project addresses this gap in practice by developing guidance on spacing and acceleration lanes. A thorough examination of crashes that occurred at twelve existing J-turn sites in Missouri was conducted. The crash review revealed the proportions of five crash types occurring at J-turn sites: 1) major road sideswipe (31.6%), 2) major road rear-end (28.1%), 3) minor road rear-end (15.8%), 4) loss of control (14%), and 5) merging from U-turn (10.5%). The crash rates decreased with the increase in the spacing to the U-turn, for both sideswipe and rear-end crashes; J-turns with a spacing of 1500 feet or greater experienced the lowest crash rates. A calibrated simulation model was used to study various volume scenarios and design variables. For all scenarios, the presence of acceleration lane resulted in significantly fewer conflicts. Thus, acceleration lanes were recommended for all J-turn designs, including lower volume sites. Second, while spacing between 1000 feet and 2000 feet was found to be sufficient for low volume combinations, spacing of 2000 feet was recommended for medium to high volume conditions.

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EXECUTIVE SUMMARY

The Missouri Department of Transportation (MoDOT) sponsored this research project to investigate treatments that can reduce crashes and fatalities to further the goal of Toward Zero Deaths (TZD). One major objective was to synthesize the literature and state of practice on system-wide safety treatments and document their effectiveness. Specifically, the objective was to examine those treatments that have not been implemented already in Missouri. Another major objective was to provide guidance on the J-turn intersection design, which eliminates or reduces crossing conflicts.

A synthesis of system-wide safety treatments from other states and countries was conducted. The safety effectiveness, implementation guidelines, limitations, costs, and concerns of the treatments were documented. The identified safety treatments are consistent with the 'Necessary Nine' strategies identified in the Missouri's Blueprint. Accordingly, the synthesis covered three areas: 1) horizontal curves, 2) intersections, and 3) wrong way crashes. The reviewed treatments include signing, geometric design and access management, ITS, pavement markings, and signal control enhancements to improve safety. This synthesis provides a systematic method of selecting system-wide treatments for future deployments in the state of Missouri.

Signage, design, ITS, and driver countermeasures were reviewed to address wrong way crashes. Innovative signage strategies including lowering height, oversized signs, illumination, doubling the number of signs, are low-cost solutions that can be deployed across the system. Design countermeasures such as avoiding left side exit ramps, using raised medians on crossroads, improving sight distance are also recommended. ITS technology options, due to their higher costs, may not be suitable for system-wide deployment but are appropriate for isolated treatments. The detection and alert systems based on video radar, or in-pavement sensors have been piloted in a few states.

Countermeasures targeting horizontal curve crashes may include signage treatments that exceed the minimum recommended MUTCD signage and device requirements for horizontal curves. Such treatments include improved curve signing through the use of additional chevrons, flashing beacons at sharp curves, dynamic curve guidance systems, and dynamic speed warning systems. Other recommended horizontal curve safety treatments include pavement treatments such as speed reduction markings, warning symbols painted on the pavement, and high friction pavement treatment. Missouri DOT has successfully utilized two pavement marking treatments in the past - wider edge lines and rumble strips/stripes.

Treatments to enhance signalized intersection safety include increasing clearance interval, changing left turn from permissive to protected-permissive, flashing yellow arrow, dynamic signal warning, red light cameras, and improving signal visibility. Based on the safety effectiveness reported in literature, dynamic signal warning and improving signal visibility are recommended for future consideration as system-wide treatments at signalized intersections in Missouri. At stop-control intersections, the use of bigger signs, LEDs, and flashing beacons were found to reduce crashes due to the increased visibility and illumination of signs.

In the last few years, MoDOT has replaced several high crash intersections on rural highways in the state with J-turns. Given their safety effectiveness and low cost, compared to grade separated interchanges, the J-turn has become a preferred alternative to replace high crash two-way-stop-controlled intersections on high speed highways. Unfortunately, national guidance on the design of J-turns is very limited. For example, there are no recommendations on the spacing between the main intersection and the U-turn. Similarly, there is no guidance on when acceleration lanes are recommended, i.e., at what level of traffic volume. This project addressed this gap in practice by developing guidance on spacing and acceleration lanes. A thorough examination of crashes that occurred at twelve existing J-turn sites in Missouri was conducted. The objective of this review was to determine if the crash frequencies and types of crashes were influenced by the aforementioned design parameters.

The crash review revealed the proportions of five crash types occurring at J-turn sites: 1) major road sideswipe (31.6%), 2) major road rear-end (28.1%), 3) minor road rear-end (15.8%), 4) loss of control (14%), and 5) merging from U-turn (10.5%). Vehicles merging with the major road traffic or changing lanes to access the U-turn lane caused most of the major road side swipe and rear-end crashes. Other common contributing factors include driver inattention and the large speed difference between the merging vehicles from the minor road and the vehicles on the major road. Crash rates, expressed as per million vehicle miles of travel, decreased with an increase in the U-turn spacing for both sideswipe and rear-end crashes. A longer spacing allowed merging vehicles to reach major road operating speeds, thus making it safer to follow other vehicles in the lane and to make lane changes. J-turn sites with a spacing of 1500 feet or greater experienced the lowest crash rates.

In addition, traffic simulation experiments were conducted to study the effect of different design parameters and traffic volumes on safety of the J-turn design. A base simulation model was created and calibrated using field data collected in a previous MoDOT project on J-turns. The calibrated model was then used to study various combinations of major road and minor road volumes and design variables. For all the studied scenarios, the presence of acceleration lane resulted in significantly fewer conflicts. Thus, acceleration lanes are recommended for all J-turn designs, including lower volume sites. Second, while a spacing between 1000 feet and 2000 feet was found to be sufficient for low volume combinations, a spacing of 2000 feet is recommended for medium to high volume conditions.

1. BACKGROUND

Traffic fatalities in Missouri have decreased steadily in the last decade. The chart to the right shows the trend in road fatalities since 2005, as reported in the current edition of the Missouri's Blueprint to Save MOre Lives (MCRS, 2012). A major factor that led to this reduction in fatalities is the Missouri Department of Transportation's (MoDOT) targeting of specific crash types with system-wide safety treatments. This approach has been shown to be more effective than spot improvements due to the inherent randomness in crash occurrence locations on road segments. In the last decade, MoDOT has implemented system-wide safety treatments, such as median cable barrier and rumble strips, that produced significant safety results. For example, it is estimated that the 800 miles of cable median barrier installed in Missouri has resulted in saving at least 300 lives in over a decade. Missouri's Blueprint established a short-term goal of reducing traffic fatalities to 700 per year by 2016. This goal is geared towards achieving the long-term vision of zero roadway deaths in the state. MoDOT initiated this research project to accomplish two major objectives. The first objective is to synthesize existing practices on system-wide safety treatments, especially those treatments that have not been implemented already in Missouri. The second objective is to develop design guidance for J-turns that are being increasingly adopted across Missouri. J-turns are an effective and low-cost safety treatment, especially at rural high-speed expressway intersections. Taken together, these two objectives will assist MoDOT in decreasing crashes and saving lives in Missouri.

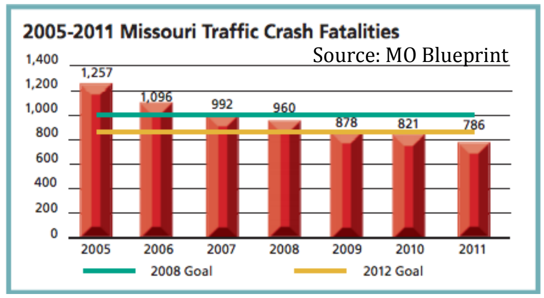


Figure 1.1. MO Fatalities (2005-2011)

Figure 1.2. Median cable barrier

1.1. Goal 1: Synthesis of System-wide Safety Treatments

A synthesis of system-wide safety treatments from other states and countries was conducted. The safety effectiveness, implementation guidelines, limitations, costs, and concerns of the treatments were documented. The identified safety treatments work in conjunction with the 'Necessary Nine' strategies identified in the Missouri's Blueprint (MCRS, 2012). The necessary nine strategies were identified as the strategies with the greatest potential to save lives and reduce serious injuries. They include: 1) increase safety belt use, 2) expand the installation of rumble strips/stripes, 3) increase efforts to reduce the number of impaired drivers, 4) improve intersection safety, 5) improve curve safety, 6) change traffic safety culture, 7) improve roadway shoulders, 8) increase enforcement efforts, and 9) expand and improve roadway visibility. System-wide safety treatments that address these strategies will be of immediate value to transportation agencies in Missouri and can be implemented in the near future. Similarly, the identified treatments are associated with the emphasis and focus areas within the Blueprint. For example, the 'serious crash types' emphasis area focuses on reducing horizontal curve crashes and intersection crashes, among others.

> *"A driver is three times more likely to be involved in a crash on a horizontal curve than on a straight stretch of roadway. In Missouri, 33.2 percent of all fatalities and 27 percent of all serious injuries during the past three years occurred along horizontal curves."*
> Missouri Blueprint

The focus of the synthesis was on treatments that have not been implemented previously in Missouri. For example, literature on rumble strips/stripes was not considered to be of high importance to MoDOT since they have already been deployed on several highways across the state. Accordingly, the review was broadly grouped into treatments applicable to three areas: 1) horizontal curves, 2) intersections, and 3) wrong way crashes. These three areas were also recommended by the project's technical advisory panel. The numbers of fatalities and serious injuries that occurred in Missouri, including those that occurred on horizontal curves and intersections, are presented in Table 1. The three areas, horizontal curves, intersections, and head-on crashes, accounted for more than 65% of fatalities in Missouri from 2009-2011. The last row of Table 1 shows head-on crashes, a majority of which occurred on two lane highways due to vehicles crossing the center line and colliding with oncoming traffic. Countermeasures such as centerline rumble stripes are already used by MoDOT at several two lane highways across the state to alert drivers of lane departures. Another cause of head-on crashes is wrong-way driving. MoDOT is currently placing a high emphasis on mitigating wrong-way crashes across the state, including pilot deployments in the St. Louis region.

Table 1.1. Fatalities and serious injury statistics in Missouri (Source: Missouri Blueprint)

	2009		2010		2011	
	Fatalities	Serious Injuries	Fatalities	Serious Injuries	Fatalities	Serious Injuries
Missouri Total	878	6540	821	6096	786	5644
Horizontal Curves	293	1783	262	1636	270	1521
Intersections	150	1926	165	1747	113	1642
Head-on	140	582	106	478	121	487

1.2. Goal 2: Design Guidance for J-turns

At a traditional two-way-stop-control (TWSC) intersection on a four-lane divided highway, vehicles accessing the major highway from the minor road can make a left turn or through movement at the intersection by crossing major road movements. Highways with high volumes and/or high speeds may make these minor road movements challenging to execute. In contrast, in a J-turn design, vehicles accessing the major highway from the minor road make a right turning movement and then use a U-turn at a downstream location. The major road vehicles accessing the minor road via a left turning movement may or may not have to use the U-turn for their movements. One variation of the J-turn design allows for major road turning movements to occur at the intersection, but still requires the minor road movements to use the U-turn. A conceptual schematic of the J-turn intersection is shown in Figure 1.3. In Figure 1.3, the left-turning movement from the minor road is shown using red arrows. The safety of the J-turn design stems from the reduction of severe high-risk conflict points, including crossing conflicts, which result in right-angle crashes. According to NCHRP 650 *(*Maze et al., 2010*)*, a TWSC intersection on a four-lane divided highway has 42 conflict points while a J-turn intersection has 24 conflict points.

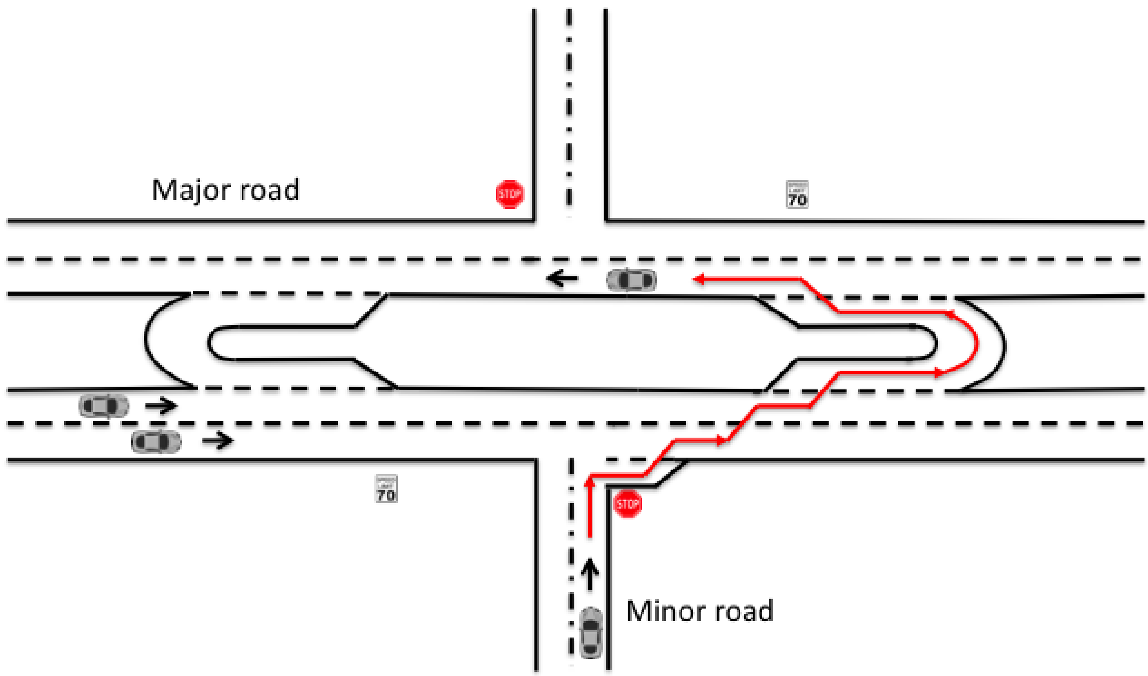


Figure 1.3. Conceptual schematic of J-turn intersection (Not to scale)

MoDOT has replaced several high crash intersections on rural highways in the state with J-turns. A recent study (Edara et al., 2014) quantified the overall safety benefits of J-turns in Missouri. Given their safety effectiveness and low cost compared to grade separated interchanges, the J-turn has become a preferred alternative to replace high crash TWSC locations on high speed highways. The J-turn design has been in use in the US for several years under other names, such as Superstreet in North Carolina and Restricted Crossing U-turn in Maryland. Despite their long use, there is no specific national guidance on the design of J-turns. For example, there are no recommendations on the spacing between the main intersection and the U-turn. Similarly, there is no guidance on when acceleration lanes are recommended, i.e., at what level of traffic volume. To this end, this project uses a two-pronged approach to develop guidance for designing J-turns. First, a thorough review of crashes that occurred at existing J-turn sites in Missouri was conducted. The objective of this review was to identify how the crash frequencies and types of crashes were influenced by any design parameters. Second, traffic simulation experiments were conducted to study the effect of different design parameters and traffic volumes. The simulation experiments measured the safety effect of the presence of acceleration lane and the spacing between the main intersection and the U-turn.

Various combinations of minor road and major volumes were analyzed for different spacing values. Vehicle trajectories were extracted from simulation. The vehicle trajectories provide information about the longitudinal and lateral location of vehicles, speed, acceleration, and other characteristics at every 0.1 seconds. The vehicle trajectory data was used to extract conflict safety measures such as the time to conflict (TTC), post-encroachment time, and conflict angle, which were in-turn used to quantify the number of lane change conflict. Recall that crossing conflicts resulting from minor road left turns in a TWSC were replaced by lane change conflicts in a J-turn. FHWA's Surrogate Safety Assessment Model (SSAM), used in previous studies to generate conflict measures from simulation models (Gettman and Head, 2003, Kim et al., 2007) produced the aforementioned safety performance measures.

2. SYNTHESIS OF WRONG WAY CRASHES

Wrong way driving is a rare but dangerous event that could lead to severe crashes. Existing research on wrong way driving crashes focuses on contributing factors and countermeasures to mitigate them. Contributing factors include driver, vehicle, and facility characteristics. A synthesis of the contributing factors and countermeasures is presented next.

2.1. Contributing Factors

2.1.1. Age

Drivers over the age of 70 and young drivers are overrepresented as at fault drivers in wrong way crashes (Braam, 2006). Most of the crashes caused by young drivers were due to inattention, while most crashes caused by older drivers occurred because of some physical illnesses such as dementia or confusion (Braam, 2006; Kemel, 2015; Zhou et al., 2012). Figure 2.1 shows a comparison of the ages of wrong way drivers with the ages of the other vehicle involved in the fatal collision driving the right way. The age distribution of the other vehicle involved (i.e., right-way driver) represents what a typical age distribution should look like in such crashes.

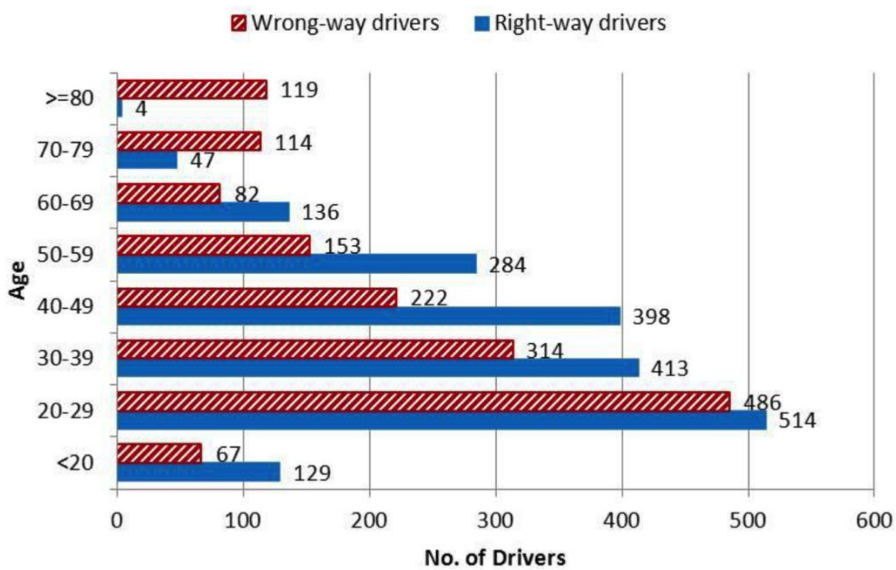


Figure 2.1. Comparison between wrong way and right way driver ages fatal collisions (Zhou et al., 2012)

2.1.2. Gender

Male drivers are overrepresented in wrong way crashes. In a study conducted in Texas, 67% of wrong way crashes involved male drivers. The finding was also true outside the US–76% in France and 81% in Holland (Kemel, 2015; Zhou et al., 2012; Cooner et al., 2004; SWOV, 2012).

2.1.3. Impaired Driving

A recent study performed by the NTSB using FARS data found that 60% of wrong way crashes involved drivers impaired by alcohol and another 3.4% involved drivers who were drinking without going over the legal alcohol limit (NTSB, 2012). The NTSB (2012) study also reported that drug use was found in 4.4% of impaired drivers involved in wrong way crashes.

Figure 2 shows the numbers of sober and drunk drivers involved in fatal wrong way collisions on divided highways. Figure 2.2 shows that only a small percentage of the right-way drivers were impaired.

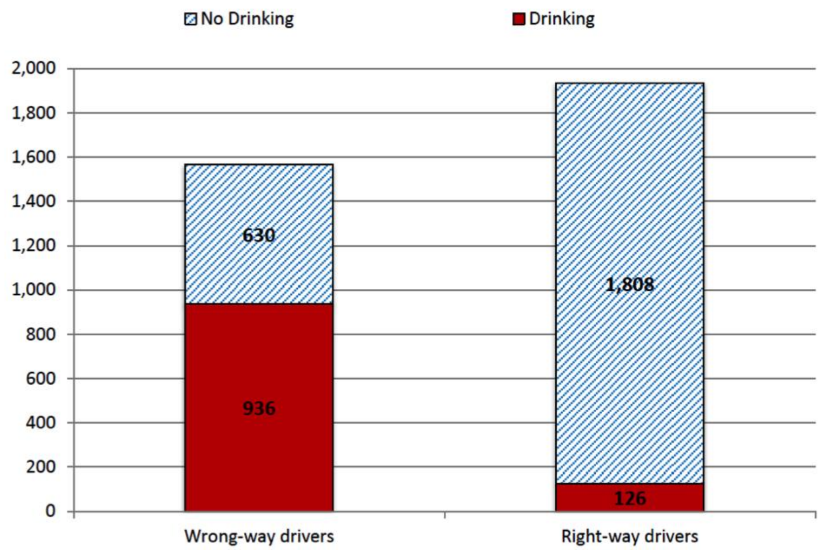


Figure 2.2. Wrong way fatal crashes caused by impaired drivers (NTSB, 2012)

2.1.4. Presence of Passenger
About 85% of wrong way crashes involved drivers with no passengers indicating the possibility that passengers could aid in the prevention of wrong way crashes (NTSB, 2012).

2.1.5. Vehicle
A study using Illinois data found that passenger cars were the most common type of vehicle involved in wrong way cashes. Table 2.1 shows the percentages of wrong way crashes by vehicle type in Illinois (Zhou et al., 2012). The small number of commercial vehicles could be explained by the fact that commercial drivers are highly regulated, but the difference between passenger vehicles and pickups/SUVs/Mini-vans is more difficult to explain.

