2+1 Roadway Design Guidance Update

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Kentucky Transportation Center
College of Engineering, University of Kentucky, Lexington, Kentucky

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Research Report
KTC-23-11

2 + 1 Roadway Design Guidance Update

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The frequency and severity of crashes on rural two-lane roadways have increased in the US relative to other road types. This trend can be explained by the growing number of vehicles, higher speeds, narrow shoulders, and vehicle mixes. One solution for improving traffic flow and safety outcomes on rural two-lane roadways is to adopt a 2+1 design, which confers the benefits of four-lane highways but at a lower cost. Transportation agencies throughout Europe — and increasingly the US — have seen good results from 2+1 layouts. Crash data from Sweden, Germany, Finland, and Denmark reveal better safety outcomes following the implementation of 2+1 designs, with reductions in fatal and fatal and injury crash rates of 25 – 80 percent. Studies in the United States have found crash declines of 35 – 44 percent following the transition to 2+1 layouts. Over the past 10 years, the Kentucky Transportation Cabinet (KYTC) has built several 2+1 roadways. Evaluations of three 2+1 segments in the state found lower crash rates on two segments, however, not enough crash data are available to draw definitive conclusions. Despite this lack of confirmatory data, there is consensus among practitioners that 2+1 designs hold considerable promise for improving rural roadway operations. Building off of 2+1 guidance originally issued by KYTC in 2013, this report outlines updated policies that account for lessons learned at the agency during the design and construction of 2+1 roadways as well as best practices adopted by other states.</td></tr>
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Executive Summary

Compared to other road types, the frequency and severity of crashes on rural two-lane roadways have increased in the US. This trend is attributable to the growing number of vehicles, higher speeds, narrow shoulders, and the mix of vehicles traveling on rural two-lane highways. 2+1 designs — sometimes referred to as alternating passing lanes or Super 2s — offer passing opportunities to improve traffic flow. In situations where faster vehicles want to pass slower ones but encounter oncoming traffic, a 2+1 configuration functions as a safety countermeasure and improves roadway performance. The design is well-suited to corridors that suffer from high numbers of head-on collisions or where traffic volumes are not high enough to justify a four-lane highway.

Crash data from Europe demonstrate the effectiveness of 2+1 designs. When Sweden implemented 2+1 roadways along with cable barrier, injury and fatal crashes dropped by 55 percent, while fatal crashes fell by about 80 percent. Similarly impressive reductions in severe crashes were recorded in Germany, Finland, and Denmark. Transportation agencies in the US and Germany have not typically used median barriers due to concerns over their performance in transition areas and around lane drops and their propensity to increase property damage only crashes. Previous studies in the US have shown crash reductions on 2+1 roadways of between 35 and 44 percent. Because KYTC has only recently begun constructing 2+1 roadways, insufficient crash data are available to fully evaluate their safety. Analysis of three 2+1 segments in Kentucky found crash rates fell at two sites. However, continued observations are warranted to understand the local performance of 2+1 designs.

In 2013, KYTC released 2+1 design guidance. While valuable, it needs to be updated to account for lessons learned during the design and construction of 2+1 roadways. Based on lessons learned and a review of policies adopted in other states, this report presents an updated policy for 2+1 design. Key elements are summarized below. Appendix A contains the full policy.

Traffic Volumes for Recommended Use

- 2+1 configurations may be considered the ultimate design for facilities that have design-year ADTs ≤ 15,000.
- If the design-year ADT is 15,000 – 20,000, begin with a 2+1 configuration but acquire sufficient right of way to expand to a four-lane facility.
- 2+1 roadways are not the best option when one-way flow rates exceed 1,200 vehicles/hour. Perform a traffic engineering analysis to determine if a 2+1 or four-lane configuration is appropriate.

Recommended Passing Lane Lengths

- Values listed in the table below **do not** include passing lane tapers at the beginning or end of passing lanes.

One-Way Flow Rate (veh/h)	Recommended Passing Lane Length (mi)
100 – 200	0.5
201 – 400	0.50 – 0.75
401 – 701	0.75 – 1.00
701 – 1,200	1.00 – 2.00

Design Considerations

- Reserve 2+1 designs for level or rolling terrain. They can also be used on steep grades to support climbing lanes. Uphill grades are preferred — but not required — for passing lanes.
- Maintain adequate sight distance on approaches to lane-addition and lane-drop tapers. Provide stopping sight distance continuously along 2+1 corridors. Decision sight distance is an option at intersections or lane drops.
- Avoid closing a passing lane over a hill or around a horizontal curve as the end of a taper may not be visible from the beginning of a taper.
- Traffic departing an incorporated area should be given the preference for passing.
- Locate passing lanes away from major intersections and high-volume driveways to minimize speed differentials between turning and passing traffic.
- Review geometric factors (e.g., horizontal curve radius, superelevation) to determine if they can support expected operating speeds.

- Passing lanes are most effective when drivers enter the right lane at the lane transition and only use the left lane when passing a slower vehicle.
- When transitioning from a 2+1 segment to a two-lane segment, maintain stopping sight distance between the end of a lane-closure taper and obstacles (e.g., guardrail, narrow bridges, busy intersections).

Passing Lane Transitions

- Locate transitions that begin or end a passing lane so drivers have a full view of the change. Options are head-to-head transitions and tail-to-tail transitions. Use *Green Book* equations 3-38 and 3-39 to compute lane- drop taper length. A lane-addition taper should be ½ the length of a lane-drop taper.

Access Management

- Site intersections to minimize turning movements in passing lanes or provide dedicated left- and right-turn lanes.
- In passing-lane sections, place turning lanes in the same locations as on a conventional two-lane road.
- Low-volume intersections and driveways may be accommodated within passing lane sections.
- Consider using lower turning-lane warrants if the road context demands extra safety measures.
- Avoid placing entrances that require left-turns within the first 1,000 feet of a passing lane — higher speeds and overtaking maneuvers are most common in this area.
- Do not locate entrances in areas with lane drops, tapers, or transitions.
- An alternative strategy for turning movements is permitting only right-in/right-out access.

Typical Section – Lane and Shoulder Widths

- Lane width on 2+1 sections should match the lane width on adjacent two-lane segments.
- If site or budget constraints require narrowing a cross section, base decisions about reduced widths on traffic volumes, roadside conditions, geometric alignments, and crash data.
- Use typical shoulder widths along a passing lane unless reducing the width would significantly cut costs or avoid significant impacts. Shoulder widths may differ between the passing lane and the single-lane side.
- Where practical, do not use a narrower shoulder in a passing lane section than on adjacent two-lane sections.
- Consider providing full shoulders (8 feet – 10 feet) in areas with high driveway density.

Flush Median

- While passing lanes can operate effectively with no separation from opposing traffic, a flush median separation of 4 feet between opposing directions of travel is preferred. Use centerline rumble strips and pavement markers all 2+1 roadways.

Lane Pavement Crown Point and Superelevation

- If a two-lane roadway is restriped or widened to a 2+1 layout, the crown may be placed in the traveled way. If an existing roadway is widened on one side, the crown can be located on the lane line.
- On new construction, place the crown at a lane boundary. When the crown point needs to be transitioned along the roadway, do so along the lane-drop or lane-addition tapers.

Signing and Pavement Markings

- Consult the following layout sheets for guidance: Typical Signing Scenarios for 2+1 Roadways, Typical Markings Scenarios for 2+1 Roadways (Part 1; Part 2), and Centerline Markings and Rumble Strip Arrangements for 2+1 Roadways.

Public Involvement

- Because 2+1 designs are unique, robust public involvement can help inform and engage communities in project development.