Table 2.1. Vehicle type for wrong-way crashes (Zhou et al., 2012)

Vehicle Type	Crash Frequency	Percent (%)
Passenger	139	68.5%
Pickup	26	12.8%
SUV	18	8.9%
Van/Mini-Van	12	5.9%
Unknown	4	2.0%
Tractor with Semi-Trailer	2	1.0%
Motorcycle (over 150cc)	1	0.5%
Tractor without Semi-Trailer	1	0.5%
Total	**203**	**100%**

2.1.6. Facility
The type of roadway facility and location on the facility plays an important role in wrong way driving. Research conducted in California (Copeland, 1989) and Texas (Conner et al., 2004) found that urban areas have significantly more wrong way crashes than rural areas. NTSB (2012) reports the main findings of research on wrong way crashes at interchange facilities, as reported on the next page.

According to NTSB (2012) report,

- *Full, four-quadrant cloverleaf ramps have the lowest wrong-way entry rate, and left-hand exit ramps have the highest (NTSB, 2012; Lew, 1971)*
- *Partial interchanges have twice the wrong-way entry rate of full interchanges (NTSB, 2012; Tamburri and Lowden, 1968)*
- *High rates of wrong-way entry occur at incomplete interchanges and loop exit ramps with crossroad terminals adjacent to the entrance ramp (NTSB, 2012; Parsonson and Marks, 1979)*
- *Exit ramps that terminate at two-way streets have high wrong-way entry rates (NTSB, 2012; Lew, 1971)*
- *Interchanges with short sight distances at their decision points have a disproportionately high number of wrong-way movements (NTSB, 2012; Copelan, 1989)*
- *Exit ramps with rounded corners tend to encourage rather than deter wrong-way movements (Vaswani, 1973). Since rounded corners provide less of a distinction between the roadway and the ramp than sharp corners, they may mislead drivers into continuing along their current path of travel so that they mistakenly enter the exit ramp (NTSB, 2012)*

Zhou et al. (2015) investigated wrong way entry points by interchange types in Illinois. Table 2 shows the interchange types and the corresponding entry points reported in Zhou et al. (2015). The right-most column in Table 2.2 lists the ranks of different designs based on wrong way crash rate. The Compressed Diamond, SPUI, and Partial Cloverleaf designs are the top three ranked interchange types, meaning they have the most wrong way crashes. Diamond interchanges, which outnumbered the other types with 308 in Illinois, have a lower crash rate than many other interchange types including the Full Cloverleaf design.

Table 2.2. Wrong way crash entry points by interchange type (Zhou et al., 2015)

Interchange Type	Recorded		1st Estimated Entry Point		2nd Estimated Entry Point		Total No. of Interchanges in IL		WW Crash Rate	Rank
	#	%	#	%	#	%	#	%	% per year	
Compressed Diamond	12	25.53	44	29.93	44	30.14	56	7.64	13.39	1
Diamond	16	34.04	39	26.53	38	26.03	308	42.02	2.44	6
Partial Cloverleaf	5	10.64	28	19.05	23	15.75	79	10.78	5.22	3
Cloverleaf	3	6.38	12	8.16	12	8.22	59	8.05	3.39	5
Rest Area	1	2.13	9	6.12	6	4.11	64	8.73	1.82	6
Freeway Feeder	5	10.64	3	2.04	6	4.11	30	4.09	4.44	4
Modified Diamond	3	6.38	4	2.72	4	2.74	61	8.32	1.64	6
Semi-Directional	0	0.00	3	2.04	4	2.74	19	2.59	2.19	6
SPUI	1	2.13	2	1.36	3	2.05	8	1.09	5.73	2
Trumpet	0	0.00	2	1.36	4	2.74	25	3.41	1.33	7
Directional	1	2.13	1	0.68	2	1.37	24	3.27	1.39	7
Total	47	100.00	147	100.00	146	100.00	733	100.00	3.57	–

Additionally, Vaswani (1973) studied the possible wrong way entries at an interstate highway interchange. Figure 2.3 shows the possible entry points at a conventional diamond interchange and Figure 2.4 shows in more detail the wrong driving for left and right turning vehicles at a ramp terminal.

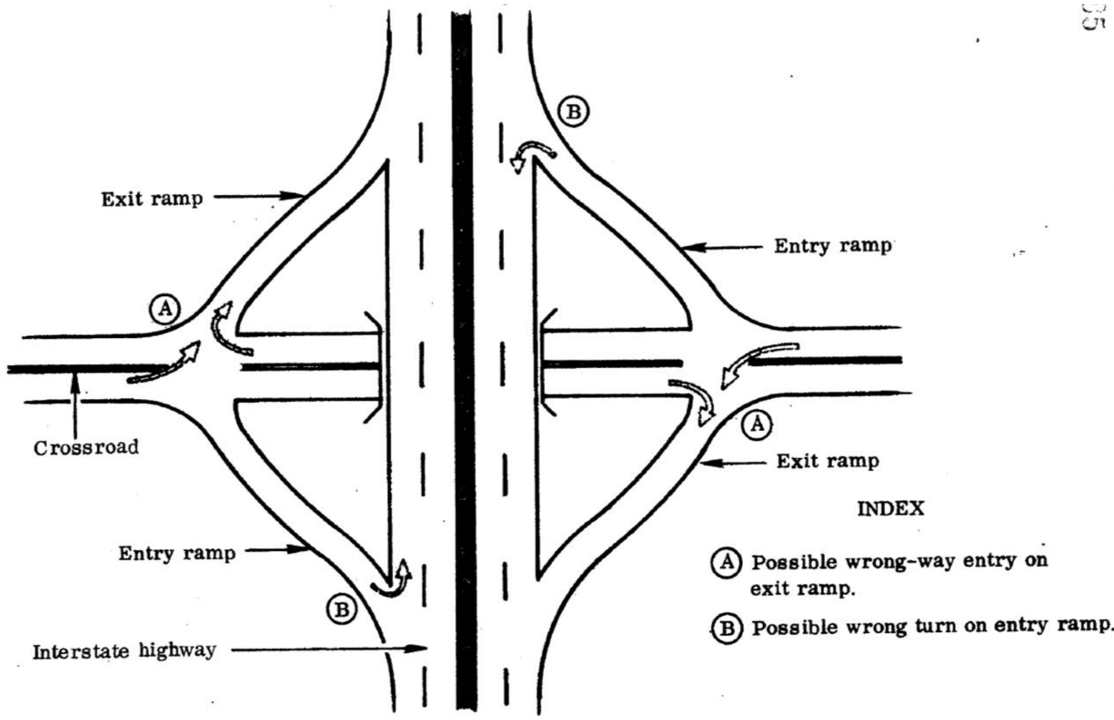


Figure 2.3. Wrong way entry points at a diamond interchange (Vaswani, 1973)

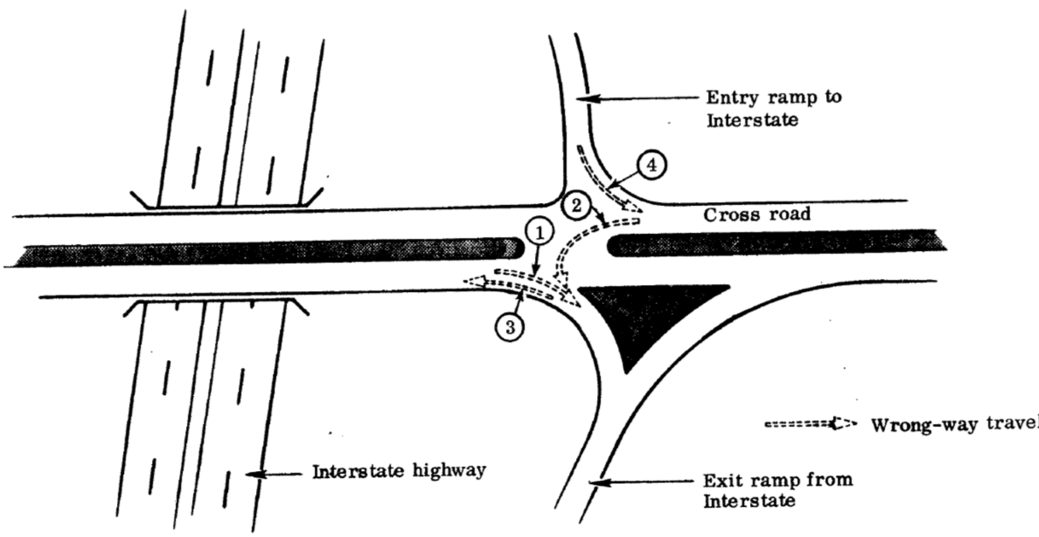


Figure 2.4. Wrong way entry points at a ramp terminal (Vaswani, 1973)

With the increasing popularity of Diverging Diamond Interchanges (DDI), there has been a growing concern about wrong way crashes because of the type of geometric configuration at such ramp terminals. Recent research performed in Missouri found that wrong-way crashes were 4.8% of fatal and injury crashes that occurred at the ramp terminal. These crashes are due to wrong way driving on the crossroad between the ramp terminals when vehicles first enter the crossover intersection. Figure 2.5 illustrates the types of crashes occurring at DDI ramp terminals (Claros et al., 2015). The crash type labeled 6 shows the typical location of a wrong way crash on cross road.

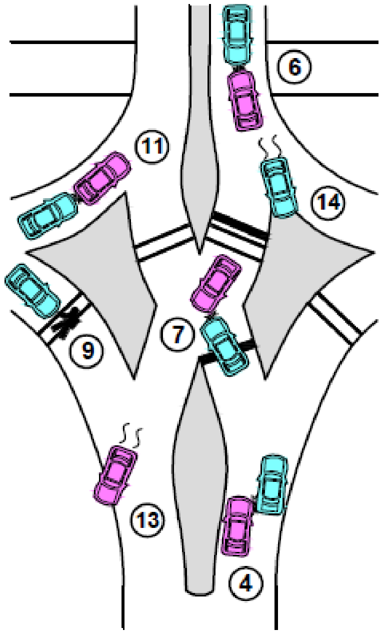


Figure 2.5. DDI crash types (Claros et al., 2015)

Vaughan et al. (2015) monitored traffic movements and conflicts at five DDIs from different states during a 6-month period. Video recordings of ramp terminals were processed using video detection. They found a high number of wrong way maneuvers at five sites, but none of them resulted in a crash. They also reported that wrong way maneuvers were more frequent during the night.

2.2. Wrong Way Crash Statistics

Wrong way crashes have a higher risk of resulting in severe injuries and fatalities. Using nationwide crash data from 2004-2011, a study by Ghorghi et al. (2014) found that the total number of fatal crashes decreased, but fatal wrong way crashes remain fairly constant during that same period (see Figure 2.6). While the reduction in total number of fatal crashes can be attributed to the various safety countermeasures adopted by safety professionals, the lack of a decline in wrong way driving fatal crashes shows a need to address this crash type.

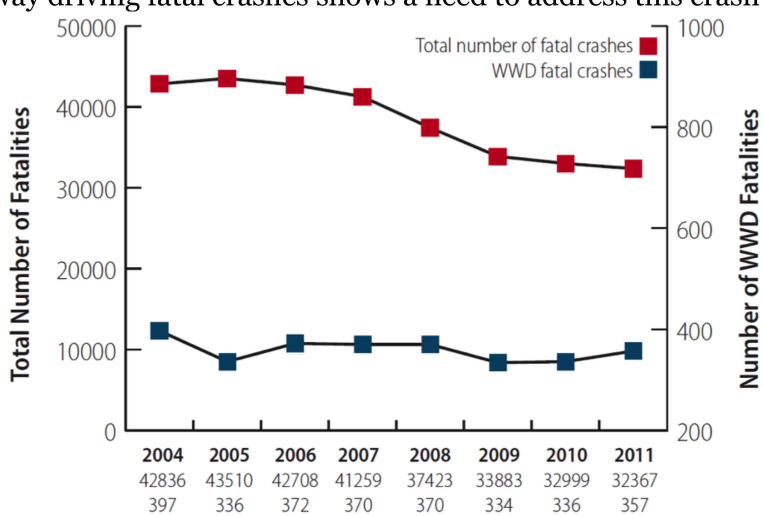


Figure 2.6. Trends in total number of fatalities and number of wrong way fatalities (Ghorghi et al., 2014)

Ghorghi et al. (2014) further reported that 57% of wrong way driving fatal crashes occurred on urban roads and 43% occurred on rural roads, while only 24% of highway miles are designated as urban. A few studies have analyzed the time of occurrence of wrong way driving crashes. Cooner et al. (2004) reported that 52% of crashes occurring between midnight and 6:00 am in Texas were attributed to wrong way driving; only 10.4% of all freeway crashes occurred during the same time period. In North Carolina, Braam (2006) reported that 33% of wrong way crashes occurred during dark conditions without any street lighting and 28% occurred at night on roads with lighting.

Zhou et al. (2012) summarized the contributing factors of wrong way crashes into six categories. These categories are: 1) traffic violation, 2) inattention, 3) impaired judgment, 4) insufficient knowledge, 5) infrastructure deficiency, and 6) others such as inclement weather. Traffic violation factors include impaired driving and reckless driving. Inattention includes distracted driving and falling asleep at the wheel. Impaired judgment includes ill drivers and elderly drivers. Insufficient knowledge includes a lack of understanding of highway driving and lack of familiarity with the facility. And, infrastructure deficiency includes insufficient sight distance and lighting.

2.3. Countermeasures

Braam (2006) reported that wrong way crashes are spread out over several miles of freeways with no identifiable concentrations, thus making the selection of treatment locations challenging. A few states have implemented countermeasures to address wrong way driving crashes and have reported their effectiveness. This section reviews countermeasures involving signage, geometric design, use of ITS technology, and driver behavior.

2.3.1 Signing

The MUTCD (FHWA, 2012) provides guidance on signage and pavement markings to prevent wrong way driving. There are two types of signage that are available to prevent wrong way crashes at ramp terminals: minimum required and optional.

Minimum Signing
The minimum required for exit ramps that intersect with the crossroad should be equipped, with a single "One Way Sign" (R6-1), a single "Do Not Enter Sign" (R5-1), and a single "Wrong Way Sign" (R5a-1) *(15, 37)* as shown in Figure 2.7.

(a) (b) (c)

Figure 2.7. Signing at exit ramps (a) R6-1 One way, (b) R5-1 Do not enter, (c) R5a-1 Wrong way
(NTSB, 2012; FHWA, 2012)

Optional Signing
Optional signage additions include turn prohibition signs on the crossroad: “No Right Turn” or “No Left Turn”. Pavement markings include a slender and elongated wrong-way arrow, or bidirectional red-and-white raised pavement markers in the shape of an arrow (NTSB, 2012; FHWA, 2012). Figure 2.8 shows signage at a ramp terminal for both minimum and optional signing. The NTSB (2012) recommends, as an option, doubling the number of minimum required signs at candidate locations as shown in Figure 2.9.

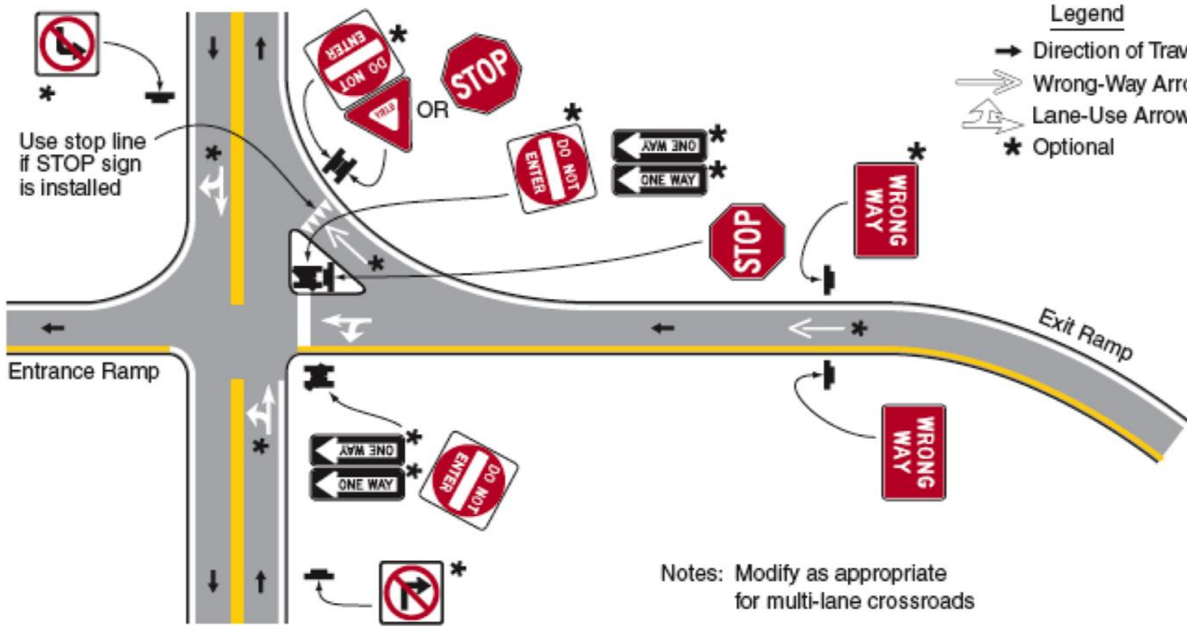


Figure 2.8. MUTCD required and optional signing and paving marking at a ramp terminal (NTSB, 2012; FHWA, 2012)

Figure 2.9. Optional double posted “Do Not Enter Sign” (R5-1) and “Wrong Way Sign” (R5a-1) (NTSB, 2012)

The NTSB (2012) report mentions that many states have adopted innovative signage strategies for controlled-access highway interchanges to reduce wrong-way driving. The strategies are shown on the next page.

- *Lowering the height of "Do Not Enter" and "Wrong Way" signs. [The minimum sign mounting height is 5 ft. in rural areas and 7 ft. when line of sight is obstructed by parked vehicles or pedestrians movements. There is a provision in the MUTCD (Section 2B. 41) to lower the signs located along the exit ramp to 3 ft. if an engineering study indicates that a lower mounting height would address wrong way driving on freeway or expressway exit ramps.]*
- *Using oversized "Do Not Enter" and "Wrong Way" signs (36 versus 30 inches) (FHWA, 2012)*
- *Mounting both "Do Not Enter" and "Wrong Way" signs on the same post, paired on both sides of the exit travel lane [i.e., ramp]*
- *Implementing a standard wrong-way sign package with larger dimension signs and twice the number of signs required by the MUTCD*
- *Illuminating "Wrong Way" signs that flash when a wrong-way vehicle is detected*
- *Installing a second set of "Wrong Way" signs on the exit ramp farther upstream from the crossroad*
- *Posting controlled-access highway entrance signs on each side of entrance ramps (FHWA, 2012)*
- *Applying red retroreflective tape to the vertical posts of exit ramp signs*
- *Installing red delineators on each side of exit ramps.*
- *Installing LED-illuminated in-pavement markers or delineators parallel with the stop bar at the crossroad end of exit ramps*
- *Installing trailblazing lines or reflective markers that channel travel in an arc to guide motorists making a left turn from the crossroad into an entrance ramp, to keep them from inadvertently entering an exit ramp (Morena and Leix, 2012)*

2.3.2 Geometric Countermeasures

Existing literature makes some recommendations on geometric design countermeasures that address wrong way driving crashes. These countermeasures are listed to the right.

Geometric countermeasures
-Avoid left side freeway exit ramps
-Install raised medians
-Use channelization devices
-Use tighter corner radius at exit ramp terminals
-Improve sight distance at intersections

2.3.2.1. Avoiding Left Side Freeway Exit Ramps

Research performed in Texas and California (Cooner et al. 2004; Copeland, 1989) found that left side exit ramps on freeways can cause driver confusion and contribute to wrong way driving. Figure 2.10 illustrates how the typical expectation of drivers to enter a freeway from the right hand side can result in wrong way entry at a left hand side exit ramp.

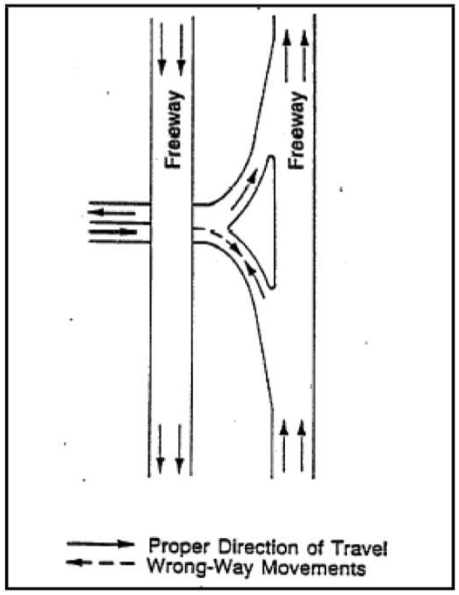


Figure 2.10 Wrong way movement at a left hand freeway exit ramp (Cooner et al., 2004)

2.3.2.2. Raised Median

Cross streets at interchanges with traversable medians may result in wrong way entries into the exit ramps. This situation can be avoided by installing non-traversable medians on cross streets, thus making it physically challenging for vehicles to make a wrong way maneuver. Figure 2.11 shows an example of a non-traversable median (Pour-Rouholamin and Zhou, 2015) with a wrong way maneuver shown in red and a safe maneuver shown in green.