Chapter 1 Introduction to 2+1 Roadway Design

1.1 Overview

The growing number of vehicles on rural two-lane highways has raised concerns about road safety. The combination of high speeds, narrow shoulders, and the mix of drivers and vehicle types tend to increase the severity of crashes on rural two-lane highways relative to other roadway types (Kononov et al. 2020).[1] Adopting 2+1 roadway configurations can help improve safety outcomes.

2+1 designs offer the benefits of a four-lane highway at a lower cost (Brewer et al. 2011).[2] The design improves roadway performance and functions as a safety countermeasure on two-lane highways where faster vehicles want to pass slower vehicles but encounter oncoming traffic. Safety benefits conferred by 2+1 roads are contingent on factors such as traffic flow, along-route access points, and driver perception of roadway markings. They are well-suited for corridors with a high number of head-on collisions, or where traffic volumes are not high enough to justify a four-lane highway but are sufficiently high to benefit from alternating passing lanes (Romana et al. 2018).

2+1 designs have been successfully used for over two decades in Germany, Sweden, Finland, and Norway. By 2003, Germany had about 220 miles of 2+1 roadways that were constructed by restriping wider two-lane roads. (Potts 2003). Surveys of the German public between 1983 and 1988 found most drivers preferred 2+1 roads over other two-lane designs because they felt they offer better opportunities for passing and they support faster vehicle speeds (Potts 2003). When Sweden restriped two-lane roads and added cable barriers, there was a 55 percent reduction in fatal and injury accidents. The reductions in fatalities saw shifted media and public opinion in favor of 2+1 designs. Anecdotal evidence from Texas also suggests the public is more receptive to 2+1 roadways once they are implemented (Brewer et al. 2011).

1.2 Problem Statement

With traffic increasing on Kentucky's rural highways, the Kentucky Transportation Cabinet (KYTC) wants to determine the most effective strategy of maintaining good levels of service. Historically, KYTC has widened two-lane highways to four lanes once traffic volumes reach a level to warrant expansion. But with increased demands on funding, when average daily traffic does not justify the expense of expanding a road to four lanes, KYTC is increasingly opting for 2+1 configurations. KYTC's adoption of the 2+1 design is driven by two goals — (1) reduce crash rates and (2) improve travel times.

Most 2+1 designs maintain a continuous three-lane cross section, with the center lane serving as a passing lane in alternating directions. Compared to two-lane highways, 2+1 facilities are more efficient and have lower crash rates. They are also much less expensive to build than four-lane divided highways, with a savings of 50 to 90 percent.

1.3 Background

KYTC's Division of Highway Design released design guidance for 2+1 roads in August 2013. This guidance was developed in conjunction with Kentucky Transportation Center (KTC) researchers. Since then, KYTC has built several miles of 2+1 highways, with more scheduled for construction. KTC helped design these projects and monitor their operation after they opened. Other state departments of transportation (DOTs) that have built and maintained 2+1 roads provided a valuable source of information. Since the release of Kentucky's original design guidance, many lessons have been learned through project development and observations of traffic operations — both at KYTC and other agencies. This study draws on research and guidance from other DOTs to propose Cabinet design guidelines for 2+1 roads. Signing and pavement markings are the primary focus of this study as traffic control is vital to the proper operation of 2+1 facilities. This report outlines guidance for KYTC to use when implementing 2+1 road designs, with the goal of implementing the design on rural 2-lane highways. Table 1.1 summarizes the report's structure and contents.

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[2] They are sometimes called Super 2 highways.

Table 1.1 Report Structure

Chapter	Contents
Chapter 2	• Reviews research on 2 +1 designs from Europe, Australia, and the US • Compares highway design practices adopted by transportation agencies • Analyzes guidance on pavement markings and signage used on 2+1 designs
Chapter 3	• Highway safety summary of Kentucky's existing 2+1 roadways
Chapter 4	• 2+1 Roadway Geometry • Comparison Table • Proposed 2+1 Road Guidance for KYTC: KYTC's 2+1 Roadway Design Guidance
Chapter 5	• 2+1 roadway signing and markings • Proposed KYTC 2+1 roadway guidance
Chapter 6	• Conclusion and recommendations

Chapter 2 Literature Review

2.1 Introduction to 2+1 Roadways

The growing number of vehicles and types of vehicles (including CMVs) on rural two-lane highways have raised concerns about safety. Due to a combination of factors — high speeds, narrow shoulders, and a mix of drivers and vehicles — rural two-lane highway crashes tend to be more severe than crashes on other roadway types (Kononov et al. 2020).[3] One design strategy for improving safety outcomes in passing zones on rural two-lane highways is adopting 2+1 roadway configurations.

2+1 (sometimes called Super 2 highways) roadways offer the benefits of a four-lane highway at lower cost (Brewer et al. 2011). However, the magnitude of safety benefits is contingent on factors such as traffic flow, along-route access points, and driver perception of roadway markings. 2+1 highways are well-suited for corridors with a high number of head-on collisions or where traffic volumes are not high enough to justify a four-lane highway, but are sufficient to benefit from alternating passing lanes (Romana et al. 2018).

2+1 designs have been successfully used for over two decades in Germany, Sweden, Finland, and Norway. By 2003, Germany had about 220 miles of 2+1 roadways that were constructed by restriping wider two-lane roads. (Potts 2003). The design can improve rural roadway performance and function as a safety countermeasure on two-lane highways where faster vehicles want to pass slower vehicles but face oncoming traffic. Public surveys administered in Germany between 1983 and 1988 found most drivers preferred 2+1 roads over other two-lane roads. Respondents perceived that they offered better opportunities for passing and supported faster vehicle speeds (Potts 2003). When Sweden restriped existing two-lane roads and added cable barriers, a large reductions in fatalities shifted media and public opinion in favor of 2+1 roadways. Anecdotal evidence from Texas suggests the public views 2+1 roadways favorably once they are implemented (Brewer et al. 2011).

In 2003 National Cooperative Highway Research Program (NCHRP) Project 20-7 evaluated the performance of 2+1 roadways in Europe to determine whether they should be adopted in the United States (MRI 2003). Comparing the safety performance of 2+1 roadways to two-lane roads with various passing lanes, the study found 2+1 roads had crash rates 22 to 55 percent lower than conventional two-lane highways.

2.2 Literature Review: The 2+1 Design and Roadway Geometrics

The AASHTO Green Book (7th Edition) has guidance on implementing 2+1 designs, with the primary consideration being traffic volumes. 2+1 configurations should not be used where projected flow rates exceed 1,200 vehicles per hour in one direction of travel, and their use should be reserved for level or rolling terrain. The location of major intersections and high-volume driveways should be a key consideration when evaluating the appropriateness of 2+1 roadways along with decision sight distance at intersections and lane drops.

Colorado recently evaluated a 2+1 design consistent with the expectation of US-based drivers that the slow lane is the ending lane and designed with a gentler taper (Figure 2.1; Kononov et al. 2020). US designs adopt a longer lane taper than what is used in Sweden.

[3] Much of the information presented in this review was originally sourced from Kononov et al. (2020).