Figure 2.11. Raised median implemented at intersection (Pour-Rouholamin and Zhou, 2015)

2.3.2.3. Channelization

Similar to the use of raised medians, channelization devices can be used to discourage wrong way turning movements. The use of longitudinal delineators for a left turn lane can direct traffic into the desirable turning path (see Figure 2.12). Another common channelization treatment is the use of islands. A height of at least 4 inches is recommended because lower islands may still allow vehicles to drive over it.

Figure 2.12. Channelization at an intersection (Pour-Rouholamin and Zhou, 2015).

2.3.2.4. Radius at Corners

The radius at the corner of intersecting roads can be used to prevent wrong way movements. At ramp terminals, the corner radius could discourage right turning movements in the wrong direction from the crossroad to the exit ramp (NTSB, 2012; Pour-Rouholamin and Zhou, 2015). Guidance suggests that circular larger radii may encourage wrong way movements; therefore, angular or tight radii make this movement difficult and have been found to be effective in states like Virginia (Pour-Rouholamin and Zhou, 2015; Vaswani, 1977). An example of a sharper turn to discourage wrong direction turn is shown in Figure 2.13.

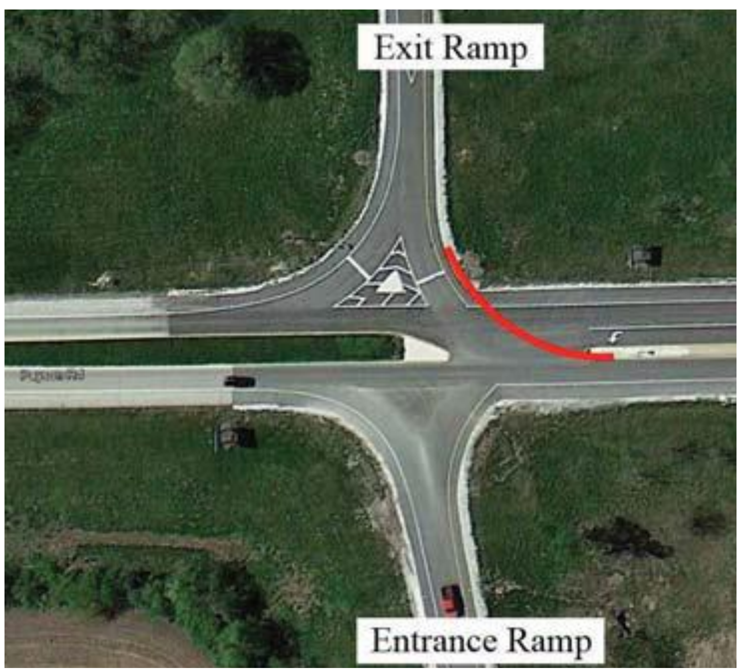


Figure 2.13. Radius treatment at ramp terminals (Pour-Rouholamin and Zhou, 2015)

2.3.2.5. Sight Distance

Providing adequate sight distance at intersections allows drivers to identify the traffic control and geometric features of roadway facilities. Improving lighting, removing obstructions limiting sight distance, and placing stop bars and signal heads appropriately are all helpful measures to discourage wrong way entry at intersections.

2.3.3 Intelligent Transportation Systems (ITS) Countermeasures

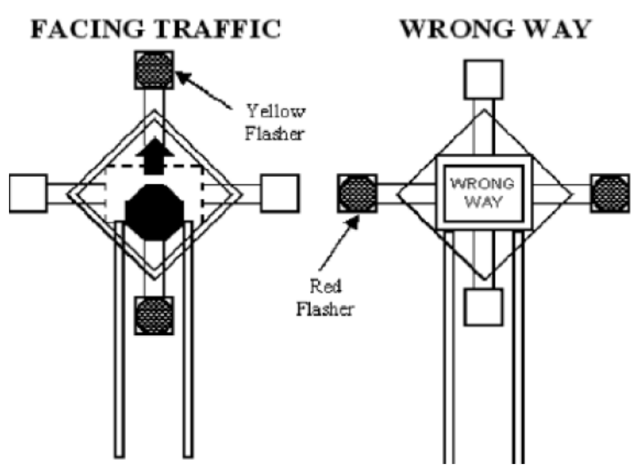
Many devices and technologies have been developed over the years to address wrong way crashes. Some ITS measures include in-vehicle alerts based on GPS, video-based detection and alerts, and in-pavement sensors and radar sensors to detect and alert drivers. Due to the high installation and maintenance costs of ITS devices, it may not be cost-effective to deploy ITS countermeasures on a system-wide basis. A more feasible approach would be to deploy them at locations with a history of wrong way driving crashes.

2.3.3.1. Wrong Way GPS Vehicle Alerts
Several automobile companies have invested in developing wrong way alert systems using GPS devices embedded in vehicles. Nissan, Toyota, and BMW companies have independently developed GPS-based alerts. Some of these technologies are already operational in countries like Japan and will be soon available in the United States (NTSB, 2012). The NTSB reported that wrong way alerts with GPS systems on vehicles are effective and reliable (NTSB, 2012).

2.3.3.2. Video-based Detection and Alerts
Video-based detection and alert systems rely on camera(s) deployed to monitor ramp vehicles. Image processing software is used in real-time to detect any vehicles going the wrong way. If a wrong way driver is detected, the alerts are sent to the local Traffic Management Center (TMC), police department, and Dynamic Message Signs. The wrong way driver is also alerted using flashing lights installed on signs adjacent to the ramp. Some deployments have complemented such signs with 'Wrong Way' LED signs.

Washington DOT tested a video detection and warning system at the I-90/161st Avenue Southeast interchange. When a wrong-way movement was detected, a message sign was activated, which flashed a "Wrong Way" message to the wrong-way drivers (Zhou et al., 2012). The video-based detection systems have some limitations with respect to their need for ambient lighting during different time of day and weather conditions.

2.3.3.3. In-pavement Sensors and Alerts
Washington DOT tested pavement embedded with electromagnetic sensors at I-5/Bow Hill Rd. to detect wrong way movements. A mounted dynamic sign with flashing lights was installed at the exit ramp to alert wrong way drivers. Figure 2.14 shows the image of the dynamic sign. The state of New Mexico also tested a wrong way alert system based on data from loop detectors and dynamic signs on both sides of the ramp (Zhou et al., 2012; Cooner et al., 2004).



(a) **(b)**

Figure 2.14. (a) Dynamic sign in Washington (Zhou et al., 2012; Moler, 2002) and (b) Directional traffic sign in New Mexico (Zhou et al., 2012; Cooner et al., 2004)

2.3.3.4. Radar and Warning Alerts

Radar detection of wrong way drivers has been tried in a few states including Florida and Texas. Unlike video-based detection, radar performance is not sensitive to the weather conditions or lighting.

Florida DOT installed a radar-based wrong way detection driving and warning systems on Pensacola Bridge. The system alerted drivers using signs and overhead flashing lights. For the wrong way driver, a combination of “Do Not Enter” and “Wrong Way” signs with flashing lights form the alerts. Overhead flashing lights are used to alert traffic traveling in the correct direction of wrong way vehicles. Figure 2.15 shows an image of the system with the overhead signs (Zhou et al., 2012; Cooner et al., 2004; Williams, 2006).

Figure 2.15. Wrong way system at Pensacola Bridge, FL (Zhou et al., 2012)

In Houston, Texas, a wrong way detection and alert system was deployed on the Harries County Tollway. The deployment consisted of 12 microwave radar detectors that detected wrong way drivers and alerted the TMC. The TMC personnel then manually verified the event using CCTV footage. After verification, dynamic message signs alerted correct way drivers of the approaching wrong way vehicle. The TMC also immediately notified the police (Zhou et al., 2012; Pour-Rouholamin and Zhou, 2015; NTTA, 2009).

Additional ITS deployments are currently being planned in Texas (Zeng et al., 2012), Arizona (Simpson and Karimvand, 2015), Florida (Sandt et al., 2015), and Germany (Oeser et al., 2015). However, the deployments have not yet been evaluated for their effectiveness.

2.3.4 Driver-related Countermeasures

Even though driver-related countermeasures to combat wrong way driving are not engineering countermeasures, a brief review of the main technologies is presented here to provide a better overall context of wrong way driving countermeasures. Alcohol impairment is a major contributing factor to wrong way crashes. Research using FARS data for 2004-2009 found that 9% of wrong way drivers had been convicted of DWI within the 3 years prior to the wrong way crash. Those results were 3 times higher than a control group of drivers (NTSB, 2012). NTSB has recommended the implementation of Alcohol Ignition Interlock devices for several years. An alcohol ignition interlock is a device connected to the vehicle ignition circuit. It prevents the engine from starting unless a breath sample is determined to be lower than the required limit. Alcohol ignition interlock devices have been developed for passenger vehicles (NTSB, 2012; Jurnecka, 2015; Blanco, 2015) and for buses and commercial trucks (NTSB, 2012; Podda, 2012).

3. HORIZONTAL CURVES

Horizontal curves are of interest because of road departure crashes that could lead to severe injuries or fatalities. Around 4 out of every 10 fatal crashes involve vehicles leaving the roadway, and there are more than twice as many lane departure crashes on rural roads than on urban roads (AASHTO, 2008). Some types of crashes involving lane departures are rollovers (42%) and collisions with trees (25%). In 2006, a total of 25,082 lane departure crashes were recorded which represented 58% of total fatalities during that year (AASHTO, 2008). Figure 3.1 shows the proportion of total fatalities that are caused by lane departure crashes in each state.

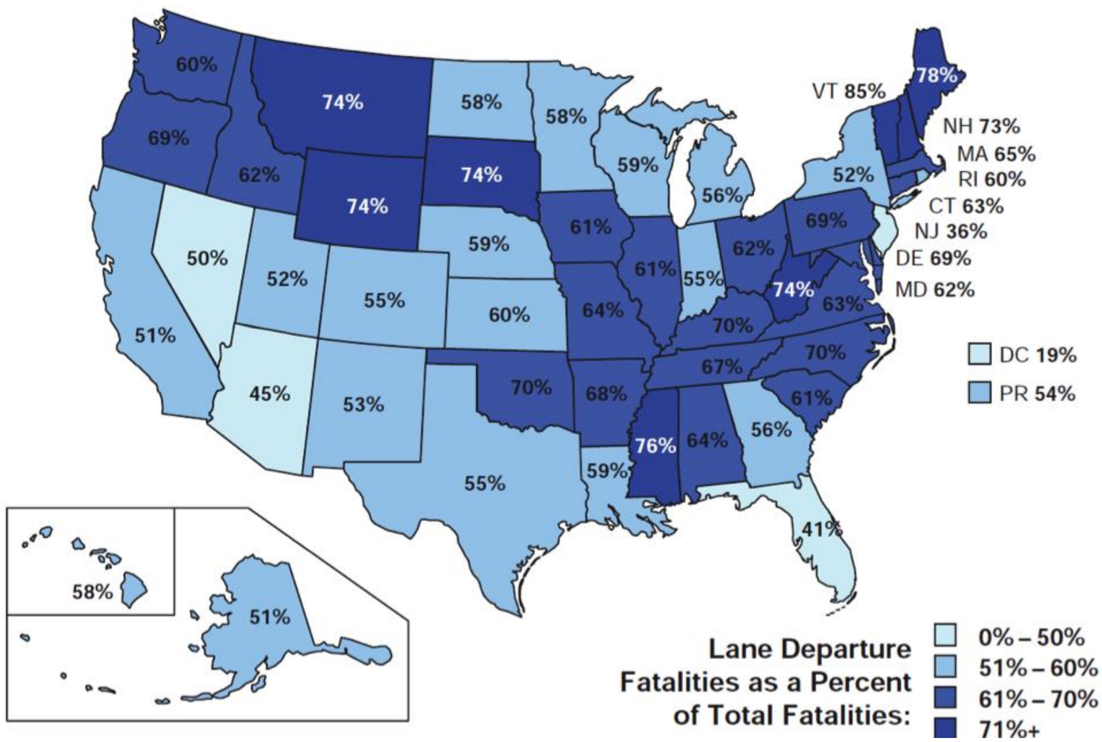


Figure 3.1. Lane departures fatalities during 2006 (AASHTO, 2008)

In Missouri, system wide treatments such as cable median barrier and edge line rumble strips have been deployed on the primary roadway system. As a result, lane departure fatalities fell by 37% between 2005 and 2011 (MoDOT, 2012). The following discussion examines other system wide treatments can be applied in the state to further lower lane departure fatalities, especially on horizontal curves.

3.1. Signing

3.1.1. MUTCD Guidance

The MUTCD provides specific guidance for warning signs on horizontal curves. A combination of alignment warning signs, pavement markings and delineation is recommended to provide guidance to drivers when driving through a horizontal curve (FHWA, 2012). Figure 3.2 shows standard signs used on horizontal curves.

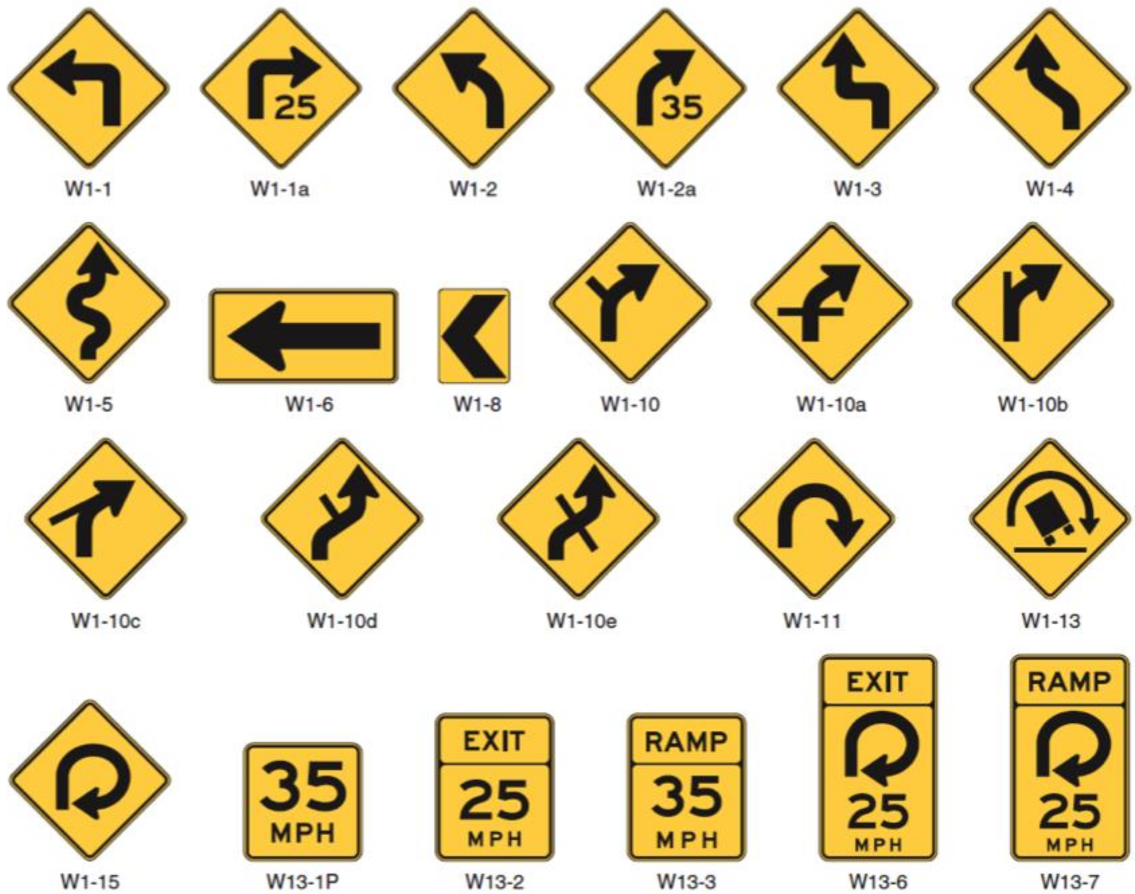


Figure 3.2. MUTCD horizontal curve warning signs (FHWA, 2012)

Selection of the applicable set of signs is based on AADT, functional classification of the road, and posted or statutory speed limit or 85th percentile speed. If traffic is less than 1,000 AADT, the horizontal curve signing configuration is based on engineering judgment (FHWA, 2012). Figure 3 provides an example of horizontal curve signing on a two-lane roadway. At both approaches, a W1-1L/R combined with a W13-1P (see Figure 3.3) are provided upstream of the curve to warn drivers of the presence of the curve and the recommended speed. The curve may have another W1-1aR sign, as shown for the right turn, which reinforces the presence of the curve and the recommended speed at the beginning of the curve. Chevron signs (W1-8L/R) are provided along the curve, and directional signs (W1-6L/R) may be included to reinforce the direction of travel.

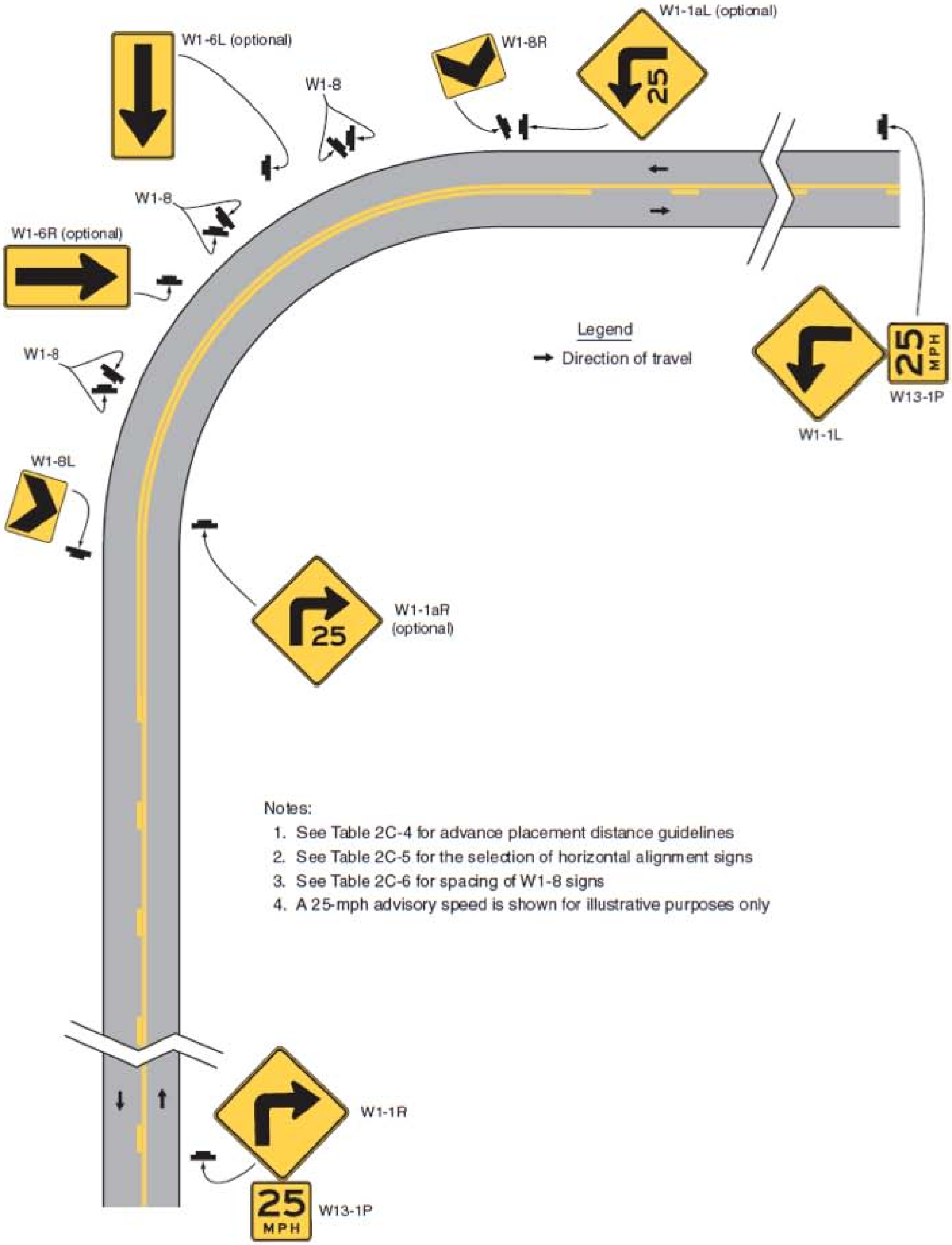


Figure 3.3. Example of MUTCD signing standards at horizontal curve (FHWA, 2012)

Another example is shown in Figure 3.4 for exit ramp horizontal curves. In Figure 3.4, warning signs are provided at the beginning of the speed-change lane taper and at the gore. The recommended speeds are based on the location of the facility. Chevrons signs are installed along the curve. Additional truck overturn warning signs with speed recommendation may be included.