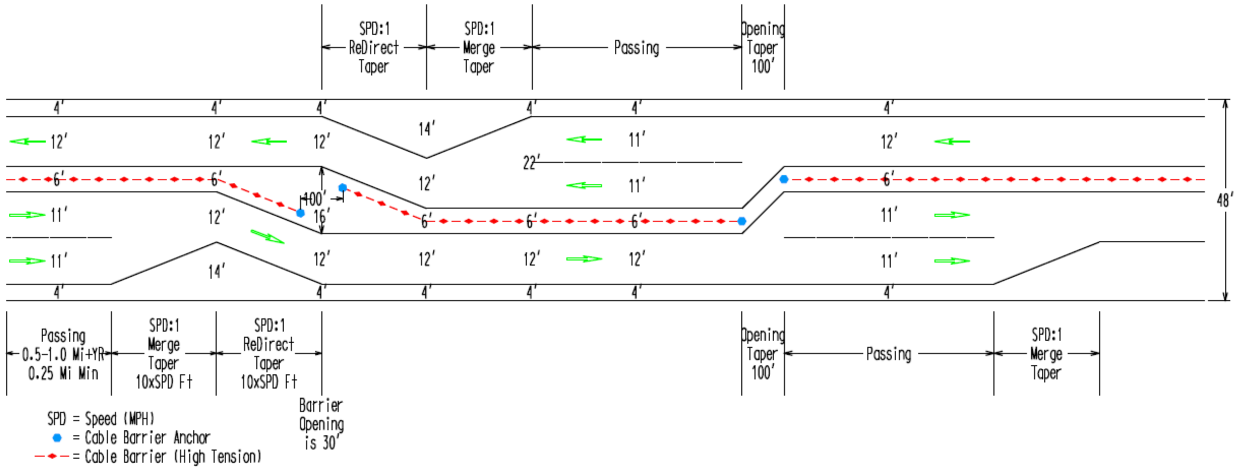


Figure 2.1 Sketch Layout of Proposed Colorado 2+1 with Barrier Configuration

Traffic Volumes

2+1 roadways are usually implemented on roads with medium to medium-high traffic volumes. Germany found that 2+1 roads operate effectively at traffic volumes of 15,000 to 25,000 vehicles per day, with a maximum operating limit of 30,000 vehicles per day (Potts 2003). Finland and Sweden have established slightly lower maximum traffic volumes per day of 25,000 and 20,000, respectively. Finland observed issues with 2+1 roadway operations when traffic volumes approach the upper limit. At a traffic rate of 1,200 to 1,400 vehicles per hour, drivers tend to queue in the right lane beginning at the lane drop. Higher traffic flow resulted in greater travel speeds but drivers occasionally experienced areas of slow speeds for short periods, increasing traffic on 2+1 sections (Potts 2003).

Passing Lanes

Passing is not a primary cause of crashes on two-lane highways. But providing a continuous passing lane for each direction reduces the pressure on drivers to find gaps and pass slower vehicles by traveling into a lane carrying oncoming traffic (Romana et al. 2018).

Passing lane lengths vary. The Texas Roadway Design Manual provides guidance on passing lane length and spacing between passing lanes based on average daily traffic (ADT). Roads with ADT less than 5,000 are potential candidates for 2+1 designs (Brewer et al. 2011). In general, passing lengths in the US are shorter than in Europe and tied more closely to ADT. Most DOTs specify a passing lane length of 0.5 to 1 mile, depending on traffic volume. Passing lanes should be long enough to reduce queues, but not so long that the design is ineffective and interferes with locations at junctions (Romana et al. 2018). Potts (2003) recommended a passing lane length of 0.6 to 1 mile, noting that beyond a mile the downstream portion of the passing lane could be underutilized.

The location of a periodic passing lane may be influenced by areas where there are high levels of platooning, curvature, or hilly terrain. Texas guidance states that “a passing lane is appropriate for areas where passing sight distances are limited. The location of the proposed lane addition should offer adequate sight distances and lane taper. The location selection should also consider the presence of intersections and high volume driveways in order to minimize the volume of turning movements on a roadway section where passing is being encouraged” (Brewer et al. 2011).

Alignment and Terrain

Higher traffic volumes on two-lane roads magnify the effects of limited sight distance. 2+1 designs can offer significant benefits in these areas (Brewer et al. 2011). Potts (2003) recommended constructing 2+1 roads in rolling or level terrain and using conventional truck climbing lanes on roads with long, steep grades. Alignments tend to have a lower degree of curvature to accommodate higher speeds.

Because most 2+1 roadways aim to improve traffic efficiency, alignments are specified for speed limits between 100 and 110 km/h. US design speeds are lower, as is the case in Texas where the speed for two-lane highways is 65 km/h (Romana et al. 2018). On sharp curves, the road typically transitions to a two-lane section. Germany is the exception as 2+1 designs are considered adaptable to any terrain (Potts 2003). The designs lack a crown section, and instead construct a continuous cross slope from one edge of the pavement to the other.

Transition Areas

Critical transition areas are an enormous safety concern. Vehicles executing late passing maneuvers in the marked merge transition zone at the end of the passing lane section can trigger head-on collisions. In Denmark, 24 percent of all accidents occurred in transition sections and usually involved vehicles traveling in the same direction (Romana et al. 2018). Romana et al. found large differences in international design criteria for the length of the critical transition area, ranging from 180 meters (590 feet) in Germany to 500 meters (1640 feet) in Finland. Colorado's design specifies a 150-meter (492 feet) critical transition length. A common solution is to place a substantial buffer between vehicles traveling in opposite directions (Kononov et al. 2020). A noncritical transition is located immediately upstream of a lane addition, where vehicles in the middle lane head away from each other. Germany specifies a noncritical transition length of 100 to 160 feet, where Sweden specifies 100 feet (Potts 2003).

Intersections and Access Points

In Colorado and Sweden officials have expressed concerns over the use of 2+1 designs on corridors with many access points and interchanges. A solution to this problem is transitioning to traditional two-lane roadways in locations with more densely spaced access points or side roads. In Finland 2+1 roads are controlled access only, typically at interchanges (Potts 2003). In Germany and high-traffic locations in the UK split level intersections are preferred. These designs force drivers to slow down or stop at at-grade intersections, offering greater safety benefits and uniform speed levels (Romana et al. 2018). Mutabazi (1998) recommended that side road intersections not be placed within a passing lane section; if this cannot be avoided the intersection should be located near the middle of the passing lane. Romana et al. (2018) suggested placing intersections in the buffer area between passing lanes and to include left-turn lanes.

The consensus is to avoid placing side road intersections within a lane drop or a lane addition. For routes that do not carry numerous heavy vehicles, roundabouts are a good option for allowing U-turns at a junction. 2+1 road designs that incorporate barriers often include openings in the barrier so maintenance and emergency vehicles can turn. Both Colorado and Sweden place the barrier openings in non-critical transition zones (Potts 2003). Texas prefers that passing lanes not be placed where there are driveways and intersections; if an intersection is unavoidable they should be placed at the midpoint of the passing lane (Brewer et al. 2011).

2.3 2+1 Roadway Performance

Safety and Crash Statistics

For moderate to low traffic volumes, 2+1 configurations have lower total crash rates than two-lane roads (Romana et al. 2018). Factors which influence the safety of 2+1 roadways include terrain, traffic volume (AADT), number and type of access intersections, percentage of heavy vehicles, and length/spacing of passing lanes. Researchers have not yet established safety performance measures for 2+1 layouts.

A key safety concern with 2+1 configurations is the critical transition zone, which is where vehicles merge just downstream of the new passing lane section. Late passing maneuvers can contribute to head-on collisions and provoke some drivers to continue passing throughout the entire merge zone. A second safety concern relates to access points. At intersections, the potential for high-speed differential conflicts with vehicles leaving or entering the roadway is elevated.

MRI's (2003) review of 2+1 roads in Europe found that:

- Germany had approximately 220 miles of 2+1 roads, each with an effective ADT volume of 15,000-20,000 vehicles per day. Crash rates were 36 percent lower than on conventional two-lane highways. Germany did not use cable barriers, finding their use undesirable.