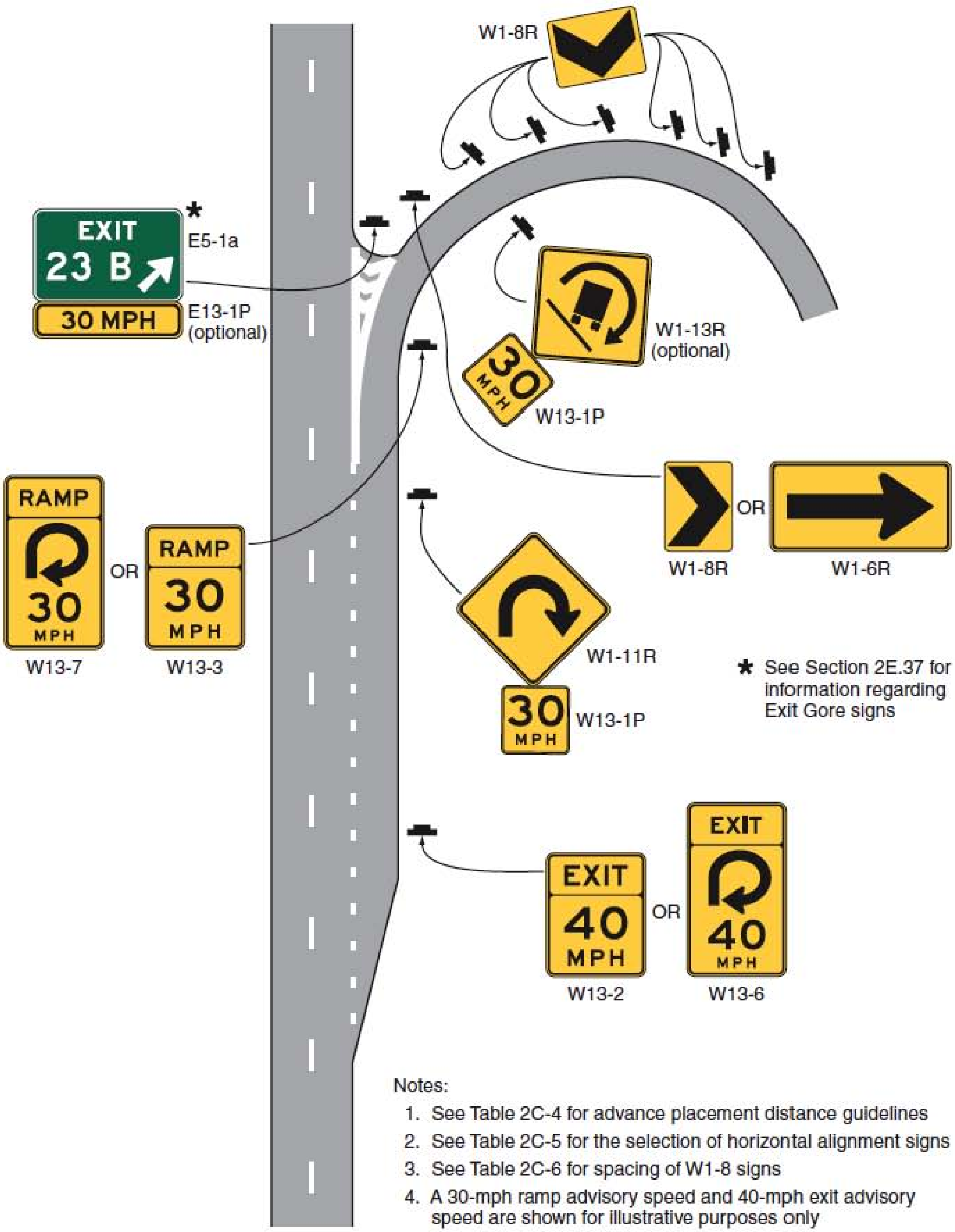


Figure 3.4. Example of MUTCD signing standards at exit ramp (FHWA, 2012)

Countermeasures targeting horizontal curve crashes may involve augmenting the minimum recommended MUTCD signs and devices at horizontal curves. Research studies experimenting with and evaluating the safety effectiveness of such countermeasures were examined.

3.1.2. Improved Curve Signing

In a FHWA pooled-fund study of 26 states (Missouri was not a participant), low-cost safety treatments for improving curve delineation was examined by Srinivasan et al. (2009). Treatments on two lane roads included the addition of new signs: chevrons, arrows, and advance warning. Also existing signs were made more retroreflective using fluorescent yellow sheeting. Data from deployments in Connecticut and Washington were used for the safety evaluation. Figure 3.5 provides an example of chevrons installed on a curve in Connecticut. An eighteen percent reduction in injury and fatal crashes and a twenty-five percent reduction in lane departure crashes during dark conditions were achieved by improving curve delineation.

Figure 3.5. Example of improved curve signing in Connecticut (Srinivasan et al., 2009)

A study performed in Italy found that the installation of warnings signs, chevron signs, and sequential flashing beacons along horizontal curves reduced total crashes by 47.6%, injury crashes by 38.2%, and nighttime crashes by 76.9% (Montella, 2009). In a Florida study, the total number of crashes was reduced by 30% due to flashing beacons deployed on curves (Gan et al., 2005). Figure 3.6 shows an image of a flashing beacon installed on both sides of a sharp curve. Flashing beacons are signals that operate in a continuous flashing mode to warn drivers of the curve and the posted lower advisory speed limit (FHWA, 2012).

Figure 3.6. Flashing beacons (Bowman, 2015)

Dynamic flashing chevrons (see Figure 3.7) were deployed on a few curves in Iowa, Missouri, Texas, Washington, and Wisconsin (Smadi et al., 2015). These LED illuminated chevrons are wirelessly synchronized and show drivers the direction of the curve. The treated sites witnessed a slight reduction in vehicle speeds–about 1 mph. Nine treatment sites experienced reductions in crashes ranging from 17% to 91%. Two sites experienced an increase of 7% and 11%. Two sites did not experience any crashes after the treatment.

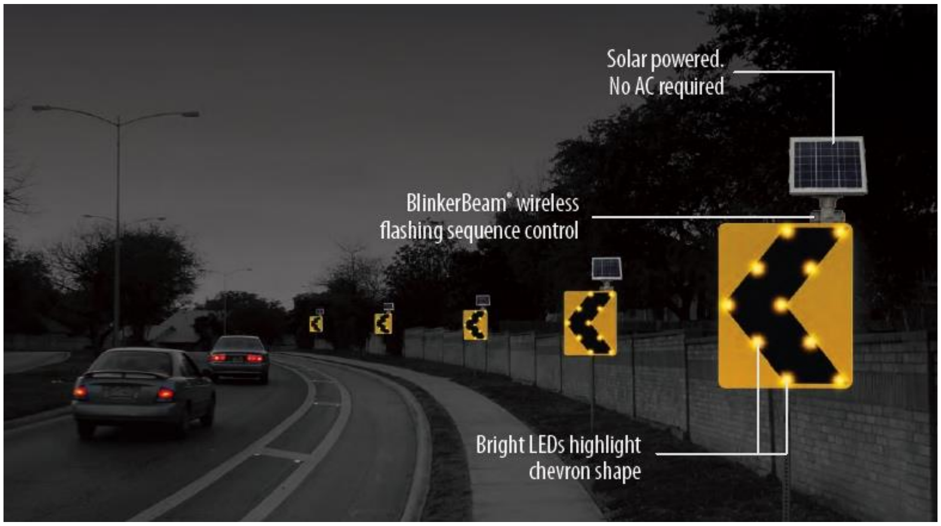


Figure 3.7. Dynamic curve guidance systems (TAPCO, 2015)

Oversized chevrons are also good candidates for improving curve safety. The typical size of chevrons (W1-8) specified in the MUTCD is 12 x 18 inches, and oversized chevrons are 18 x 24 inches. The larger signs provide greater sight distance to drivers. MUTCD recommends that oversized signing be used when engineering judgment indicates the need for larger signing because of vehicle speed, driver expectancy, traffic operations, or roadway conditions (FHWA, 2012).

Dynamic speed warning systems for horizontal curves were piloted in Iowa (see Figure 8). These systems detect the speed of an approaching vehicle, display it on a LED panel, and contain a 'Slow Down' LED sign as shown in Figure 3.8. Hallmark et al. (2015) found the dynamic speed warning systems to reduce total crashes by 5% to 7%. Also important is the finding that these systems reduced the proportion of drivers exceeding the posted speed limit (Hallmark et al., 2012).

Figure 3.8. Dynamic speed warning signs (Hallmark et al., 2012; Hallmark et al., 2015)

3.1.3. Vertical Delineation

Roadway delineation is used at locations where the alignment might be confusing or unexpected. Delineators are effective guidance devices at night and during adverse weather conditions. According to the MUTCD, retroreflective elements for delineators shall have a minimum dimension of 3 inches (FHWA, 2012). Figure 3.9 provides an example of delineator placement at a curve (FHWA, 2012). While the use of delineators has not been shown to reduce crashes on curves, their use in combination with edge lines and centerlines reduced 45% of all fatal and injury crashes (CMF Clearinghouse and Elvik et al., 2004).

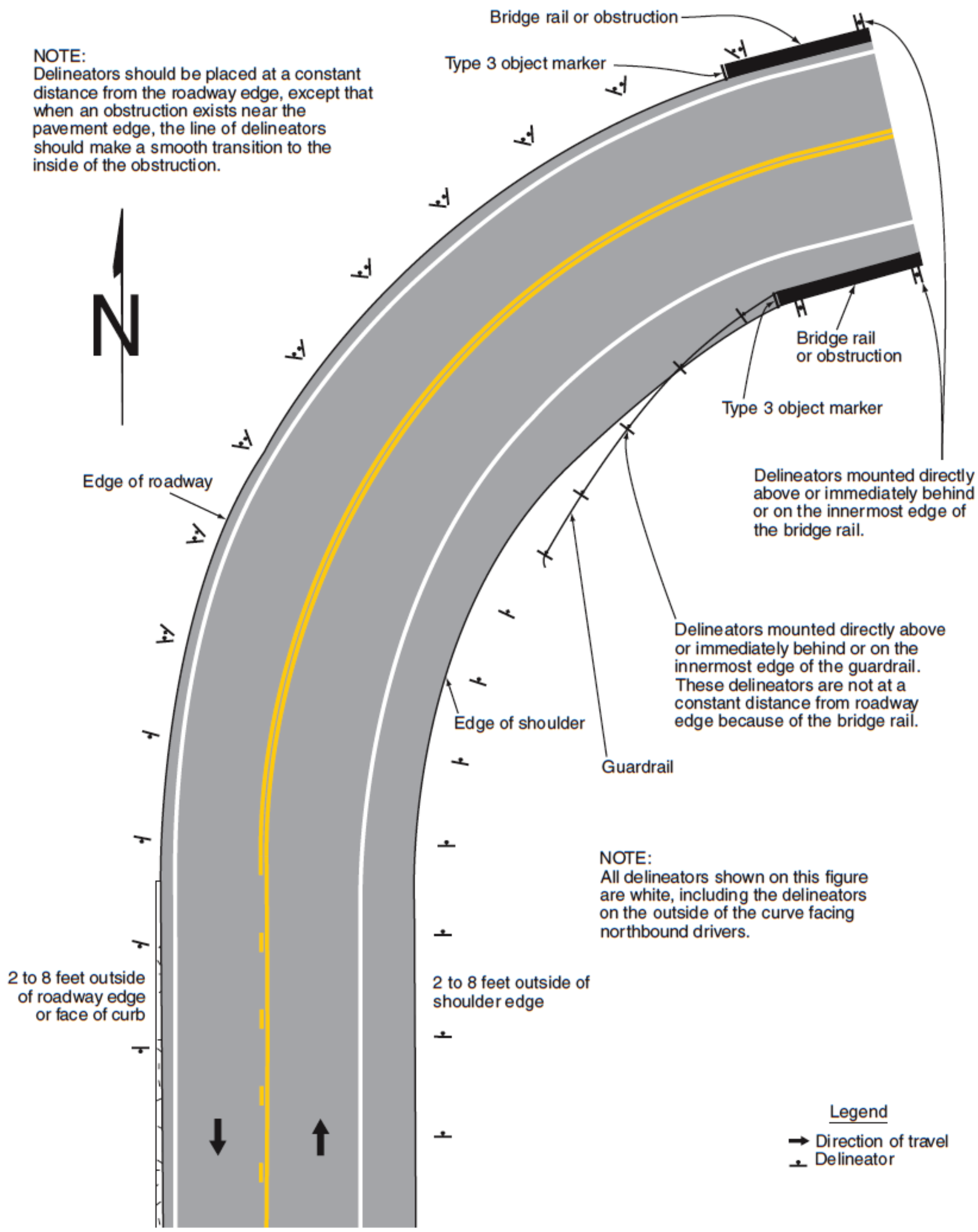


Figure 3.9. Example of curve delineator deployment (FHWA, 2012)

Finally, the addition of retroreflective devices to chevron vertical posts were found to slow down drivers around curves. An example treatment in Iowa is shown in Figure 3.10. While the vehicle speeds decreased, the crash numbers did not change (Hallmark et al., 2002; Re et al., 2010; Vest et al., 2005).

Figure 3.10. Chevron sings with retroreflective posts (Hallmark et al., 2002)

3.2. Pavement Markings and Treatments

3.2.1. Wide Edge Lines

The width of pavement line marking indicates the degree of emphasis. Edge line pavement markings delineate the right and left edges of roadways. Edge lines provide a visual reference to guide users during adverse weather conditions and reduced visibility conditions. Wider edge line markings may be used for greater emphasis. The MUTCD (FHWA, 2012) requires a width of four to six inches for normal edge lines and double that size (i.e., 8 to 12 inches) for a wide edge line. Widening of edge lines was found to: 1) slow down drivers earlier when entering a horizontal curve (McGee and Hanscome, 2006), 2) decrease crashes with fixed objects by 17% (Donnell et al., 2006), and 3) decrease nighttime crashes (Tsyganov et al., 2005).

3.2.2. Speed Reduction Markings

Speed reduction markings are a pavement marking treatment used to slow down drivers approaching a sharp horizontal curve. As shown in Figure 3.11, these transverse markings are placed along both edges of the lane with the spacing decreasing as drivers negotiate the curve (FHWA, 2009). The MUTCD (FHWA, 2009) states: *"If used, speed reduction markings shall be a series of white transverse lines on both sides of the lane that are perpendicular to the center line, edge line, or lane line. The longitudinal spacing between the markings shall be progressively reduced from the upstream to the downstream end of the marked portion of the lane."*

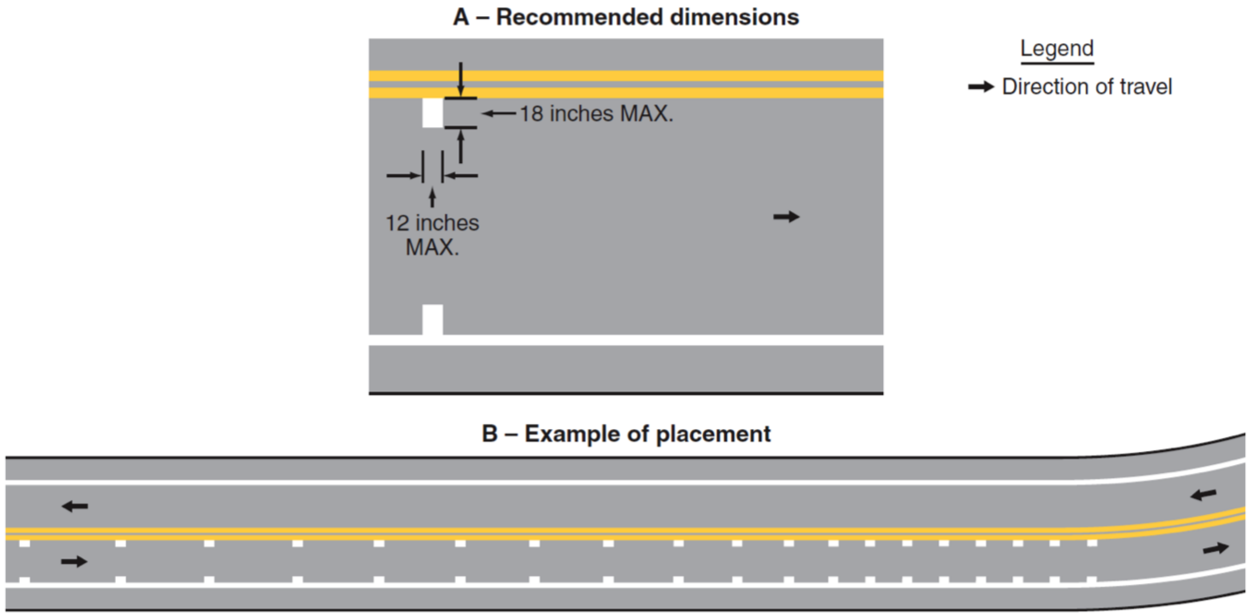


Figure 3.11. Application of speed reduction markings (FHWA, 2012)

A reduction in the 85th percentile speed of up to 5 mph was reported with the use of speed reduction markings (FHWA, 2012; Tsyganov et al., 2005, Hallmark et al., 2007). A variation of the MUTCD speed reduction marking, where the transverse markings extend most of the lane width (see Figure 3.12), was also found to reduce vehicle speeds on horizontal curves (Vest et al., 2005; Katz et al., 2006). One study reported a 57% reduction in speed-related crashes due to the deployment of speed reduction markings on roundabout approaches (Griffin and Reinhardt, 1996).

Figure 3.12. Variation of speed reduction markings

3.2.3. Words and Symbols

Some states have tried combination of the MUTCD pavement marking symbols and words on horizontal curves. Figure 3.13 shows an example of the implementation of the experimental pavement symbol–SLOW and curving arrow-in Pennsylvania. A speed reduction of up to 10% from the advanced symbol/word combinations was reported in several studies (McGee and Hanscome, 2006; Chrysler and Schrock, 2005; Retting and Farmer, 1998; Nambisan and Hallmark, 2011).

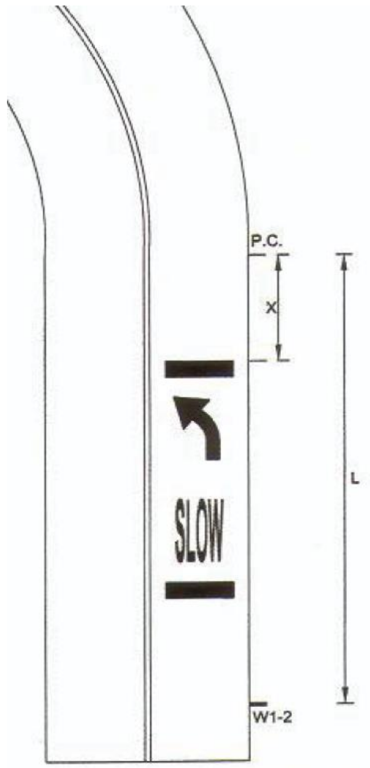


Figure 3.13. Example of a pavement marking warning symbol (McGee and Hanscome, 2006)

3.2.4. Raised Pavement Markers
Retroreflective raised pavement markers (RPM) are used to delineate the transition of the curve at night. They can be used along the centerline or edge line. The snow plowable version of RPM was recently studied for centerline deployment in rural areas by Bahar et al. (2004). For curves with radius greater than 1,640 feet, a change in nighttime crashes between 33% and -13% was found-negative value indicating an increase. For curves with radius smaller than 1,640 feet, nighttime crashes increased between -3% and -26%.

3.2.5. Rumble Strips and Stripes
Rumble strips and stripes are spaced transversal dents in the pavement that provide audible and vibration alerts when vehicle tires roll over them. They have successfully been implemented in several states to prevent lane departure. Torbic et al. (2009) reported that the safety effectiveness of centerline rumble strips on horizontal curves (a 47% reduction total target crashes) were similar to their effectiveness on tangent sections (a 49% reduction). A study in Minnesota evaluated crash rates before and after implementation of edge line rumble strips on curves and found a reduction of 15% in total crashes (Pitale et al., 2009).

3.2.6. High Friction Pavement Treatment
High friction pavement treatments work by increasing the pavement's friction, hence assisting vehicles to stay within the lane while negotiating a horizontal curve. Such treatments can be helpful during wet pavement conditions, when the friction between tires and pavement is smaller than under dry conditions. Treatments are usually composed of a combination of resins, polymers with a binder, and aggregate.

Studies of treatments on freeway ramp curves have shown that high friction pavement treatments reduced total crashes by 25%, fatal and injury crashes on wet pavement by 14%, and fatal crashes on sharp curves by 25% (Nambisan and Hallmark, 2011; Julian and Moler, 2008). In New York, high friction treatments were applied as part of a skid accident reduction program

(SKARP). The application resulted in a reduction of 24% in total crashes and 57% in crashes occurring in wet road conditions (Harkey et al., 2008).

4. INTERSECTIONS

Treatments at both signalized and stop-controlled intersections were examined. The following six signalized intersection treatments were reviewed: increasing clearance interval, changing left turn from permissive to permissive-protected, flashing yellow arrow, dynamic signal warning, red light cameras, and improving signal visibility. The stop-control intersection improvements included stop sign improvements and flashing beacons.

4.1. Signalized Intersections

4.1.1. Increasing the Clearance Interval

MUTCD states that the duration of yellow and red clearance intervals should be determined based on engineering practice. The yellow interval should be between 3 and 6 seconds, and anything longer than 6 seconds must only be considered for approaches with higher speeds. Red clearance intervals should not exceed six seconds unless clearing one lane, two-way facilities or wide intersections (FHWA, 2012).