- Finland had approximately 30 miles of 2+1 roads with an AADT of 14,000 vehicles per day (but traffic volumes as high as 20,000 to 25,000). Crash rates were 22-46 percent lower than on conventional two-lane highways. But safety performance was inconsistent, with one road performing well and another seeing many crashes in the winter. The Finnish Road Administration concluded that traffic safety on 2+1 roads without median barriers is not much better than on ordinary two-lane roads. The agency contended that median barriers can reduce head-on crashes by 80 percent. The agency also found that passes increased 20-40 percent in the daytime and more than doubled during weekend peak hours, but upstream and downstream from 2+1 roads the number of passes per vehicle fell, which has safety implications as it may reduce the number of risky passes drivers take on traditional two-lane highways close to 2+1 roads.

- Sweden has constructed over 1,500 miles of 2+1 roads with barriers over the past 20 years (Ekman 2014, Kononov et al. 2020). These roadways have ADTs between 4,000 and 20,000 vehicles per day. The country saw a 55 percent reduction in fatal and injury accidents with the implementation of 2+1 roadways.

2+1 designs that integrate barriers reduce severe crashes, fixed object collisions, and other types of roadway departures (Kononov et al. 2020). For example, Sweden's 2+1 *Collision Free Roads* design blends a median barrier with a flush divider between 4.1 and 6.6 feet wide (Potts 2003). Fatalities on roadways using this design dropped by 79 percent compared to two-lane roads of similar width (Carlsson 2009). Fatal crash rates were the same as on four-lane divided freeways with median barriers. Motorcyclists benefit the most from this roadway design since they represent a higher proportion of fatal and injury crashes on all roadway types.

Sweden typically uses cable barriers whereas Germany and Finland typically use only pavement markings to separate two directions of travel. Sweden's before-and-after studies found these designs lowered fatal crashes by 75 percent and injury crashes by 50 percent (Kononov et al. 2020). 2+1 roadways with a median barrier reduced fatal and injury crashes by 55-60 percent, while the reduction was 35–40 percent on roads without barriers (Romana et al. 2018). When Poland added short segments of 2+1 roads crashes decreased by 47 percent (Cafiso 2017). Finland began placing a flush median with barriers on newly constructed 2+1 roadways to reduce head-on collisions.

In the US and Germany cable barriers have not been used often on 2+1 roadways due to concerns over their performance in transition areas and around lane drops. Although median barriers have prevented many potentially serious crashes in Sweden, median barrier crashes remain frequent and the number of property-damage-only accidents has increased (Potts 2003). Painted medians are preferred over cable barriers because of safety concerns (e.g., to motorcyclists). AASHTO policy recommends using a flush separation of 4 feet between lanes with opposing directions of travel (Potts 2003). Texas researchers analyzed crash data on 2+1 corridors (without barrier) and found a 35 percent reduction in crashes on 2+1 segments compared to the expected number of crashes on segments without passing lanes (Brewer et al. 2011). Table 2.1 summarizes the safety performance of 2+1 designs.

Table 2.1 Comparison of 2+1 Safety Performance (Crash Reduction Compared to Two-Lane Highways)

Country	Median Barriers	% Reduction in Fatal	% Reduction in Fatal + Injury	% Reduction in All Types
Sweden[1]	Yes	76-82	55-60	--
Sweden[1]	No	35-40	35-40	--
Sweden[2]	Yes	80-90	--	--
Finland [3]	Yes	46	25	--
Germany[3]	No	--	36	28
Denmark[4]	No	50	--	--
Denmark[4]	No	0	76	--
United States[5]	No	--	27	44

Source: Ramona et al. (2018)
[1] Carlsson (2009)
[2] Str¨omgren and Bergh (2016)
[3] Potts (2003)
[4] Greibe (2016)
[5] Schumaker et al. (2017)

Operational Efficiency
2+1 designs tend to operate more efficiently than other roadway configurations. Gattis et al.'s (2006) study of roads with alternating passing sections in Arkansas found these sections decreased vehicle platooning by 14 percent. Despite annual average daily traffic (AADT) being three times higher than on rural two-lane undivided highways, crash rates at 16 locations were lower than the statewide average. Potts (2003) demonstrated that 2+1 roadways in rural Missouri operated at least two levels of service (LOS) higher than traditional two-lane roadways serving the same traffic volume and reduced crash rates 29 percent.

Following the introduction of 2+1 roads in Hokkaido (a prefecture in Japan), their performance was evaluated based on (1) average travel speed and (2) follower density, expressed as the number of following vehicles in a traffic flow in each direction over a unit length of 1 km or more. Adding a passing lane increased average travel speeds from 52 kph (32 mph) to 57-60 kph (35-38 mph). Traffic density dropped from 8 vehicles/km to 4-7 vehicles/km.

In Texas researchers found that 2+1 designs generally improve operations on two-lane rural highways, however, higher traffic volumes limit the downstream effects of passing lanes. In contravention of state law not all vehicles used the left lanes for passing (Brewer et al. 2011). Up to 92 percent of vehicles in the left lane began passing near the beginning of the two-lane section. Non-compliance with using the left lane for passing was more prevalent at the end of two-lane sections. Large trucks tended to stay right to let faster vehicles pass (right lane compliance rate = 74 percent). Although trucks used the right lane at a lower rate later in the passing section than at the entrance to the two-lane section (Brewer et al. 2011).

How 2+1 designs affect traffic capacity is an unresolved question, although single-lane sections usually govern capacity. The main impacts of 2+1 highways on traffic performance stem from vehicles passing in the passing lane. At low to medium traffic volumes the availability of a passing lane increases passing maneuvers, reduces the percentage of following vehicles, and increases average speeds. At traffic volumes close to capacity, vehicles in the passing lane encounter short gaps in the main lane when merging, which can result in merge areas functioning as bottlenecks that reduce capacity and overall traffic efficiency (Romana et al. 2018).

Cost Criteria
Compared to interstates and freeways, 2+1 highways tend to cost less and have fewer environmental impacts. Work in Canada and Germany in the late-1990s demonstrated 2+1 designs are cost-effective solutions where a four-lane expansion cannot be justified by traffic flow, cost, or environmental issues (Romana et al. 2018). Cross-section width is also an important cost consideration as it tends to be wider on newer construction. Internationally, cross-section widths on 2+1 roadways vary; road designs with cable barriers are typically wider than roads with painted medians (Romana et al. 2018).

2.4 Implementation Examples and Model Simulations
Simulation studies of 2+1 roadways have found that ADT impacts operating characteristics, particularly amount of time following, and that adding passing lanes on two-lane roads reduces delays and time following (Brewer et al. 2011). When considering a long corridor, adding more passing-lane sections results in incremental improvements. For example, the increase in benefits from having six passing lanes instead of three is less pronounced than having three passing lanes rather than zero. While going from three to six lanes produces additional benefits, they are less effective than the first three. Lengthening passing lanes is more likely to improve operations than adding several short passing lanes. An ideal passing lane is 1 – 2 miles long.

Colorado proposed piloting modified 2+1 roadways that incorporate barriers in 12 locations (1) where the predicted benefit/cost (B/C) ratio was 3:1 or greater, (2) that had at least 1 injury crash per mile, and (3) that qualified for federal Highway Safety Improvement Program funds. The state developed a model based on five years of crash history on rural two-lane undivided highways. B/C sensitivity analysis assumed a crash reduction factor (CRF) of 50 percent for injury crashes, construction costs of $500,000 per mile, and maintenance costs of $100,000 per mile. Reports were generated for two-lane roads with AADT between 3,000 and 8,000 and for roads above 8,000 AADT. Analysis concluded that over 90 percent of fatal crashes on roadways with AADT over 8,000 could be prevented by employing the 2+1 with barrier design (Kononov et al. 2000).