NCHRP 17-35 (Srinivasan et al., 2011) studied the effect of increasing yellow and red clearance times on intersection safety. A summary of the results is shown in Table 4.1. When both yellow and red clearance intervals were increased, yellow by 0.8 seconds and red clearance by 1.0 seconds on average, there was a modest reduction in angle and overall crashes, and an increase in fatal and injury crashes and rear-end crashes. When only the yellow interval was increased, on average by 1 second, there was an increase in overall crashes and fatal and injury crashes, and a decrease in rear-end crashes. When only the red clearance interval was increased, on average by 1.1 seconds, all crash types and severities experienced reductions in crashes (Srinivasan et al., 2011). The authors note that the small sample sizes used in the study contributed to the lack of statistical significance of most findings.

Table 4.1. Safety effect of change interval increase (Srinivasan et al., 2011)

TREATMENT: Increase Signal Change Interval
METHODOLOGY: Before-After EB
REFERENCE: NCHRP Project 17-35 final report
STUDY SITES: • The sample included 2 sites from Howard County, Maryland, 6 sites from Montgomery County, Maryland, 16 sites from San Diego, California, and 7 sites from San Francisco, California. • In the before period, the average major road AADT was 17,417 (minimum major road AADT was 5,950 and maximum major road AADT was 31,600) and the average minor road AADT was 8,484 (minimum minor road AADT was 2,650 and the maximum minor road AADT was 20,225). • Modifications to the yellow and all red time were not equivalent for all sites. For sites where both the yellow and all red time were increased, the average increases in the yellow and all red times were 0.8 seconds and 1.0 seconds, respectively. For sites where only the yellow interval was increased, the average increase in the yellow interval was 1.0 seconds. For sites where only the all red interval was increased, the average increase in the all red time was 1.1 seconds. For sites where the total change interval was increased, but still less than the ITE recommended practice, the average increase was 0.9 seconds. For sites where the total change interval was increased and exceeded the ITE recommended practice, the average increase was 1.6 seconds. • The sample of sites used in this evaluation is limited. So these results should be used with due caution.

CRASH TYPE STUDIED AND ESTIMATED EFFECTS		
Treatment, Crash Type, and Severity	**No. of Treated Sites**	**CMF (S.E. of CMF)**
Increase Yellow and All Red (All)	11	0.991 (0.146)
Increase Yellow and All Red (Injury & Fatal)		1.020 (0.156)
Increase Yellow and All Red (Rear end)		1.117 (0.288)
Increase Yellow and All Red (Angle)		0.961 (0.217)
Increase Yellow Only (All)	5	1.141 (0.177)
Increase Yellow Only (Injury & Fatal)		1.073 (0.216)
Increase Yellow Only (Rear end)		0.934 (0.237)
Increase Yellow Only (Angle)		1.076 (0.297)
Increase All Red Only (All)	14	0.798 (0.074)[#]
Increase All Red Only (Injury & Fatal)		0.863 (0.114)
Increase All Red Only (Rear end)		0.804 (0.135)
Increase All Red Only (Angle)		0.966 (0.164)
Increase Change Interval (< ITE) (All)	12	0.728 (0.077)[#]
Increase Change Interval (< ITE) (Injury & Fatal)		0.662 (0.099)[#]
Increase Change Interval (< ITE) (Rear end)		0.848 (0.142)
Increase Change Interval (< ITE) (Angle)		0.840 (0.195)
Increase Change Interval (> ITE) (All)	15	0.922 (0.089)
Increase Change Interval (> ITE) (Injury & Fatal)		0.937 (0.114)
Increase Change Interval (> ITE) (Rear end)		0.643 (0.130)[#]
Increase Change Interval (> ITE) (Angle)		1.068 (0.156)

[#] Statistically significant at the 0.05 level.

4.1.2. Change Left Turn Phasing from Permissive to Protected-Permissive

The NCHRP 17-35 project studied the changes in crashes due to the conversion of left turn phasing from permissive to protective-permissive at a few locations in Toronto and North Carolina. Table 4.2 provides a summary of the main findings (Srinivasan et al., 2011). The treatment was successful at reducing the number of fatal and injury crashes. There were slight increases in crashes observed for rear-end and the total number of crashes.

Table 4.2. Left turn phase from permissive to protected-permissive (Srinivasan et al., 2011)

TREATMENT: Change Left-Turn Phase (from Permissive to Protected-Permissive)
METHODOLOGY: Before-After EB
REFERENCE: NCHRP 17-35 Final Report
STUDY SITES: • 59 intersections from Toronto and 12 from North Carolina. All of them were four leg intersections from urban areas. • In Toronto, in the before period, the average major road AADT was 35,267 (minimum was 14,489 and maximum was 74,990) and the average minor road AADT was 18,096 (minimum was 1,466 and maximum was 42,723). • In North Carolina, in the before period, the average major road AADT was 12,302 (minimum was 4,857 and maximum was 18,766) and the average minor road AADT was 5,124 (minimum was 1,715 and maximum was 9,300).
COMMENTS: • It is important to note that left-turn phasing was not constant throughout the day for most of the sites (especially in Toronto), and hence, the sites were categorized based on the predominant phasing system. • Among the 21 sites where more than 1 approach was treated, 17 of them had 2 approaches treated, 2 of them had 3 approaches treated, and 2 of them had 4 approaches treated.

CRASH TYPE STUDIED AND ESTIMATED EFFECTS

Number of Treated Approaches and Crash Type at Intersection Level	No. of Sites	CMF (S.E. of CMF)
Change from Permissive or Permissive/Protected		
All sites (all crashes)	71	1.031 (0.022)
1 treated approach (all crashes)	50	1.081 (0.027)$^{\#}$
>1 treated approach (all crashes)	21	0.958 (0.036)
All sites (injury and fatal crashes)	71	0.962 (0.035)
1 treated approach (injury and fatal crashes)	50	0.995 (0.043)
>1 treated approach (injury and fatal crashes)	21	0.914 (0.055)
All sites (left-turn opposing through crashes)	71	0.862 (0.050)$^{\#}$
1 treated approach (left-turn opposing through crashes)	50	0.925 (0.067)
>1 treated approach (left-turn opposing through crashes)	21	0.787 (0.072)$^{\#}$
All sites (rear-end crashes)	71	1.075 (0.036)$^{\#}$
1 treated approach (rear-end crashes)	50	1.094 (0.045)$^{\#}$
>1 treated approach (rear-end crashes)	21	1.050 (0.059)

• $^{\#}$ Statistically significant at the 0.05 level.

4.1.3. Installation of Flashing Yellow Arrow for Permissive Left Turns

A flashing yellow arrow is designed to advise drivers of a permissive left turn, alerting them to yield to the oncoming traffic. The NCHRP 17-35 project used data from 55 treated sites from Washington, Oregon, and North Carolina. Total crashes and left turn crashes at locations were reduced where the before condition had permissive or a combination of permissive and protective-permissive signal configuration (see Table 4.3). In the case of a before condition with protected only, the installation of the flashing yellow arrow was found to increase total crashes, including left turn crashes.

Table 4.3. Installation of flashing yellow arrow (Srinivasan et al., 2011)

Left-Turn Phasing Before (sites) (legs treated)	Crash Type	CMF (S.E.)
Permissive or combination of permissive and protected-permissive (at least 1 converted leg was permissive in the before period) (9 sites) (20 legs treated)	Total Intersection Crashes	0.753 (0.094) #
	Total Intersection Left-Turn Crashes	0.635 (0.126) #
Protected-Permissive (all converted legs had protected-permissive in the before period) (13 sites) (27 legs treated)	Total Intersection Crashes	0.922 (0.104)
	Total Intersection Left-Turn Crashes	0.806 (0.146)
Protected (all converted legs had protected in the before period) (29 sites) (56 legs treated)	Total Intersection Crashes	1.338 (0.097) #
	Total Intersection Left-Turn Crashes	2.242 (0.276) #

Note: # Statistically significant at the 0.05 level

4.1.4. Installation of Dynamic Signal Warning Flashers

Dynamic signal warning flashers, that warn drivers of an approaching traffic signal turning red, are currently used in some states to enhance intersection safety. An example of the treatment used in Oregon is shown in Figure 4.1. The NCHRP 17-35 evaluated dynamic signal warning flashers implemented at sites in Nevada, Virginia, and North Carolina. The safety effectiveness results are shown in Table 4.4. A reduction in crashes was observed for all categories: total, rear-end, angle, injury and fatal, and heavy vehicle crashes. Another study using Nebraska data (Appiah et al., 2011), also reported reductions in crashes from this treatment.

Figure 4.1 Dynamic signal warning flasher (Oregon)

Table 4.4. Installation of dynamic signal warning flashers (Srinivasan et al., 2011)

	Total Crashes	Rear-end	Angle	Injury & Fatal	Heavy Vehicle
CMF	0.814#	0.792#	0.745#	0.820#	0.956
Standard Error	0.062	0.079	0.086	0.083	0.177

Note: # Statistically significant at the 0.05 level (based on the ideal standard errors reported in this table)

4.1.5. Installation of Red Light Cameras

Red light cameras (RLC) are a treatment aimed at preventing drivers from running red lights, thereby preventing a severe angle crash. A comprehensive study of RLCs was conducted by Council et al. (2005), who analyzed data from 132 treatment sites and found that RLCs were successful at decreasing angle crashes. Rear-end crashes, however, increased after RLC installation. The study results are presented in Table 4.5.

Table 4.5. Aggregated red light camera safety effectiveness (Council et al., 2005)

	Right-angle		Rear end	
	Total crashes	(Definite) injury	Total crashes	(Definite) injury
EB estimate of crashes expected in the after-period without RLC	1,542	351	2,521	131
Count of crashes observed in the After-period	1,163	296	2,896	163
Estimate of percentage change (standard error)	- 24.6 (2.9)	- 15.7 (5.9)	14.9 (3.0)	24.0 (11.6)
Estimate of the change in crash frequency	- 379	- 55	375	32

Note: A negative sign indicates a decrease in crashes.

4.1.6. Improved Signal Visibility

Treatments that improve signal visibility include increasing signal lens size, adding backplates, adding reflective tape to existing backboards, and using an alternative signal configuration. Larger signal heads can be used to increase visibility and light output to provide awareness to drivers at greater distances (Sayed et al., 2007; Janoff, 1994). The MUTCD contains standards regarding the location of signals. Table 4.6 from MUTCD shows the minimum sight distance necessary for a signal for a given 85th percentile speed. If the minimum sight distance is not met, a sign should be installed to warn drivers of the traffic signal (FHWA, 2012).

Table 4.6. Sight distance for signal visibility (FHWA, 2012)

85th-Percentile Speed	Minimum Sight Distance
20 mph	175 feet
25 mph	215 feet
30 mph	270 feet
35 mph	325 feet
40 mph	390 feet
45 mph	460 feet
50 mph	540 feet
55 mph	625 feet
60 mph	715 feet

A study concerning improved signal visibility considered 171 intersections (8 municipalities) in Canada. The study improved or increased signal lens size and added reflective tape to existing or new backboards. The results of the study showed a 8.5% reduction in property damage only crashes, 5.9% reduction in daytime crashes, 6.6% reduction in nighttime crashes, and 7.3% reduction in overall crashes (Sayed et al., 2007).

Signal heads with backplates and retroreflective edges have also been encouraged by the FHWA as they improve signal visibility and conspicuity for older and color blind drivers (see Figure 4.2). The addition of the reflective edge is even more advantageous during power outages when the signals are not operational (FHWA, 2014a). The MUTCD recommends augmenting backplates with yellow retroreflective edge border with a one to three inch width, as shown in Figure 3. Sayed et al. (2005) reported a 15% reduction in crashes from the backplate treatments, and a FHWA (2010b) study reported even higher reductions of 28.6% in total crashes, 36.7% in injury crashes, and 49.6% in nighttime crashes.

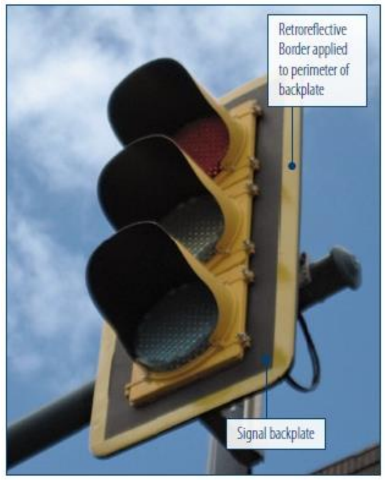


Figure 4.2. Signal head with backplate and retroreflective edges (FHWA, 2014a)

4.2. Stop-Controlled Intersections

4.2.1. Improvement of STOP Signs

STOP signs can be enhanced for better visibility by increasing their size and retroreflectivity, and by using LED lights. While there are no formal studies quantifying the benefits of enhancing the size of the STOP signs, larger signs have been used in many states to increase their visibility (Amparano and Morena, 2006). Persaud et al. (2007) conducted a safety evaluation of increasing retroreflectivity of STOP signs. The dataset consisted of 231 sites in Connecticut and 108 sites in South Carolina. The results of the study showed a statistically significant reduction in rear-end crashes in South Carolina. Three-leg and low-volume configurations experienced reductions in crashes. Also, a slight reduction in nighttime crashes was recorded in both states. The use of flashing LED lights on STOP signs, as shown in Figure 4.3, have been found to reduce the failure to stop (Timothy et al., 2003). Also, a study performed in Minnesota (Davis et al., 2014) that included 15 intersections reported an estimated reduction of crashes of 41.5%. No significant changes in speed, deceleration, and compliance were observed in the Minnesota study.

Figure 4.3. Stop sign with LED lights (Arnold and Lantz, 2007)

4.2.2. Flashing Beacons

The use of flashing beacons at stop-controlled intersections can bring heightened driver awareness to the presence of the intersection. Srinivasan et al. (2008) conducted a safety evaluation using three types of flashing beacons: overhead signals, signals on top of stop signs, and actuated flashers with the sign "Vehicles Entering When Flashing". Flashing beacons were deployed at 64 sites in North Carolina and 42 sites in South Carolina. They reported reductions of 5.1% in total crashes, 13.3% in angle crashes, and 10.2% in fatal and injury crashes. Additionally, flashing beacons were found to be more effective in rural areas and at four-way stop-controlled intersections. A more recent study evaluated 74 stop-controlled intersections in North Carolina (Simpson and Troy, 2013). The study focused on "Vehicle Entering When Flashing" signs. The results of the study showed that the signs were most effective at two lane stop-controlled intersections with a reduction of 25% of total crashes.

When available in the literature, cost estimates of safety treatments were noted. Quotes from equipment vendors were also sought to supplement the cost information. These estimates are included in Appendix A.

5. DESIGN GUIDANCE FOR J-TURNS

5.1. Crash Analysis

J-turn crash reports were reviewed to identify patterns in crashes. Data were collected for after the J-turns were in operation. The crash information was then used to develop crash diagrams illustrating different crash types. This section discusses sampling, site characteristics, crash data collection, and crash type analysis.

The master list of J-turns in Missouri consisted of 18 facilities that were in operation at the time of this research. The criteria used for selecting sites for detailed collision diagram analysis consisted of crash data availability, pre-J-turn intersection configuration, lack of influence from other facilities, and no significant geometric or other changes during the post-J-turn analysis period. Twelve of the eighteen facilities satisfied the site selection criteria. These twelve facilities are listed in Table 5.1.

Table 5.1. J-turn Facilities Selected

J-turn	City	Location	Open	Distance (ft.)	
				U-turn 1	U-turn 2
1	Imperial	RT M and Old Lemay Ferry Connector	Sep-07	800	1,900
2	Byrnes Mill	MO 30 and Upper Byrnes Mills Rd	Dec-12	1,500	1,700
3	Jefferson City	US 54 and Honey Creek Rd	Nov-11	1,900	1,900
4	Jefferson City	US 54 and Route E	Oct-11	1,700	N/A
5	Columbia	US 63 and Route AB	Nov-12	2,300	3,000
6	Columbia	US 63 and Bonne Femme Church Rd	Nov-12	900	1,400
7	Osceola	MO 13 and Old MO 13/364 E	Jul-09	1,100	980
8	Ridgedale	US 65 and Rochester Rd	Dec-12	730	990
9	Sheridan	US 65 and MO 215/ RT O	Nov-09	630	630
10	Jackson	US 65 and MO 38	Nov-09	630	630
11	Jackson	US 65 and Ash St/ Red Top Rd	Nov-09	630	630
12	Sheridan	US 65 and RT AA	Nov-09	650	1,300

Additional site characteristics, including urban/rural classification, and major and minor road AADTs, are presented in Table 5.2. Satellite images and distances between the minor road and the U-turn are also shown in this section.

Table 5.2. Designation Area and AADTs

J-turn	Location	Area[1]	AADT Major Road	AADT Minor Road
1	RT M and Old Lemay Ferry Connector	Urban	9320[2]	358
2	MO 30 and Upper Byrnes Mills Rd	Urban	23091	2226
3	US 54 and Honey Creek Rd	Rural	18213	435
4	US 54 and Route E	Rural	15097	1017
5	US 63 and Route AB	Rural	26956	1020
6	US 63 and Bonne Femme Church Rd	Urban	26388	1504
7	MO 13 and Old MO 13/364 E	Rural	11109	467
8	US 65 and Rochester Rd	Rural	11584	486
9	US 65 and MO 215/ RT O	Rural	7573	982
10	US 65 and MO 38	Rural	6975	822
11	US 65 and Ash St/ Red Top Rd	Rural	6631	524
12	US 65 and RT AA	Rural	9407	932

Notes: [1]Rural is less than 5000 population, else urban.; [2]AADT for year 2013.

1. RT M and Old Lemay Ferry Connector. Figure 5.1 shows the aerial image of the facility. This facility is a three-leg intersection with two U-turns. The U-turn to the east is at 1,900 ft. and to the west is at 800 ft. from the minor road. Left turns from the major road are not allowed at the intersection.

Figure 5.1. RT M and Old Lemay Ferry Connector Aerial Image

2. MO 30 and Upper Byrnes Mills Rd. Figure 5.2 shows the aerial image of the facility. This facility is a four-leg intersection with two U-turns. The U-turn to the east is at 1,500 ft. and to the west is at 1,700 ft. from the minor road. There is a median opening to allow left turns from the major road to turn at the intersection.

Figure 5.2. MO 30 and Upper Byrnes Mills Rd Aerial Image

3. US 54 and Honey Creek Rd. Figure 5.3 shows the aerial image. This facility is a four-leg intersection with two U-turns. The U-turns are both at a distance of 1,900 ft. from the minor road. There is a median opening to allow left turns from the major road to turn at the intersection.

Figure 5.3. US 54 and Honey Creek Rd Aerial Image

4. US 54 and Route E. Figure 5.4 shows the aerial image of the facility. This facility is a four-leg intersection with only one U-turn. The U-turn east of the minor road is at a distance of 1,700 ft. There is a median opening to allow left turns from the major road to turn at the intersection.

Figure 5.4. US 54 and Route E Aerial Image

5. US 63 and Route AB. Figure 5.5 shows the aerial image of the facility. This facility is a four-leg intersection with two U-turns. The U-turns to the right (north) is at a distance of 3,000 ft. and to the left (south) at 2,300 ft. from the minor road. Left turns from the major road are not allowed at the intersection.

Figure 5.5. US 63 and Route AB Aerial Image

6. US 63 and Bonne Femme Church Rd. Figure 5.6 shows the aerial image of the facility. This facility has two four-leg intersections between the U-turns. The U-turn to the right (north) is at a distance of 1,400 ft. and to the left (south) at 900 ft. to the closest minor road access. Left turns from the major road are not allowed at the intersection.

Figure 5.6. US 63 and Bonne Femme Church Rd Aerial Image

7. MO 13 and Old MO 13/364 E. Figure 5.7 shows the aerial image of the facility. This facility is a four-leg intersection with two U-turns. The U-turn to the right (north) is at a distance of 980 ft. and to the left (south) at 1,100 ft. from the minor road. There is a median opening to allow left turns from the major road to turn at the intersection. The U-turns have additional islands to facilitate turning movements by larger vehicles.

Figure 5.7. MO 13 and Old MO 13/364 E Aerial Image

8. US 65 and Rochester Rd. Figure 5.8 shows the aerial image of the facility. This facility is a four-leg intersection with two U-turns. The U-turn to the right (north) is at a distance of 990 ft. and to the left (south) at 730 ft. from the minor road. There is a median opening to allow left turns from the major road to turn at the intersection. The U-turns have additional islands to facilitate turning movements by larger vehicles.

Figure 5.8. US 65 and Rochester Rd Aerial Image

9. US 65 and MO 215/ RT O. Figure 5.9 shows the aerial image of the facility. This facility is a four-leg intersection with two U-turns. The U-turns are at a distance of 630 ft. from the minor road. Left turns from the major road are not allowed at the intersection. There are additional islands to facilitate turning movements by larger vehicles.

Figure 5.9. US 65 and MO 215/ RT O

10. US 65 and MO 38. Figure 5.10 shows the aerial image of the facility. The facility is a four-leg intersection with two U-turns. The U-turns are at a distance of 630 ft. from the minor road. Left turns from the major road are not allowed at the intersection. There are additional islands to facilitate turning movements by larger vehicles.

Figure 5.10. US 65 and MO 38 Aerial Image

11. US 65 and Ash St/ Red Top Rd. Figure 5.11 shows the aerial image of the facility. This facility is a four-leg intersection with two U-turns. The U-turns are at a distance of 630 ft. from the minor road. Left turns from the major road are not allowed at the intersection. There are additional islands to facilitate turning movements by larger vehicles.