2.5 Challenges and Feasibility of Use

Agencies must consider the volume and impact of heavy vehicle traffic when deciding if a 2+1 design is appropriate. Heavy vehicles slow the average travel speed and increase the number of passes. If a route is a freight corridor, the cross section design is impacted — along with other design characteristics — which can limit the 2 +1 design operation. Some disadvantages of the 2+1 roadway design include (Romana et al. 2018):

- Reduced capacity due to the merging operation when traffic volumes are high
- Potential safety concerns at traffic volumes close to capacity
- Fewer opportunities to pass slow vehicles in single-lane sections
- Higher speeds in passing lanes lead to more incidents with vehicles and roadside objects or loss of control in slippery conditions
- Complex transition from one to two carriageways, which requires significant land occupation and work zones stage by stage
- Potentially requiring a separate network for farm vehicles and cyclists
- Higher cost and land occupation required for split level junctions

Romana et al. proposed a three-tied classification of 2+1 highways to aid decision making (Table 2.2).

Table 2.2 Classification of 2+1 Highways

Class	Motorist Speed Expectations	Configuration
I	• High (100 km/h)	• 3 lanes • No left turns
II	• Not high	• 2+1 sections alternate with 1 + 1 sections • Some intersections with left turns
III	• Not high	• 3 narrow lanes

Another challenge faced when planning 2+1 corridors is right-of-way acquisition. Where access points to private or commercial properties are located can potentially offset the safety benefits of 2+1 designs. Texas DOT recommends considering structures and right of way along the entire corridor and installing passing lanes in locations that require minimal earthwork, widening, and right-of-way acquisition (Brewer et al. 2011).

When evaluating the feasibility of constructing 2+1 roadways, agencies should consider several factors:

- Estimated AADT
- Spacing and length of passing lanes
- Percentage of heavy vehicles
- Crash data
- B/C analysis that includes construction and maintenance expenses

Better performance measures are needed for all rural highways, particularly for evaluating the safety and efficiency of 2+1 designs. *The German Highway Capacity Manual* (Strassen et al. 2015) contains the only available method for evaluating quality of traffic flow. Additional microsimulation research could benefit decision making related to 2+1 designs. But to have utility simulations must account for a broad range of traffic demands and accurately characterize driving behaviors such as car following, lane changing, passing maneuvers, merging, or speeding (Romana et al. 2018). This study proposes a formalized methodology transportation agencies can use for selecting and implementing 2+1 roadway designs.

2.6 Introduction to Signing and Markings

Signs and pavement markings are used to communicate critical information to motorists about highway operations. While the Manual on Uniform Traffic Control Devices (MUTCD) establishes the minimum traffic control needed along highways, 2+1 roadways may warrant an expanded set of traffic control devices. With an eye toward developing recommended signing and marking details for 2+1 roadways, the research team reviewed material focused on the signing and marking of 2+1 roadways, passing lanes, and lane reductions, including:

- Previous research
- KYTC policies and standards
- Guidance from other states
- MUTCD — 2009 edition with Revisions 1 and 2.
- Notice of Proposed Amendments (NPA) to the MUTCD, dated December 14, 2020 — The review of NPA content is provided for informational purposes only as there is no guarantee that proposed language will be included in the next edition of the MUTCD.

A survey was sent to the AASHTO Committee on Traffic Engineering (CTE) to identify states with experience in 2+1 roadways. Appendix # includes the email and a summary of the responses. Of the 14 states that responded, only Texas and Missouri use the 2+1 concept. Signing and marking policies from other states were examined, with emphasis on passing lanes and lane reductions as both are critical components of 2+1 roadways. The analysis included any agency with passing lane policies — the states adjacent to Kentucky as well as states mentioned in the literature review. Some research included information on the signing and marking policies in other countries; this information is included in this discussion for informational purposes. Signing and marking schematics from the states and other countries is provided in Appendix #.

2.7 Signing

Signing associated with passing lanes is traditionally provided in five areas along the passing lane section (Figure 2.2):

- Approach to Passing Lane
- Lane Addition Taper and Passing Lane
- Approach to Lane Reduction
- Downstream Area
- Upstream and Opposing Area

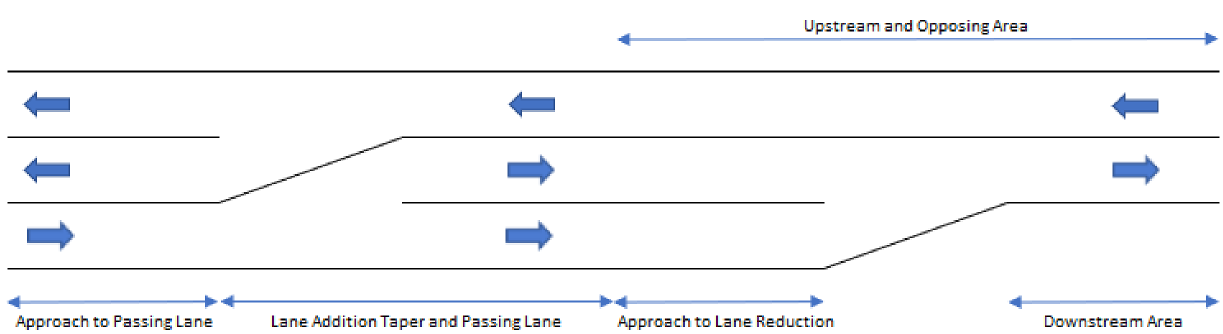


Figure 2.2 Location of Signs in Passing Area

2.7.1 Approach to Passing Lane

Harwood et al. (1988) recommended that:

- A PASSING LANE 1/2 MILE sign should be placed ½ mile in advance of each passing lane. This sign provides advance notice of the passing lane to drivers of slow-moving vehicles and following vehicles so they can prepare to make effective use of the passing lane.
- Additional advance signs are ideally placed 2 – 5 miles in advance of a passing lane. Such advance signing may reduce the frustration and impatience of drivers following a slow-moving vehicle because they will soon have an opportunity to pass.

TTI (2001) found that:

- 61 percent of respondents would wait until the passing lane to pass a slower moving vehicle if a PASSING LANE 2 MILES sign were installed. Respondents indicated that this type of sign would help them decide whether to initiate a passing maneuver.
- The percentage of drivers willing to wait for a passing lane when following a slower vehicle was as follows:

Length to passing lane (miles)	Percentage of Respondents
2	55%
3	19%
4	7%
5	4%
≥6	15%

- Advance signing designed to give the optimum amount of information to users improves the operational efficiency of passing lanes.
- White-on-green PASSING LANE 2 MILES and NEXT PASSING LANE X MILES signs should be installed for advance notification of the passing lane. The latter sign should only be installed if the distance to the next passing lane is 12 miles or less.
- Notification that the passing lane is upcoming is an element that forms the basis for the defining characteristics of a passing lane so that drivers are more willing to delay passing until they reach the passing lane.

K-TRAN (1999) found:

- Drivers being delayed in platoons for a considerable time due to their inability to pass may become frustrated and perform risky passing maneuvers in front of opposing traffic. Informing drivers of an upcoming passing lane may reduce such incidents. Signs informing motorists of the distance to the beginning of a passing lane serve this purpose.
- The best policy is to locate signs where they constantly remind motorists of a passing lane ahead, which can possibly reduce high-risk passing behavior.
- There should be at least two advance signs on the approach to passing lanes — one at 2 miles and one at ½ mile.

Potts and Harwood (2004) found:

- Advance signing for passing lanes is desirable approximately ½ mi upstream of each passing lane.
- An advance sign approximately 2 miles upstream of each passing lane is also desirable.

Other Countries

Kirby, Wilmshurst, and Koorey (2014) reference New Zealand signing standards which include:

- PASSING LANE 400 m (GI-6) sign in advance of the KEEP LEFT UNLESS PASSING SIGN, which is near the lane addition taper.
- In rural areas, PASSING LANE X km AHEAD (IG.6.1) signs are used in advance of GI—6 signs.