Figure 5.11. US 65 and Ash St/ Red Top Rd Aerial Image

12. US 65 and RT AA. Figure 5.12 shows the aerial image of the facility. This facility is a four-leg intersection with two U-turns. The U-turn to the right (north) is at 1,300 ft. and to the left (south) at 650 ft. from the minor road. Left turns from the major road are not allowed at the intersection. The U-turns have islands to facilitate turning movements by larger vehicles.

Figure 5.12. US 65 and RT AA Aerial Image

5.1.1. Crash Data Collection

Crash data was collected for the entire footprint of the J-turn (U-turn to U-turn) plus additional areas of influence. The influence area upstream of the U-turn captures the area where mainline traffic is influenced by vehicles coming out of the U-turn. The influence areas consisted of 1,000 ft. beyond the U-turn in each direction for the major road, and 250 ft. of the minor road. Crashes were queried using the accident browser application of MoDOT Transportation Management System. The periods of analysis for each facility were from the date the facilities opened to traffic with the new geometric design until the end of 2014. A total of 183 crashes occurred at all facilities within the extended J-turn footprint. All 183 crash reports were manually reviewed and landed on a generic J-turn design layout in AutoCAD. Figure 5.13. shows an example of the crash landing for the J-turn at RT M and Old Lemay Ferry Connector.

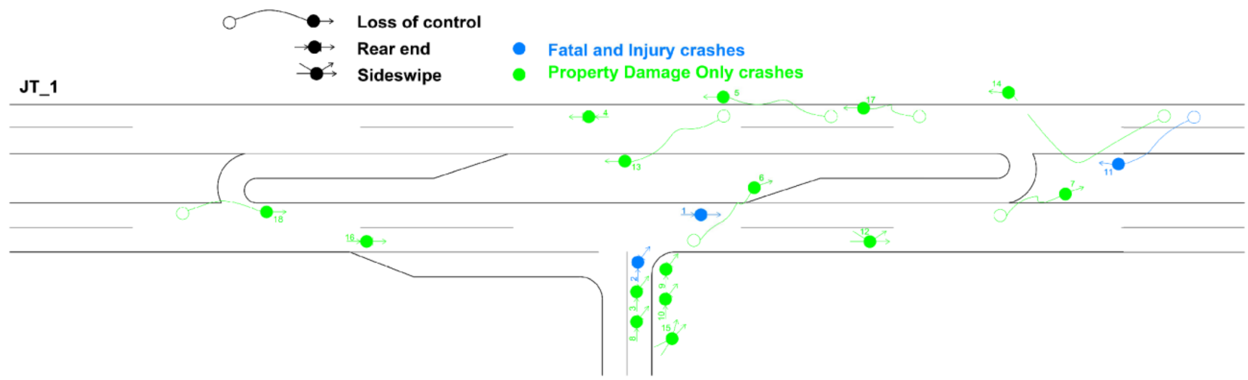


Figure 5.13. Crash Landing at RT M and Old Lemay Ferry Connector

The landed crashes were further filtered based on whether they were related to the J-turn or not. For example, crashes occurring during inclement weather, impaired driving, and other non J-turn related circumstances were not included in further analysis. This was done to eliminate any non J-turn related factors that may have contributed to the crashes. Thus, the remaining crashes occurred due to the geometrics and/or operations of the J-turn design.

5.1.2. Collision Diagram Analysis

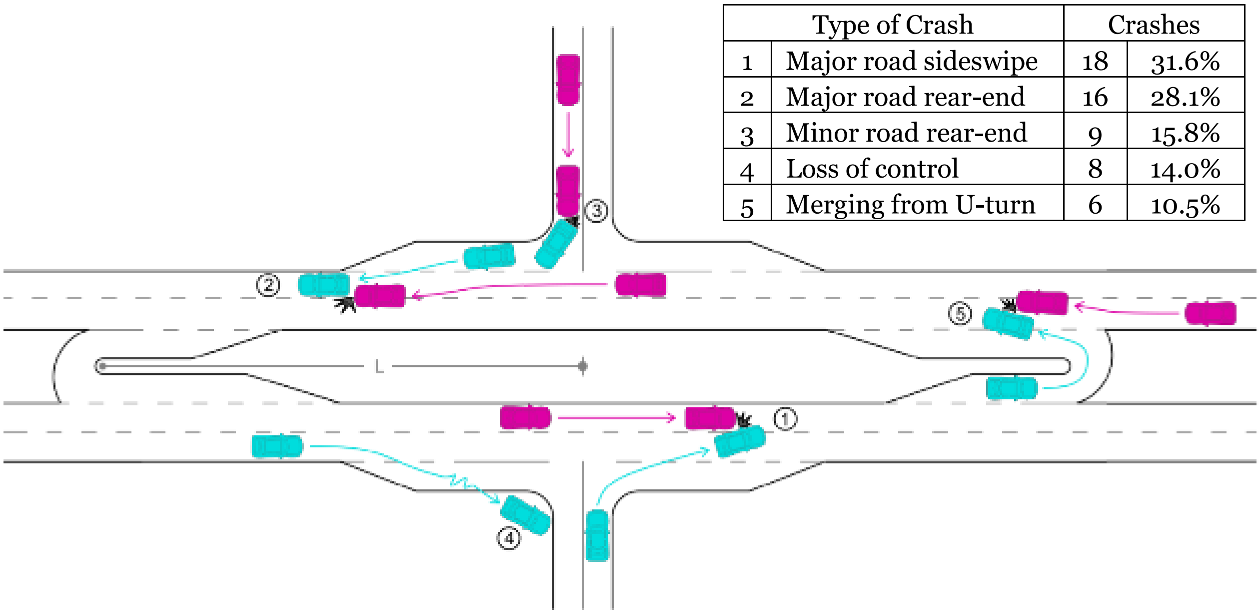
The collision diagram analysis helped to identify crashes according to the location and geometry of the J-turn. A total of 57 crashes were attributed to the J-turn samples. These crashes were separated into five types: 1) major road sideswipe, 2) major road rear-end, 3) minor road rear-end, 4) loss of control, and 5) merging from U-turn. Figure 5.14. shows the results from the collision diagram analysis, including the percentage of each crash type. The most frequent crashes at a J-turn were sideswipe (31.6%) and rear-end (28.1%) on the major road. Most of these crashes occurred while vehicles were merging with traffic or changing lanes to enter the U-turn. High speed differential and driver inattention were common circumstances in most crashes that occurred at the J-turn facilities.

The rear-end crashes on minor road occurred when drivers were unable to stop in time and collided with the vehicle ahead that suddenly stopped or slowed down to look for a gap in the through traffic on the major road. Most of the loss of control cases were due to driver intention, improper lane use, or high speeds and occurred on deceleration lanes. For the top two crash types, sideswipes and rear-end on the major road, crash rates were computed as a function of traffic exposure and segment length as follows.

$$Crashes\ per\ Million\ Vehicle\ Miles\ Traveled\ (MVMT) = \frac{A \times 1{,}000{,}000}{L \times AADT \times 365} \quad (5.1)$$

Where,

A - average number of crashes per year;
L - segment length (miles);
$AADT$ - total entering vehicles per year.



	Type of Crash	Crashes	
1	Major road sideswipe	18	31.6%
2	Major road rear-end	16	28.1%
3	Minor road rear-end	9	15.8%
4	Loss of control	8	14.0%
5	Merging from U-turn	6	10.5%

Figure 5.14. Results of Collision Diagram Analysis

Figure 5.15. presents the crash rates categorized by the distance between minor road and U-turn. Crash rates decreased with the increase in the distance to the U-turn, for both sideswipe and rear-end. The longer distance allows merging vehicles to reach major road operating speeds, thus making it safer to follow other vehicles in the lane and to make lane changes. J-turn sites with a spacing of 1500 feet or greater experienced the lowest crash rates.

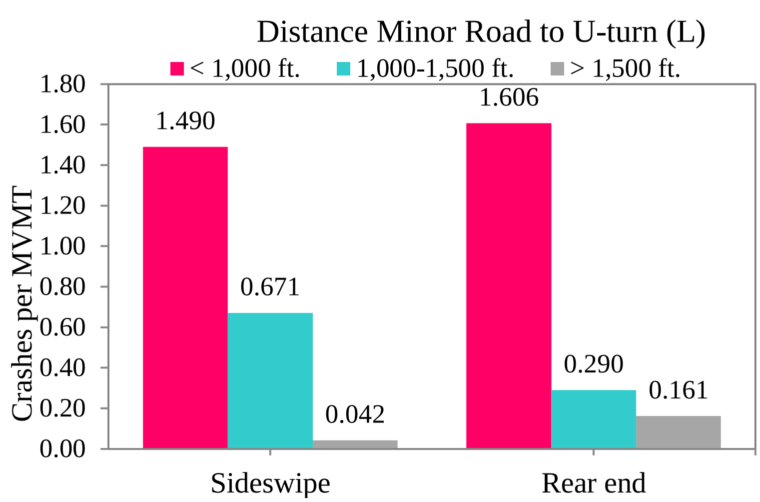


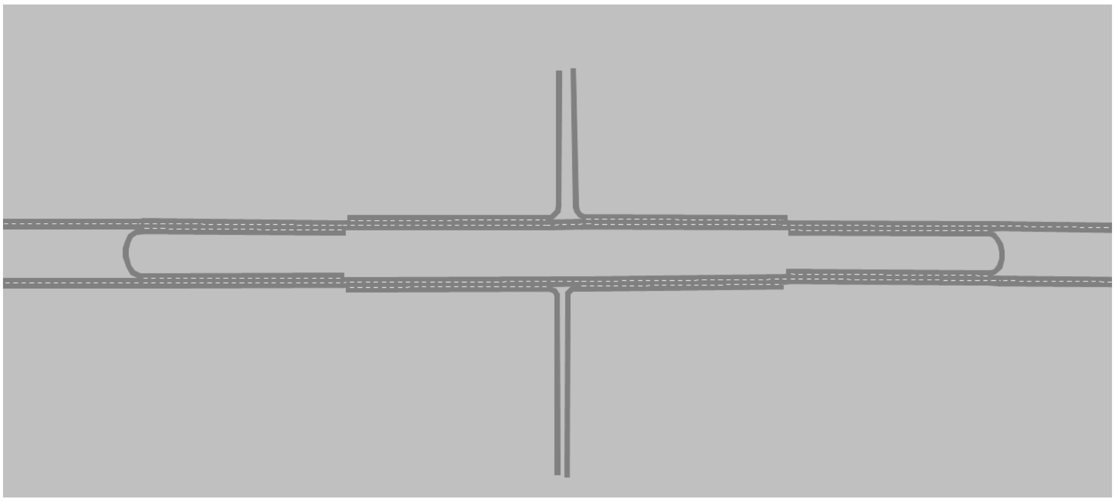
Figure 5.15. Major Road Crashes Sideswipe and Rear-End Crash Rates

5.2. Simulation Analysis

5.2.1. Simulation Model Development

Micro-simulation was the tool used to analyze the effect of two different J-turn design considerations: presence or absence of acceleration lanes and the distance between the minor road and the U-turn. The simulation model used in this research is derived from the field data collected in a previous MoDOT research project from 2013 (Edara et al., 2013). The previous J-turn field site was located near Deer Park road on Highway 63, south of Columbia, Missouri. This section of Highway 63 is a rural four-lane highway with a speed limit of 70 mph. This segment consisted mainly of tangents with no sharp horizontal curves, or steep vertical grades. The satellite image and the corresponding VISSIM simulation model layout are shown in Figure 5.16.

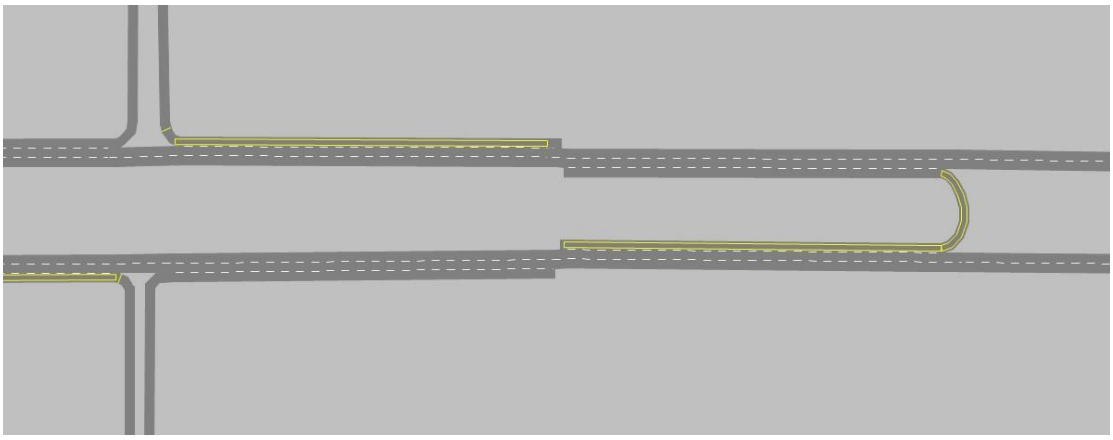
(a) Highway 63 at Deer Park Road (Google maps, 2015)



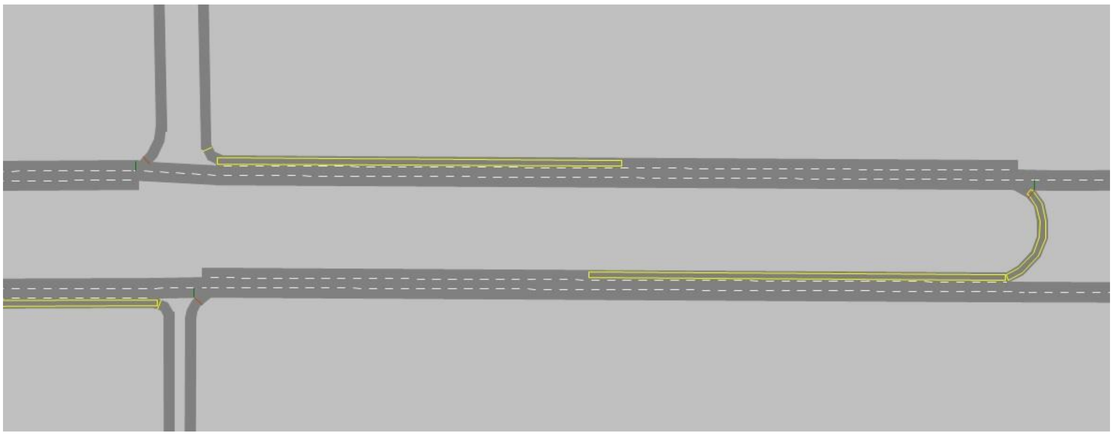
(b) VISSIM Simulation Model Layout

Figure 5.16. Satellite image and simulation layout of the J-turn

For the distance between the minor road and the U-turn, three distances were analyzed–1000 feet, 2000 feet, and 3000 feet. In terms of the presence or absence of acceleration lanes, two different layouts were analyzed as shown in Figure 5.17. The first layout (top) includes an acceleration lane extending from the minor road to half the distance to the U-turn and deceleration lane for the U-turn starting at the end of the acceleration lane and extending to the U-turn. In the other direction, an acceleration lane is provided for vehicles merging from the U-turn lane into major road and a deceleration lane to exit to the minor road. The second layout (bottom) does not contain an acceleration lane for minor road traffic or for U-turn traffic. The deceleration lane extends the entire length between the U-turn and the minor road. These two layouts were recommended by the project's technical advisory panel comprised of MoDOT safety engineers.



(a) Layout 1: acceleration lane present



(b) Layout 2: accelration lane not present

Figure 5.17. J-turn layouts with and without acceleration lane

Several parameters in VISSIM were optimized in order to accurately simulate vehicles at a J-turn. These parameters included: reduced speed areas (length and magnitude), desired speed decisions, and lane change distance upstream of a connector. For example, Figure 5.18 shows the lane change distance parameter window in VISSIM. This parameter specifies the upstream distance from a connector where vehicles start to look for lane changing gaps to stay on their desired path. This parameter value was based on trial and error through manual observation of the simulations. The value was different for the two layouts.

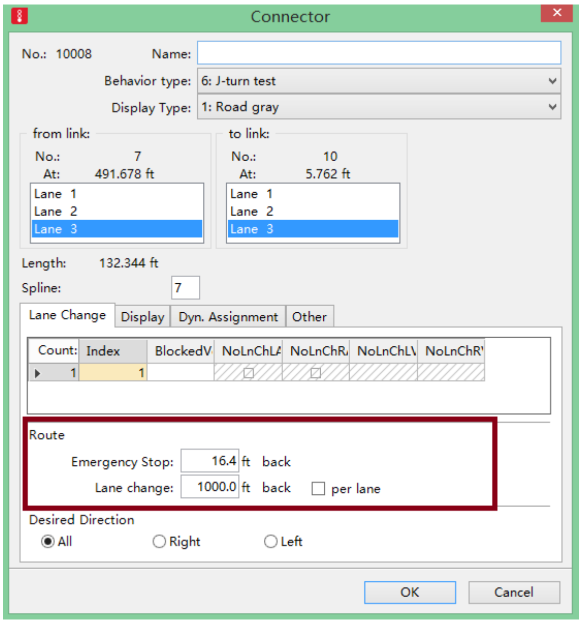


Figure 5.18. Connector tab from VISSIM

The calibration procedure in this study used disaggregated data of individual vehicle speeds measured in the field in a previous project (Edara et al., 2013). Thus, the calibration procedure was more robust than the state of practice that relies on aggregated sensor speeds on a roadway. A map of the field data collection equipment placement used in Edara et al. (2013) is shown in Figure 5.19. Several cameras and radar guns were used to extract traffic volumes and vehicle speeds (see Figure 5.20). The AM peak period data was collected in the southbound direction and PM peak period was collected in the northbound direction.

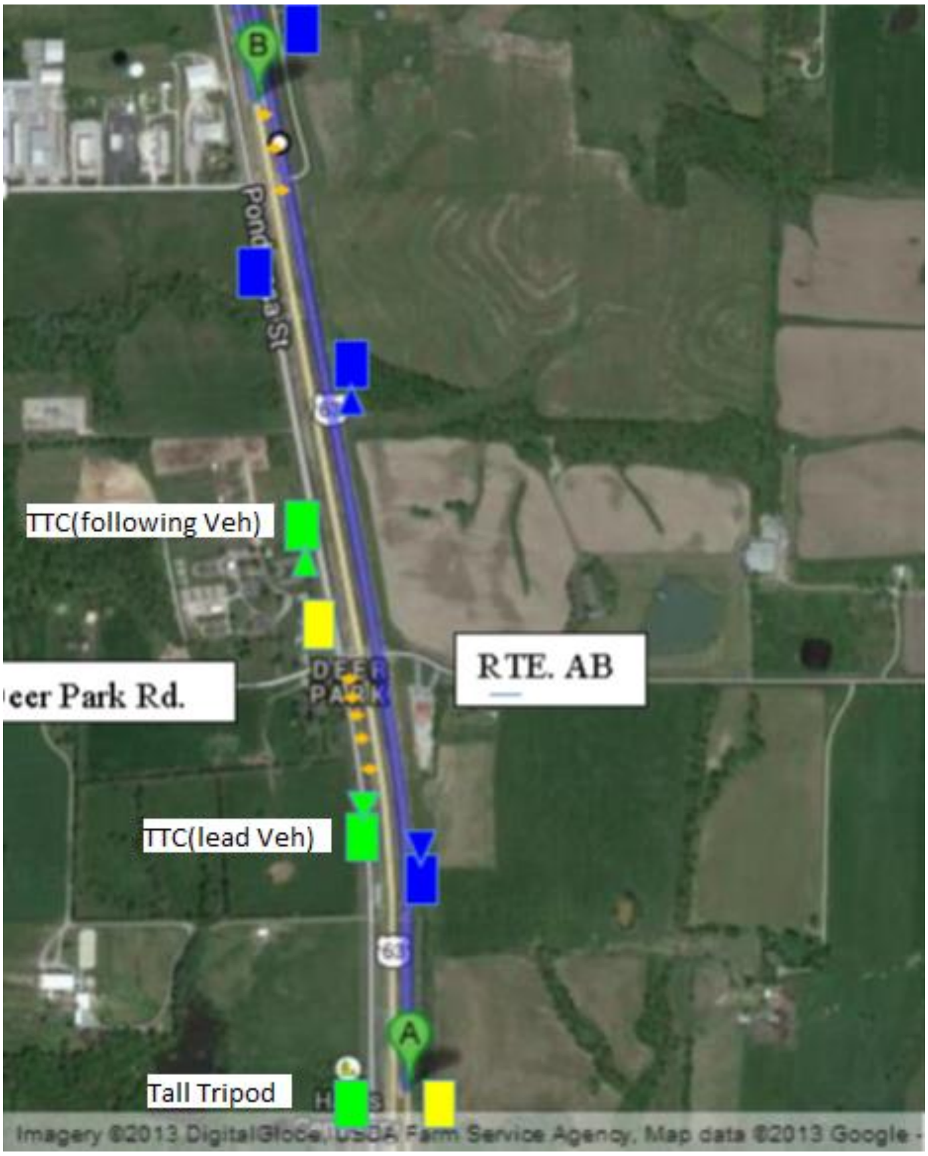


Figure 5.19. Data collection equipment in Edara et al. (2013)

Figure 5.20. Radar speed gun view

The speed distribution of merging vehicles from the minor road (Route E) and the major road vehicles are shown in Figures 5.21 and 5.22. The 85th percentile speeds of passenger cars and trucks on the major road were 75 mph and 70 mph and for merging vehicles was 64 mph.