Potts and Harwood (2003) reported that Finland installs signs 0.6 mile in advance of the passing lane. White-on-blue rectangular signs are used with two upward arrows in the direction of travel and one-downward arrow in the opposing direction.

2009 MUTCD
Section 2D.51 states that a NEXT PASSING LANE XX MILES and/or PASSING LANE XX MILES sign should be installed in advance of a passing lane.

MUTCD NPA
Section 2D.53 of the NPA states that a PASSING LANE ½ MILE sign should be installed in advance of a passing lane and that a NEXT PASSING LANE XX MILES sign should be installed after each passing lane segment in a series of passing lanes.

Review of State Policies and Standards
Various states were identified with guidance for placement of signs in the Approach to Passing Lane area. Guidance varies in terms of sign legend and placement. Table 2.3 summarizes relevant signing policies.

Table 2.3 State Polices for Approach to Passing Lane Area

State	# of advance signs to passing lane	Primary Legend	Sign Color	Distance from taper	Comments
Kentucky	1	PASSING LANE X MILE/FEET	White on Green	1/2 mile or 500'	n/a
Texas	1	PASSING LANE 2 MILES	White on Green	2 miles	May include NEXT PASSING LANE X MILES sign when applicable at end of previous passing lane.
Missouri	2	ALTERNATING PASSING LANES NEXT X MILES (symbol) NEXT PASSING LANE X MILES	White on Green Black on White	In advance of 1st in series At end of previous passing lane	Used if series continues within 10 miles
California	2	PASSING LANE 2 MILES PASSING LANE AHEAD	White on Green	2 Miles Not defined	n/a
Iowa	2	PASSING LANE 2 MILES NEXT PASSING LANE X MILES	White on Green	2 miles End of previous passing lane	
Minnesota	2	PASSING LANE X MILES AHEAD PASSING LANE 1/2 MILE AHEAD	Black on White	2-5 miles 1/2 mile	n/a
Nevada	3	PASSING LANE X MILES PASSING 1/2 MILE PASSING LANE AHEAD	White on Green	Varies 1/2 mile 300'	n/a
Washington	1	PASSING LANE X MILES	Black on White	1/2 to 1/4 mile	May include NEXT PASSING LANE X MILES sign
Wisconsin	2	PASSING LANE AHEAD X MILES PASSING LANE 1/2 MILE	White on Green	Not exceeding 3 miles 1/2 mile	n/a

Discussion
While some states use regulatory signs for the advance signing of passing lanes, most states use guide (white-on-green) signs. The MUTCD considers guide signs as the proper mechanism for advance notification of a passing lane.

The MUTCD suggests that at least one sign should be used in advance of passing lanes. All surveyed states use at least one advance sign, and most use at least two signs. The primary options for advance signing are (1) signing 2 miles in advance of the passing lane to discourage passing maneuvers prior to the passing lane and (2) signing closer to the passing maneuver (such as ½ mile) so motorists can prepare to use the passing lane. Available research supports signing at 2 miles and ½ miles in advance of the passing lane.

While research and guidance support installing two advance guide signs, transitions for passing lanes on KYTC's 2+1 corridors often occur at intersections, which complicates installation of advance signing at every passing lane. Two advance guide signs might be advisable for isolated passing lanes, but the use of two advance guide signs for every passing lane on a 2+1 corridor would result in significant sign clutter when passing lanes are closely spaced. NEXT PASSING LANE X MILES signs are less beneficial on a 2+1 corridor with a two-direction no-passing zone as motorists are unlikely to make illegal passing maneuvers until they are in a passing lane section.

It is desirable to have at least one advance sign prior to each passing lane. Various options were discussed with KYTC's Division of Traffic Operations. For the first passing lane in a series of passing lanes on a 2+1 corridor, the PASSING LANE ½ MILE sign is the preferred option as it best prepares drivers for the passing maneuver and encourages motorists to delay passing. While a sign at 2 miles might delay additional passing maneuvers, it was felt this distance was too far to sign along most 2+1 corridors without access control. Missouri uses a sign indicating ALTERNATING PASSING LANES NEXT X MILES with a symbol illustrating the typical section. This option was not selected as it (1) could potentially require a panel size sign to be legible, (2) includes an unapproved symbol that would require experimentation, (3) is not observable to motorists entering the 2+1 corridor downstream of the sign, (4) would require relocation as additional sections are open to travel, and (5) motorists are likely to quickly grasp that alternating passing lanes are provided along a corridor.

As for signing of interior passing lanes on a 2+1 corridor, Texas is the only state with a specific signing and marking detail, installing a 2 MILE sign as required with the NEXT PASSING LANE X MILES sign as optional when applicable. For Kentucky, the NEXT PASSING LANE X MILES sign is the preferred option for a single advance guide sign as it can be installed away from transitions and/or intersections. Current MUTCD language is somewhat vague as it says either this sign and/or PASSING LANE X MILES sign should be used. NPA language clarifies that the NEXT PASSING LANE X MILES sign should be used if a series of passing lanes is provided. However, the benefits of these signs would be lessened on a 2+1 corridor with closely spaced passing lanes and where passing is prohibited. In such situations, motorists are likely to quickly become aware of the alternating passing lanes. Thus, the optional use of NEXT PASSING LANE X MILES signs on the approach to interior passing lanes of 2+1 roadways could be supported.

2.7.2 Lane Addition Taper and Passing Lane

TTI (2001) found that:

- Drivers should be notified about the purpose of the additional lane so they move to the right lane unless they are passing a vehicle.
- Three similar/commonly used messages were evaluated:
  - KEEP RIGHT EXCEPT TO PASS
  - SLOWER TRAFFIC KEEP RIGHT
  - LEFT LANE FOR PASSING ONLY
- When asked which message gave the strongest meaning, 71% of survey respondents felt that LEFT LANE FOR PASSING ONLY message carried a stronger meaning.
- SLOWER TRAFFIC KEEP RIGHT had a greatly reduced level of understanding — 40% of respondents associated the SLOWER TRAFFIC KEEP RIGHT sign with vehicle speeds.
- TTI recommended use of a black-on-white sign just after the lane addition taper with the legend LEFT LANE FOR PASSING ONLY.

K-TRAN (1999) found:

- There is no clear-cut agreement among highway and traffic engineers as to whether SLOWER TRAFFIC KEEP RIGHT (R4-3) or KEEP RIGHT EXCEPT TO PASS (R4-16) signs are better.
- Those who favor the latter sign argue that operational experience and driver surveys have shown that KEEP RIGHT EXCEPT TO PASS is more effective since it encourages greater use of an outer lane (increasing the number of passes) and that drivers favor it because it is less ambiguous.
- Those who view the SLOW TRAFFIC KEEP RIGHT as an acceptable alternative agree it provides less definitive instructions.
- The percentage of vehicles using the right lane and the keep-right compliance rate was higher at existing locations using SLOWER TRAFFIC KEEP RIGHT signs.

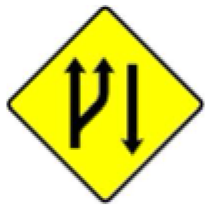
Potts and Harwood (2004) found:

- The KEEP RIGHT EXCEPT TO PASS sign informs drivers of the beginning of the passing lane and encourages them to enter the right lane unless they are immediately behind a vehicle they wish to pass.
- A SLOWER TRAFFIC KEEP RIGHT sign provides similar information to motorists but is not preferred because it provides less definitive instructions.
- Highway agencies are equally split in the use of KEEP RIGHT EXCEPT TO PASS and SLOWER TRAFFIC KEEP RIGHT signs.
- Some agencies place signs upstream of intersections within passing lane sections to warn motorists of possible left-turning vehicles.