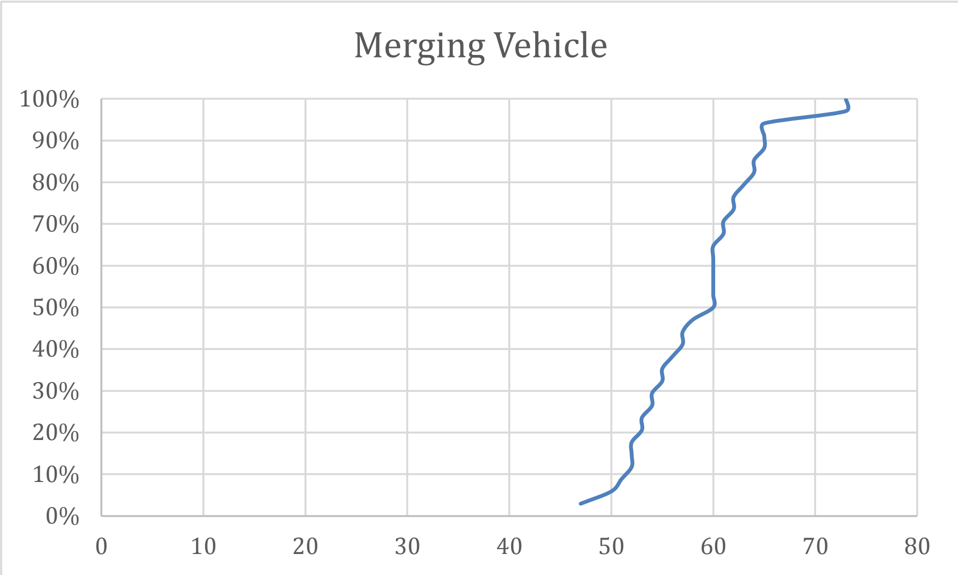


Figure 5.21. Merging Vehicle Speed Distribution

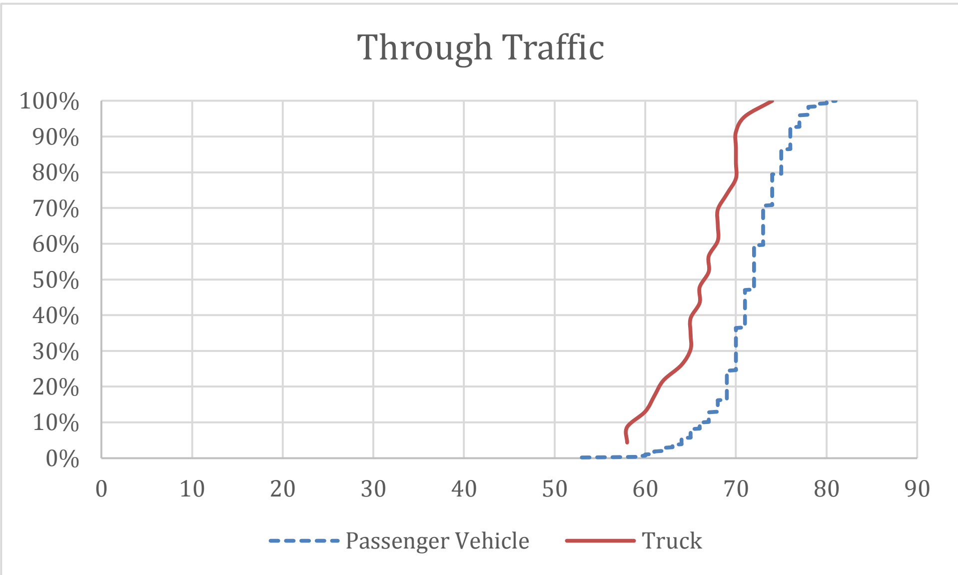
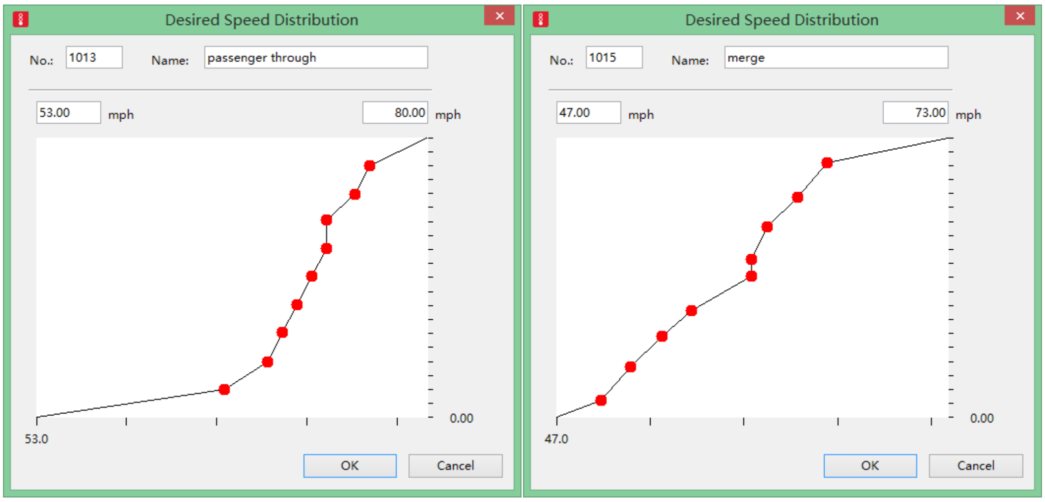


Figure 5.22. Through Traffic Speed Distribution

These speed distributions were then defined in VISSIM using the desired speed distribution parameter window shown in Figure 5.23.

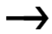


(a)Passenger Through (b)Merging/Diverging

Figure 5.23. Desired Speed Distribution in VISSIM

Different volume scenarios were generated for analyzing the J-turn performance. Table 5.3 shows the base volume scenario used. The major road volumes shown in Table 5.3 were obtained from the field data discussed earlier. The field-observed minor road volumes were low and did not generate enough conflicts to be useful for safety analysis. Thus higher values were used.

Table 5.3. Base Condition Major and Minor Road Flow Rates

No.	Movement	Diagram	Veh./Hour	Total
1	Major road through		1443	1504
2	Major road left turn		18	
3	Major road right turn		43	
4	Minor road through		22	308
5	Minor road left turn		16	
6	Minor road right turn		270	

The base case only shows one of the twelve volume scenarios that were studied in this project. Table 5.4 shows all the 12 major and minor road flow combinations. The "Minor Road Crossing" flow column includes both minor road left-turns and minor road through movements. The volume scenarios ranged from low volume to high volume. These twelve volume scenarios were then studied for the three U-turn distances of 1000 feet, 2000 feet, and 3000 feet, and for the presence/absence of acceleration lane, thus resulting in a total of 72 combinations.

Table 5.4. Volume Scenarios

	Major Road Total (veh./hour)	Minor Road Crossing (veh./hour)	Minor Road Right Turn (veh./hour)	Total Minor/Major ratio
1	1000	150	150	30%
2	1000	250	250	50%
3	1000	350	350	70%
4	1300	195	195	30%
5	1300	325	325	50%
6	1300	455	455	70%
7	1504	226	226	30%
8	1504	376	376	50%
9	1504	526	526	70%
10	1800	270	270	30%
11	1800	450	450	50%
12	1800	630	630	70%

SSAM, FHWA's Surrogate Safety Assessment Model, has an option where unrealistic conflicts (e.g. TTC (time to collision)=0) can be filtered from the output. Figure 5.24 shows the filters used in this study for all volume and design scenarios. The SSAM user manual provides guidance on selecting the threshold values for the filter (Gettman and Head, 2003).

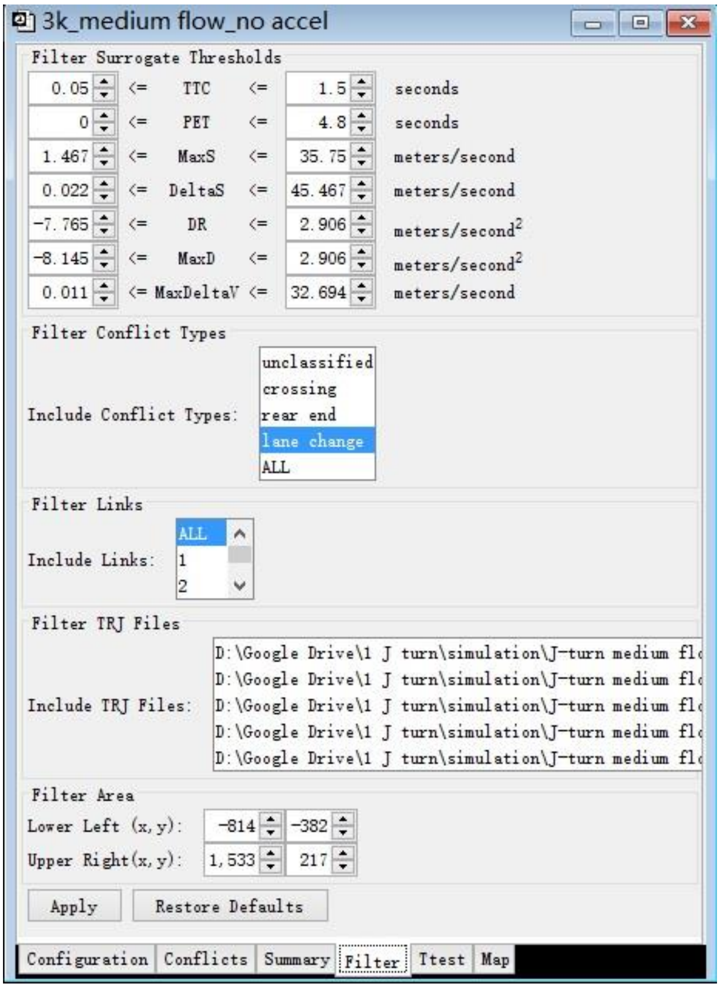
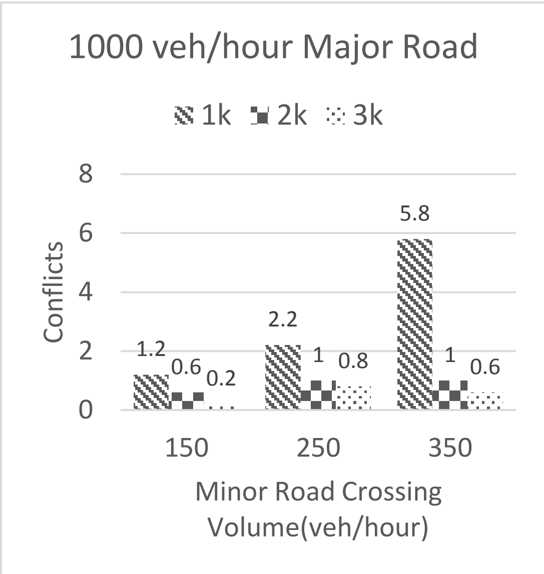


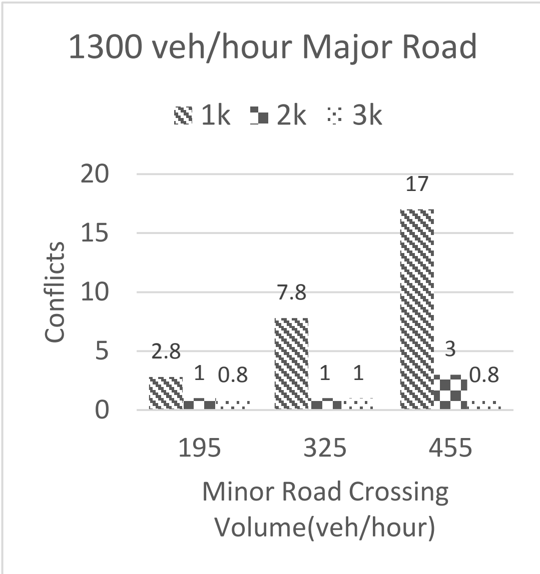
Figure 5.24. Applied SSAM filter of the conflicts analysis

5.2.2. Simulation Results

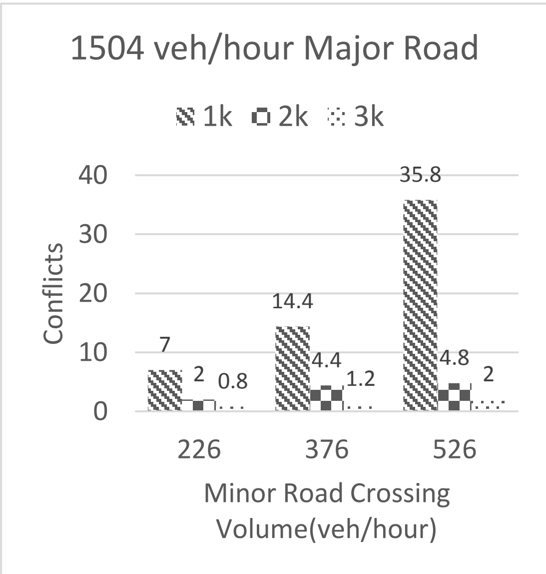
5.2.2.1. Designs with Acceleration Lanes

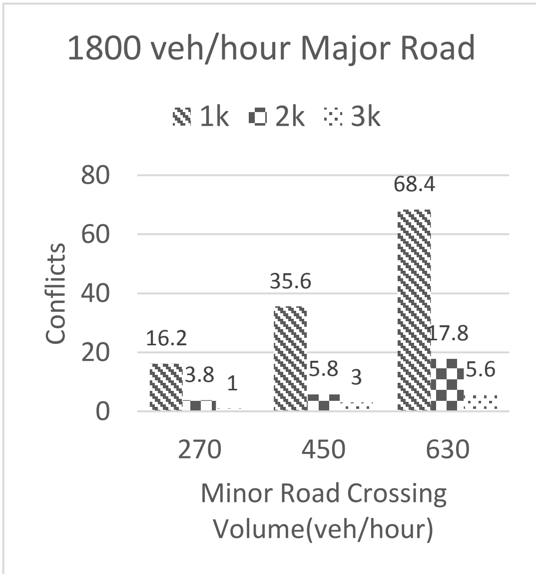
Figures 5.25 (a to d) show the average conflicts registered by SSAM from all 12 volume combinations. They are grouped by major road volume. In each chart, the x axis stands for the minor road crossing volume and the y axis stands for the conflicts. In addition to the crossing volume, an equal number of right turning vehicles were also simulated. For example, the total minor road volume for the scenario with 150 veh./hr. crossing volume is 300 veh./hr. Each scenario was run five times using different random seeds in VISSIM and the results were averaged across the five runs. Striped bars in the figures indicate 1000 feet (or 1k) spacing, squared bars indicate 2000 feet (or 2k) spacing, and dotted bars indicate 3000 feet (or 3k) spacing.





(a) (b)





(c) (d)

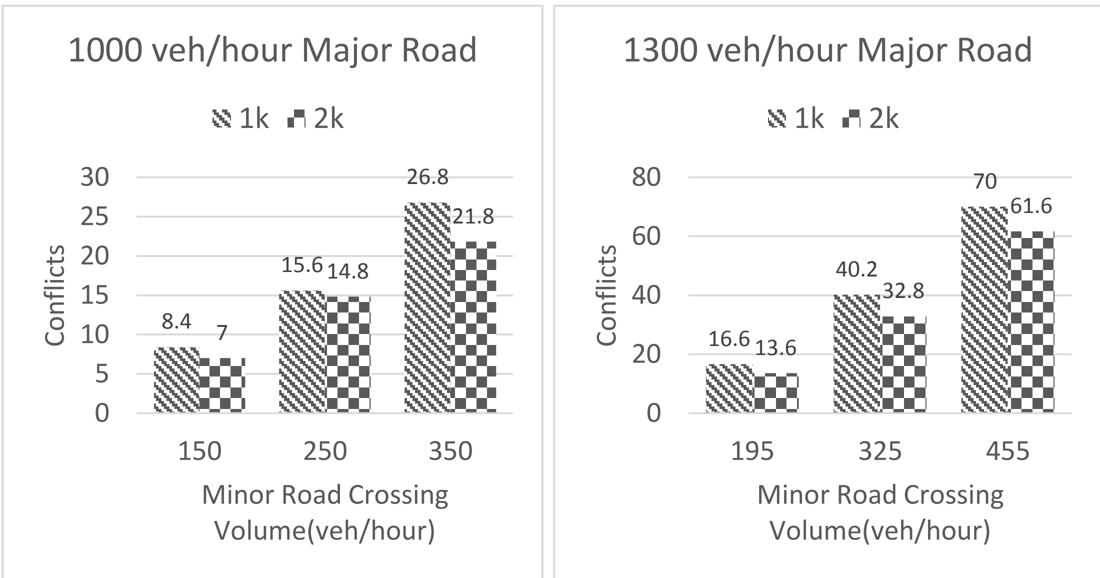
Figure 5.25. Conflict counts for designs with-acceleration lane

The results were consistent for all volume scenarios. The number of conflicts decreased with an increase in the spacing between the minor road and the U-turn. For example, the lowest volume combination, 1000 veh./hour total on the major road and 150 veh./hour on the U-turn, witnessed 1.2 conflicts for 1000 ft spacing, 0.6 for 2000 ft and 0.2 for 3000 ft. This effect is more significant when the traffic volume is higher. For the highest volume scenario of 1800 veh./hour on the major road and 630 veh./hour on the U-turn, the number of conflicts dropped from 68.4 to 17.8 for 2000 feet, a difference of 50.6, and to merely 5.6 for 3000 ft.

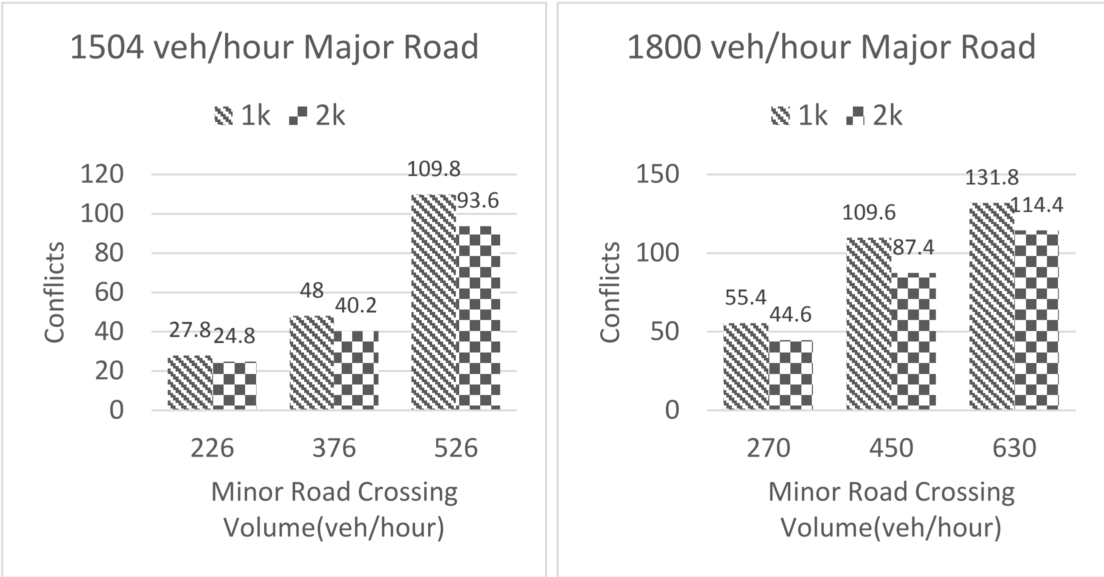
Although it is clear from the results that longer spacing values decreased the number of conflicts, the reduction of conflicts is not linear. For example, the second heaviest volume combination results in a reduction of 31 conflicts from 1000 feet to 2000 feet and merely a reduction of 2.8 conflicts from 2000 feet to 3000 feet. Thus, a spacing of 2000 feet may be sufficient for providing a good trade-off between safety and cost-effective J-turn design.

5.2.2.2. Designs without Acceleration Lane

In general, the lack of acceleration lane increased the queuing on the minor road for vehicles waiting for a gap to merge into the major road. The numbers of conflicts for designs without the acceleration lane are shown in Figures 5.26 (a to d). Due to the lack of acceleration lanes, only two spacing combinations of 1000 ft and 2000 ft were evaluated. Overall, the number of conflicts decreased when the spacing increased from 1000 ft to 2000 ft. For example in Figure 5.26 (b), conflicts dropped from 16.6 to 13.6 for 195 U-turn vehicles; 40.2 to 32.8 for 325 U-turn vehicles, and 70 to 61.6 for 455 U-turn vehicles.