Other Countries
Kirby, Wilmshurst, and Koorey (2014) reference New Zealand signing standards, which include a KEEP LEFT UNLESS PASSING (RG-22) sign 20 meters beyond where pavement widening begins. Signs may also be erected at approximately 400 m intervals along a passing lane.

Ireland's *Department of Traffic Signs Manual* (2019) lists the following signs as advising motorists of the addition of the passing lane:

- Symbol sign (W-103) indicates the addition of the passing lane. Signs should be installed on both sides of the roadway at the beginning of the lane addition taper.



- Symbol sign (W-083) should be installed at intervals along both sides of the passing lane.

Ireland, W-083

Potts and Harwood (2003) catalogued the following signing practices from other countries:

- Germany — A rectangular symbol sign (showing the two arrows in direction of travel and one arrow for opposing traffic) is installed at the beginning of the passing lane. A distance measurement at the bottom of the sign indicates passing lane length.
- Finland — A rectangular symbol sign (showing the two arrows in direction of travel and one arrow for opposing traffic) is installed at the beginning of the passing lane. A distance measurement at the bottom of the sign indicates passing lane length.
- Sweden — Signs are sometimes placed at the beginning of the lane addition on both sides of the road to inform motorists a passing lane is about to begin and to indicate the length of the passing lane. The standard sign is white-on-black with two upward pointing arrows and a distance at the bottom of the sign.

2009 MUTCD
Section 2B.31 states that if an extra lane is provided for slow-moving traffic, a SLOWER TRAFFIC KEEP RIGHT, TRUCKS USE RIGHT LANE, or other appropriate sign should be installed at the beginning of the lane.

MUTCD NPA
- No significant changes to the SLOWER TRAFFIC KEEP RIGHT language from the 2009 MUTCD.
- Incorporates a new TWO-WAY TRAFFIC ON A THREE-LANE ROADWAY SYMBOL sign that may be used on three-lane roadways. When placed along the passing lane, the sign would have the following layout:

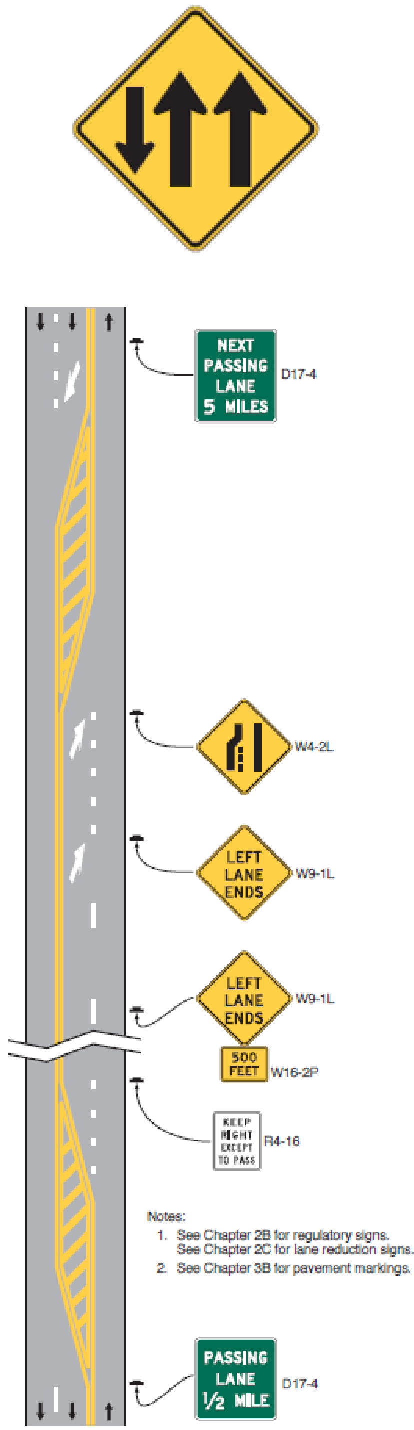


Figure 2.3 Signing for an Intermittent Passing Lane

Review of State Policies and Standards

Some states have guidance for placing signs at or in advance of the beginning of the passing lane. Guidance varies in terms of sign legend and placement. A summary of the relevant signing policies for the identified states are shown in Table 2.4.

Table 2.4 State Polices for Signs in Lane Addition Taper and Passing Lane Area

State	Advance Sign	Color	Location
Kentucky	SLOWER TRAFFIC KEEP RIGHT (R4-3)	Black on White	Beginning of lane addition taper
Texas	SLOWER TRAFFIC KEEP RIGHT (R4-3)	Black on White	Beginning of added lane
Missouri[1]	Symbol sign with 3 arrows and plaques[2]	Black on Yellow	Beginning of added lane
California	SLOWER TRAFFIC KEEP RIGHT (R4-3)	Black on White	Beginning of lane addition taper
Iowa	SLOWER TRAFFIC KEEP RIGHT (R4-3)	Black on White	Beginning of added lane
Minnesota	SLOWER TRAFFIC KEEP RIGHT (R4-3)	Black on White	Beginning of added lane
Nevada	KEEP RIGHT EXCEPT TO PASS (R4-16)	Black on White	In advance of beginning of added lane (distance of 1/4 taper length)
Washington	KEEP RIGHT EXCEPT TO PASS (R4-16)	Black on White	Beginning of lane addition taper
Wisconsin	SLOWER TRAFFIC KEEP RIGHT (R4-3)	Black on White	Beginning of lane addition taper
Montana	SLOWER TRAFFIC KEEP RIGHT (R4-3)	Black on White	Beginning of lane addition taper

[1] Includes optional use of WATCH FOR LEFT-TURNING TRAFFIC IN PASSING LANE sign in sections with no median. Mounted downstream of symbol sign with arrows.

[2] Two upward arrows in direction of passing lane and one arrrow for opposing direction. Supplemental plaques are: PASSING LANE (top) and NEXT X MILES (bottom).

Discussion

Most states surveyed use the SLOWER TRAFFIC KEEP RIGHT sign. However, KEEP RIGHT EXCEPT TO PASS signs are better understood by drivers for passing lane situations.

KYTC's standards for truck-climbing lanes stipulate that the SLOWER TRAFFIC KEEP RIGHT sign be used. The functionality of climbing lanes is different than passing lanes, so different regulatory signs may be warranted for the two types of auxiliary lanes. The statute related to such signing is KRS 189.340(7) which states:

> (7) Whenever any roadway has been divided into three (3) clearly marked lanes for travel, the following additional rules shall apply:
>
> (a) A vehicle shall be driven as nearly as may be practical entirely within a single lane and shall not be moved from that lane until the driver has first ascertained that the movement can be made with safety;
> (b) A vehicle shall not be driven in the center lane except when overtaking and passing another vehicle where the roadway is clearly visible and the center lane is clear of traffic within a safe distance, or in preparation for a left turn or where a center lane is at the time allocated exclusively to traffic moving in the direction in which the vehicle is proceeding and is signposted to give notice of the allocation; and
> (c) Official signs may be erected directing slow-moving traffic to use a designated lane or allocating specified lanes to traffic moving in the same direction and operators of vehicles shall obey the directions of such signs.

Subsection 7(b) seems to support the installation of KEEP RIGHT EXCEPT TO PASS signs, while subsection 7(c) could be used to support SLOWER TRAFFIC KEEP RIGHT signs. Options were discussed with KYTC's Division of Traffic Operations. Based on the available information, it was felt that KEEP RIGHT EXCEPT TO PASS is the preferred message and better reflects the intent of a passing lane.