(a) (b)

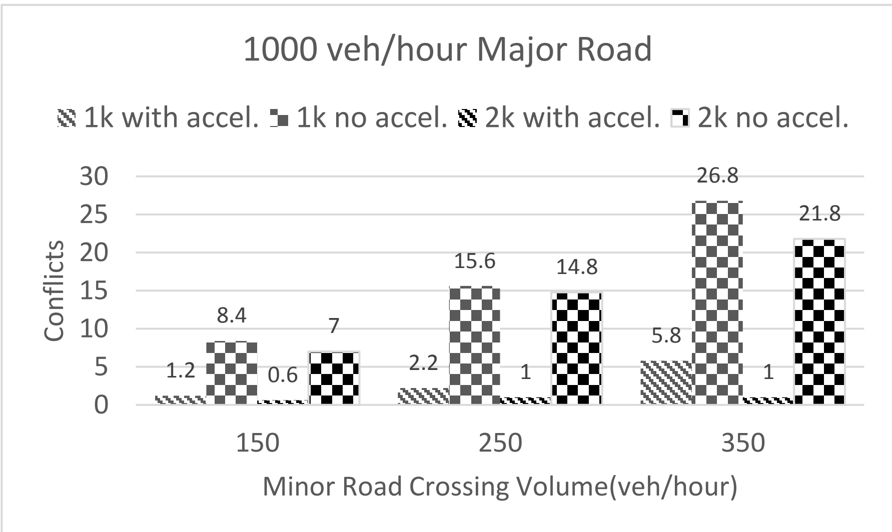


(c) (d)

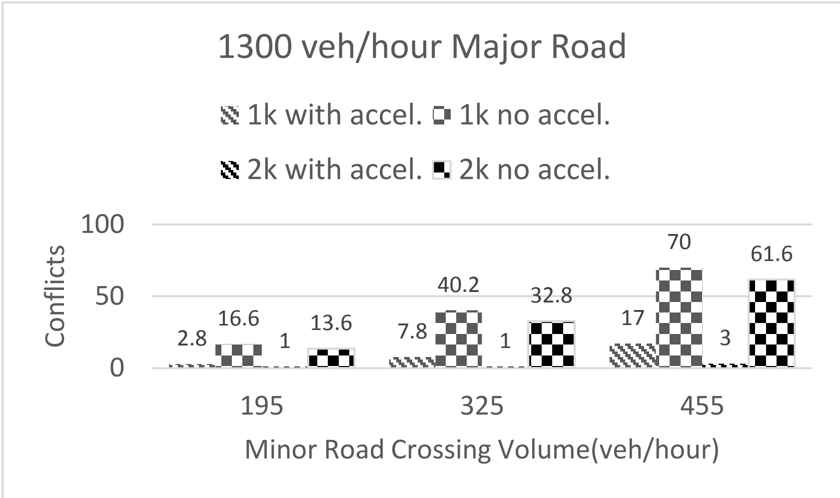
Figure 5.26. Conflict Counts for design without acceleration lanes

5.2.2.3. Comparison of with and without Acceleration Lane designs

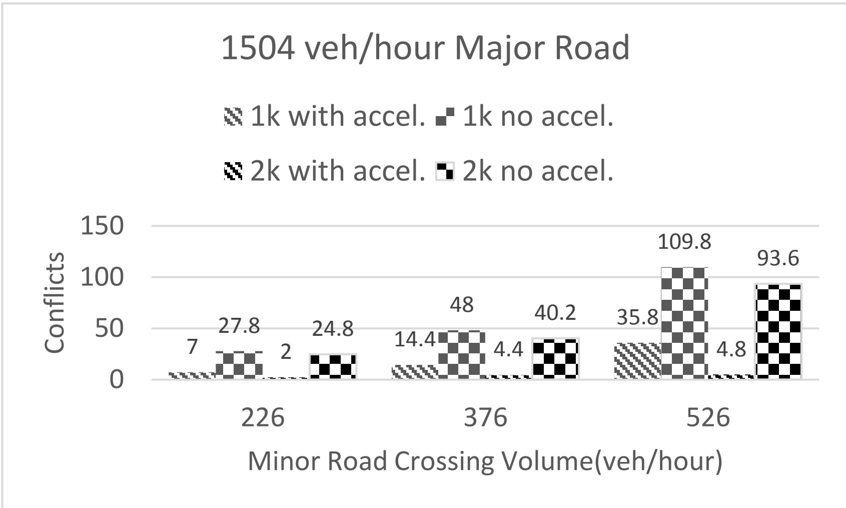
Figure 5.27 (a to d) compares the designs with and without acceleration lanes across all volume scenarios. In the figures, striped bars represent the designs with acceleration lanes while squared bars represent the designs without acceleration lanes. For each volume combination and the same U-turn spacing, the no-acceleration-lane design has more conflicts than the design with acceleration lane. Thus, acceleration lanes resulted in better safety for all spacing and volume combinations.



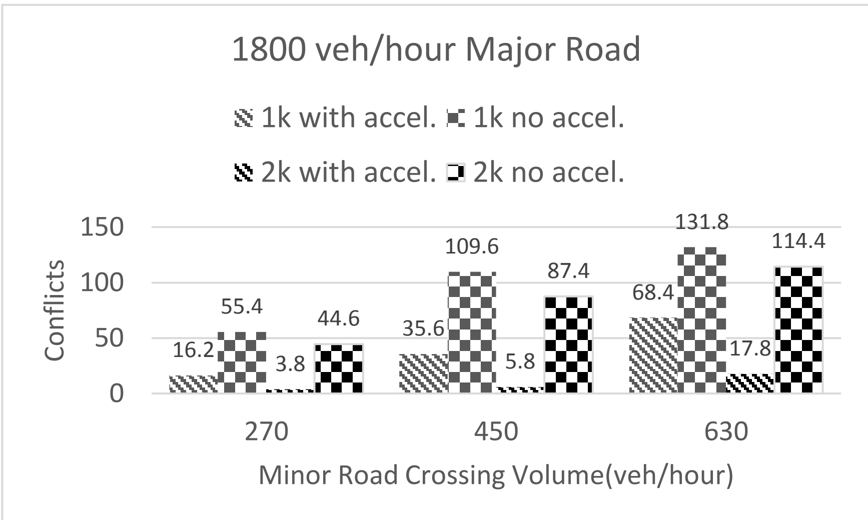
(a)



(b)



(c)



(d)

Figure 5.27. With Accel. Lane Design VS. No Accel. Lane Design

One goal of this project was to determine optimal spacing between the U-turn and the minor road for different volume and design combinations. Table 5.5 was compiled based on the results of simulation analysis. As previously concluded, acceleration lanes are safer for all volume combinations studied in this project. If acceleration lanes cannot be provided, the last column in Table 5.5 provides guidance on minimum spacing recommended for the different volume combinations. When acceleration lanes can be provided, the recommended spacing is lower for low volume combinations as shown in the fifth column in Table 5.5

Table 5.5. Recommended Minimum Spacing for Each Scenario

Major Total (veh/hr)	Minor Crossing (veh/hr)	Minor Crossing (veh/hr)	Total Minor/ Major	With Acceleration Lane (in ft)	No Acceleration Lane (in ft)
1000	150	150	30%	1000-2000	1000
	250	250	50%	1000-2000	1000
	350	350	70%	2000	1000-2000
1300	195	195	30%	1000-2000	1000
	325	325	50%	2000	1000-2000
	455	455	70%	2000-3000	1000-2000
1504	226	226	30%	2000	1000
	376	376	50%	>2000	1000-2000
	526	526	70%	>2000	1000-2000
1800	270	270	30%	2000	1000
	450	450	50%	2000	2000
	630	630	70%	3000	2000

6. CONCLUSIONS

System-wide safety treatments are aimed at treating select types of crashes occurring across a state. In Missouri, cable median barriers and shoulder line rumble strips are examples of successful system-wide safety treatments that were deployed across the state to reduce lane departure fatalities. Missouri's Strategic Highway Safety Plan established a short-term goal of reducing traffic fatalities to 700 per year by 2016 as an intermediate step towards the long-term goal of zero roadway deaths in the state. This project synthesized existing state of practice on system-wide treatments, specifically those that were not previously implemented in Missouri. The synthesis covered three areas: 1) horizontal curves, 2) intersections, and 3) wrong way crashes. The safety effectiveness, implementation guidelines, limitations, costs, and concerns of the treatments were documented. The identified safety treatments work in conjunction with the 'Necessary Nine' strategies identified in the Missouri's Blueprint. The synthesis assists MoDOT in selecting system-wide treatments for future deployments in the state.

Signage, design, ITS, and driver countermeasures were reviewed to address wrong way crashes. Innovative signage strategies including lowering height, oversized signs, illumination, doubling the number of signs, are low-cost solutions that can be deployed system-wide. Design countermeasures such as avoiding left side exit ramps, using raised medians on crossroads, improving sight distance are also recommended. ITS technology options are more expensive and therefore may not be suitable for system-wide deployment. The detection and alert systems based on video radar, or in-pavement sensors have been piloted in a few states.

Countermeasures targeting horizontal curve crashes may involve augmenting the minimum recommended MUTCD signs and devices at horizontal curves. These include improved curve signing through the use of additional chevrons, flashing beacons at sharp curves, dynamic curve guidance systems, and dynamic speed warning systems. Pavement marking treatments such as speed reduction markings, warning symbols painted on the pavement, and high friction pavement treatment are recommended for system-wide deployment in Missouri. Missouri DOT has successfully utilized two pavement marking treatments in the past - wider edge lines and rumble strips/stripes.

Treatments to enhance signalized intersection safety include increasing clearance interval, changing left turn from permissive to protected-permissive, flashing yellow arrow, dynamic signal warning, red light cameras, and improving signal visibility. Based on the safety effectiveness reported in literature, dynamic signal warning and improving signal visibility are recommended for future consideration as system-wide treatments at signalized intersections in Missouri.

A detailed analysis of the collision diagrams of crashes that occurred at twelve J-turn sites in Missouri revealed the proportion of crash types that occurred at these sites. The five crash types are: 1) major road sideswipe (31.6%), 2) major road rear-end (28.1%), 3) minor road rear-end (15.8%), 4) loss of control (14%), and 5) merging from U-turn (10.5%). Most of the major road side swipe and rear-end crashes occurred while vehicles were merging with traffic or changing lanes to enter the U-turn. Higher speed differentials between merging and major road vehicles and driver inattention were common factors in most crashes that occurred at the J-turn facilities. The crash rates computed from the collision diagram analysis showed that the rates decreased with the increase in the spacing to the U-turn, for both sideswipe and rear-end crashes. The longer spacing allowed merging vehicles to reach major road operating speeds, thus making it safer to follow other vehicles in the lane and to make lane changes. J-turns with a spacing of 1500 feet or greater experienced the lowest crash rates.

A simulation analysis was conducted to further study the impact of different design variables on the safety of J-turns. Specifically, the effect of presence of acceleration lane and the spacing to the U-turn were investigated. A base simulation model was created and calibrated using field data collected in a previous MoDOT project on J-turns. The calibrated model was then used to study various combinations of major road and minor road volumes and design variables. The simulation analysis helped develop guidance on recommended spacing for various major road and minor road volume scenarios. For all the studied scenarios, the presence of acceleration lane resulted in significantly fewer conflicts. Thus, acceleration lanes are recommended for all J-turn designs, including lower volume sites. Second, while spacing between 1000 feet and 2000 feet was found to be sufficient for low volume combinations, a spacing of 2000 feet is recommended for medium to high volume conditions.

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APPENDIX – Countermeasure Effectiveness and Costs

Priority	Facility	Countermeasure	Description	Effectiveness		Cost	
				Estimated	Effect on crash frequency	Estimated	Actual
Wrong way crashes	Ramp terminal	Minimum signing	One 36"x12" (R6-1), one 24"x24" (R5-1), and one 30"x18" (R5a-1)	Low	-	Low	$101 per site (TAPCO, 2015)
			One 54"x18" (R6-1), one 30"x30" (R5-1), and one 36"x24" (R5a-1)		-		$167 per site (TAPCO, 2015)
			One 54"x18" (R6-1), one 36"x36" (R5-1), and one 42"x30" (R5a-1)		-		$197 per site (TAPCO, 2015)
		Optional signing	Two 36"x12" (R6-1), two 24"x24" (R5-1), two 30"x18" (R5a-1), one 24"x24" (R3-1), and one 24"x24" (R3-2)		-		$282 per site (TAPCO, 2015)
			Two 54"x18" (R6-1), two 30"x30" (R5-1), two 36"x24" (R5a-1), one 30"x30" (R3-1), and one 30"x30" (R3-2)		-		$452 per site (TAPCO, 2015)
			Two 54"x18" (R6-1), two 36"x36" (R5-1), two 42"x30" (R5a-1), one 36"x36" (R3-1), and one 36"x36" (R3-2)		-		$559 per site (TAPCO, 2015)
		Double minimum signing	Four 36"x12" (R6-1), four 24"x24" (R5-1), and four 30"x18" (R5a-1)	Medium	-		$404 per site (TAPCO, 2015)
			Four 54"x18" (R6-1), four 30"x30" (R5-1), and four 36"x24" (R5a-1)		-		$668 per site (TAPCO, 2015)
			Four 54"x18" (R6-1), four 36"x36" (R5-1), and four 42"x30" (R5a-1)		-		$789 per site (TAPCO, 2015)
		Double optional signing	Four 36"x12" (R6-1), four 24"x24" (R5-1), four 30"x18" (R5a-1), one 24"x24" (R3-1), and one 24"x24" (R3-2)		-		$484 per site (TAPCO, 2015)
			Four 54"x18" (R6-1), four 30"x30" (R5-1), four 36"x24" (R5a-1), one 30"x30" (R3-1), and one 30"x30" (R3-2)		-		$786 per site (TAPCO, 2015)
			Four 54"x18" (R6-1), four 36"x36" (R5-1), four 42"x30" (R5a-1), one 36"x36" (R3-1), and one 36"x36" (R3-2)		-		$953 per site (TAPCO, 2015)
		Improved signage and lighting	Improving ramp terminal conditions with oversized retroreflective sings and illuminated approaches	Medium	-	High	$5,000 to $15,000 per site (FHWA, 2014d)
		Radius at corners	Angular or tight radii make wrong way movements difficult	Medium	-	Low	-
		Raised median	Discourages wrong way left turn entry onto interchanges: diamond, parclo, and full cloverleaf	Medium	-	Medium	-
		Channelization	Devices to direct vehicles to the correct path, block, or restrict undesired movements	Medium	-	Low	-
		Sight distance	Moving stop lines forward (50-60%) of the way through the intersection (WSDOT, 2013)	Low	-	Low	-
		ITS technologies	Video detection and TMS notification	Low	-	High	-
			Two stand alone flashing LED wrong way signs synchronized with traffic sign phase (NTTA, 2009)	High	-	High	$4,000 per site and $450 for software (NTTA, 2009)
			Pavement embedded sensors and LED warning alerts	High	-	High	-
			Inductive loops and TMS notification software *(46)*	Low	-	High	$10,000 per site and $55,000 for software (NTTA, 2009)
			Detection, TMS notification, tracking, monitoring, driver alert, and DMS warning traffic in vicinity	High	-	Very high	-
	Freeways	Avoid left side exit ramps	Drivers expect to enter freeway on the right hand side	High	-	High	-
	Frontage roads	Improved geometry and signing	Improper design of frontage roads with freeway exit ramps may cause driver confusion	High	-	Low	-
	All	Alcohol ignition interlock	Driver's breath is tested by a device connected to the vehicle to detect alcohol concentration	High	-	High	$1,200 veh/year (PennDOT, 2015)
	All	GPS vehicle alerts	The GPS provides an immediate alert to the driver when incurring on a wrong way maneuver	High	-	Medium	$100 to $500 per vehicle (Garmin, 2015)
Roadway departure	Horizontal curves	Installing reflective chevron and horizontal arrow signs	One direction road, five 18"x24" (W1-8) and one 34"X12" (W1-6)	Medium	18% (all), 25% (FI), and 35% (nighttime) (Srinivasan et al., 2009)	Low	$184 per site (TAPCO, 2015)
			One direction road, five 24"x30" (W1-8) and one 36"x18" (W1-6)			Low	$261 per site (TAPCO, 2015)
			One direction road, five 36"x48" (W1-8) and one 48"x24" (W1-6)			Low	$608 per site (TAPCO, 2015)
			Bidirectional road, ten 18"x24" (W1-8) and two 34"X12" (W1-6)			Low	$369 per site (TAPCO, 2015)
			Bidirectional road, ten 24"x30" (W1-8) and two 36"x18" (W1-6)			Low	$522 per site (TAPCO, 2015)
			Bidirectional road, ten 36"x48" (W1-8) and two 48"x24" (W1-6)			Medium	$1216 per site (TAPCO, 2015)
		Installing warning, chevrons signs, and flashing beacons	Bidirectional road, two solar flashing LED beacons, two 36"x36" (W1-1), two 24"x30" (W13-1P), and ten 36"x48" (W1-8)	High	47.6% (all), 38.2% (FI), and 76.9% (nighttime) *(5)*; 30% (all)(Gan et al., 2005)	High	$4,871 per site (TAPCO, 2015)
		Installing dynamic flashing chevrons	Single direction solar flashing LED chevrons signs along curve	Medium	-	High	$15,000 per site (complete system) (TAPCO, 2015)
		Installing dynamic speed warning sings	Solar flashing LED dynamic sign provided the approaching speed of vehicle prior entering the curve	Low	5% to 7% (all) (Hallmark et al., 2015)	High	$2,795.00 to $7,290.00 per device (TAPCO, 2015)
		Installing raised pavement markers	One hundred 2"x4" two sided reflection markers	Medium	Radius > 1,640 ft., 33% to -13%* (nighttime), inconclusive results (Bahar et al., 2004)	Low	$155 per site (TAPCO, 2015)
			One hundred 8"x8"x3.25" pyramid shape two sided reflection markers			Medium	$1,795 per site (TAPCO, 2015)
			One hundred 8"x8"x3.25" pyramid shape four sided reflection markers			Medium	$1,995 per site (TAPCO, 2015)
			One hundred solar LED 4"x4" one side illumination markers			High	$5,475 per site (TAPCO, 2015)
			One hundred solar LED 4"x4" two side illumination markers			High	$6,295 per site (TAPCO, 2015)
		Implementing rumble strips/stripes	Centerline rumble strips on tangent sections	Low	22% to -10%* (FI rural area) (Torbic et al., 2009)	Low	$0.10 to $1.20 per linear foot (FHWA, 2014b)
			Edge line in curves	Medium	15% (all) (Pitale et al., 2009)		
		Installing roadside delineators	White flexible reflective delineator on both sides of the horizontal curve (30 units)	High	45% (FI) (Elvik et al., 2004)	Low	$747 per site (TAPCO, 2015)
		Widening edge lines	4 to 6 and 8 inch wide (all materials)	Medium	22 to 25% (FI) (Potts et al., 2011)	Low	$0.05 to $1.40 per foot (FHWA, 2010a)
		Pavement symbols, optical speed, and transverse bars	Pavement marking indicating the proximity of a horizontal curve and speed awareness	Medium	-	Low	$0.05 to $1.40 per foot (FHWA, 2010a)
		Pavement high friction treatment	Increasing coefficient of friction of pavement to prevent lane departure, specially under severe weather conditions	Medium	25% (all), 14% (FI on wet pavement), and 25% (fatal on sharp curves) *(25,29)*; 24% (all), 57% (all under wet pavement) (Harkey et al., 2008)	High	$19 to $35 per square yard. A project with 750 square yard surface ranges between $14,000 to $16,000 per site (FHWA, 2014c)
Intersections	Signalized intersections	Increase clearance signal interval	Increase of all red (1.1 second)	Medium	20% (all), 14% (FI), 20% (rear end), and 3% (angle) (Srinivasan et al., 2011)	Low	-
		Change left turn phase from permissive to protected-permissive	One or more approaches treated	Low	4% (FI overall intersection crashes) and 8-21% (all left turn opposing through crashes) (Srinivasan et al., 2011)	Low	-
		Installation of flashing yellow	Left turn phase before treatment: Permissive or combination of permissive and permissive-protective	Medium	25% (all), 37% (all left turn crashes) (Srinivasan et al., 2011)	Low	-
			Left turn phase before treatment: Protective-permissive	Low	8% (all) and 19% (all left turn crashes) (Srinivasan et al., 2011)	Low	-
		Installing dynamic warning flashers	Located upstream of intersection approaches to alert drivers of phase changing as the driver approaches to the intersection. Solar powered with one or two LED flashing beacons	Medium	18% (FI), 21% (rear-end), and 26% (angle) (Srinivasan et al., 2011)	Medium	$1,800 to $2,800 per device (TAPCO, 2015)
		Installing red light cameras	Provider service to fine red light running violators	Medium	Angle: 25% (all) and 16% (FI); rear-end: -15%* (all) and -24%* (FI) (Council et al., 2005)	Low	Self-financed programs
		Improved signal visibility	Improved or replace signal sized lenses and added reflective tape to existing or new backboards	Low	7% (all), 9% (PDO), and 7% (nighttime) (Sayed et al., 2007)	Low	-
			Backplate and retroreflective edge signal head	Medium	15% (all) (Sayed et al. 2005)		
	Stop-controlled intersections	Installing solar LED stop sings	Improving the visibility of stop sings with LED devices and sign size	Medium	42% w/ 95% CI between 0-71% (angle) (Davis et al., 2014)	Medium	$1,400 to $1900 per device (TAPCO, 2015)
		Installing alert flashing sings	Flashing beacons in combination with stop or entering when flashing signs	Medium	25% (all) *(17)*; 5% (all), 10% (FI), and 13% (angle) (Srinivasan et al., 2008)	Medium	$1,800 to $2,800 per device (TAPCO, 2015)