Among other states the preferred location of the regulatory sign is nearly equally split, with five states placing the sign at or near the beginning of the lane taper and four states placing the sign at or near the beginning of the added lane. The MUTCD states that the sign should be installed after the additional lane has been added. Placement at the beginning of the taper was given consideration as this is where the regulatory sign is located for KYTC's climbing lane detail. This option was eliminated once the preferred pavement marking arrangement (a striped flush median) was selected for the beginning of a passing lane. The striped median makes placement of the KEEP RIGHT EXCEPT TO PASS sign at the taper confusing as it might encourage drivers to drive to the left and/or through the median. For this reason, it was decided the sign should be placed after the lane has been added. The sign should be placed 200 feet beyond the end of the lane addition taper to facilitate observation of the sign upon completion of the diverge maneuver. This placement also facilitates future installation of the TWO-WAY TRAFFIC ON A THREE-LANE ROADWAY SYMBOL sign should it be included in the next edition of the MUTCD.

Missouri's guidance includes a sign similar to the symbol sign in the MUTCD NPA with a PASSING LANE header plaque and NEXT X MILES supplemental plaque below the symbol sign. This sign was not considered for use at KYTC due to the non-standard symbol, which would require experimentation from FHWA. If this signing is needed in the future, the symbol sign in the NPA is a better option should it be included in the next edition of the MUTCD.

Missouri's guidance also includes the optional use of WATCH FOR LEFT-TURNING VEHICLES IN PASSING LANE signs in 2+1 sections when there is no guard cable in the median. However, no other states use this signing, and Kentucky does not use similar signing on other multi-lane undivided roadways. This signing is not recommended for inclusion in KYTC's standards but could be considered at locations with a history of rear-end collisions involving left-turn movements from the passing lane.

Additional guidance might be advisable for signing climbing lanes as various signing has been observed in the field. Upon further review and discussion with KYTC, it was determined that SLOWER TRAFFIC KEEP RIGHT is the preferred message for climbing lanes on two-lane roads and TRUCKS USE RIGHT LANE signs is preferred on multi-lane highways. For two-lane highways, the sign should be placed at the beginning of the lane addition taper (as shown in the current climbing detail) to emphasize that slower traffic should keep right. For multi-lane highways, the sign be placed 200 feet beyond the end of the lane addition taper to make it clear trucks should use the added lane.

2.7.3 Approach to Lane Reduction

Harwood et al. (1988) found that many highway agencies use two warning signs in advance of lane-drop transition areas of passing lanes, and this practice is recommended.

TTI (2001) found:

- Some agencies use one sign in advance of the passing lane termination while others use two. The sign in advance typically provides a distance to the termination of the passing lane, while the additional sign is placed at the point of termination or corresponding beginning of merge taper.
- Standard RIGHT LANE ENDS and LANE ENDS MERGE LEFT signs should be used to indicate the end of the additional lane.

K-TRAN (1999) found:

- The most critical element of a passing lane is the lane-drop where two lanes in one direction converge into one lane.
- The lane drop is critical from both an operational and safety standpoint.
- The lane drop can produce a race track phenomena where merging slower vehicles increase their speeds to merge with faster passing vehicles, while passing vehicles increase their speeds to avoid ending up behind the slower vehicle after the passing lane section.
- Recommended one advance sign at a distance of "d".

Marchese and Gonzales (2019) explored driver behavior in lane drop scenarios when exposed to different combinations of warning signs and lane line transition markings. They developed a survey that evaluated combinations of four warning signs, two advance warning signs and two lane-line transition markings. They found:

- The W4-2 (symbol) sign elicited the fastest response times while the LANE ENDS MERGE LEFT sign had the slowest response time. There was no significant difference in trials that also had an advance warning sign.
- Adding an advance warning sign resulted in earlier recognition of lane termination.
- Symbol-based warning signs may encourage earlier recognition and execution of lane changes.

Potts and Harwood (2004) recommended that the signing in advance of the lane drop of each passing lane should include a lane reduction symbol transition sign (W4-2) approximately 1,000 feet upstream of the lane drop taper and a text sign — RIGHT LANE ENDS (W9-1) or LANE ENDS MERGE LEFT (W9-2) — approximately 500 feet upstream of the lane drop taper. But sequence is not compliant with the MUTCD.

Other Countries

Kirby et al. (2014) noted that New Zealand used the following signing for lane reductions:

- PW43.2 (similar to W4-2 sign with a supplemental distance plaque) — Located 25 m – 180 m in advance of a PW43.3 sign
- PW43.3 (similar to W4-2 symbol sign) — Located at the commencement of the merge taper
- Signs are dual-mounted

Ireland's *Department of Traffic Signs Manual* (2019) includes the following signage to advise motorists of the end of the passing lane:

- Three sets of dual-mounted symbol (W-091R) signs.
- The first set of signs is installed 400 m in advance of the lane reduction taper, the second set is installed 200 m in advance of the taper, and the last set is installed 20 m in advance of the taper.
- Advance signs include supplemental distance plaques.

Ireland, W-091R sign

Potts and Harwood (2003) catalogued the following signing practices from other countries:

- Germany — Advance warning symbol signs are mounted in advance of the lane reduction taper. Signs are placed on both sides of the roadway, 1,300 feet and 650 feet ahead of the lane drop.
- Finland — Two advance warning symbol signs (white-on-blue, incorporating a curved arrow for the lane merging) are mounted in advance of the lane reduction taper. Signs are placed on both sides of the roadway 1,300 feet and 160 feet ahead of the lane drop.
- Sweden — Advance warning signs are placed on both sides of the roadway 1,300 feet ahead of the lane drop and at the beginning of the taper. Signs include a modified arrow that shows an arrow merging into the through arrow. The bottom of the advance sign lists the distance to the taper.

2009 MUTCD

Relevant material from Section 2C.42 of the MUTCD:

- W9-2 (LANE ENDS MERGE LEFT[RIGHT]) or W4-2 (symbol) signs should be used to alert drivers to the reduction in the number of traffic lanes on a multi-lane highway. Since this is the only recommended sign, one can assume that this sign needs to be mounted a distance of "d" in accordance with Table 2C-4.
- A RIGHT (LEFT) LANE ENDS sign (W9-1) may be used in advance of the required W9-2/W4-2 sign.
- For Table 2C-4, the advance placement distance is based on posted or 85th percentile speed.

MUTCD NPA

Relevant material from Section 2C.47 of the NPA:

- The LANE ENDS MERGE LEFT (RIGHT) sign (W9-2) is no longer an option.
- A W4-2 (symbol) sign should be installed near the taper's start.
- A RIGHT (LEFT) LANE ENDS (W9-1) sign should be installed in advance of taper at distance "d."
- Supplemental W9-1 signs may be installed in advance of the W9-1 sign at the advanced placement distance.
- Supplemental W9-1 signs should include a supplemental distance plaque.
- Deleted guidance that required placement of LANE ENDS signs adjacent to lane reduction arrows.
- On one-way streets and multi-lane highways where the left lane ends and the median width permits, lane reduction signs should be mounted on the left-side of the road.

Review of State Policies and Standards

All surveyed states use warning signs to denote upcoming lane reductions. Guidance varies in terms of the number of signs used, signs used, order of signs, mounting (right side, left side, or dual mounting), and distance in advance of the lane taper. Table 2.5 summarizes state polices.

Table 2.5 State Polices for Approach to Lane Reduction Signing

State	Advance Sign	Distance in Advance of Warning Sign	Warning Sign	Distance in Advance of Taper	Dual-mounted?
Kentucky	LEFT (RIGHT) LANE ENDS (W9-1)	200'	Lane Ends (W4-2) symbol sign	d	Y
Texas	LEFT (RIGHT) LANE ENDS (W9-1)	300' to 500'	LANE ENDS MERGE LEFT (RIGHT) (W9-2)	d	N
Missouri	PASSING LANE ENDS[2]	d	LANE ENDS MERGE LEFT (RIGHT) (W9-2)[1]	d	Y
Iowa	LANE ENDS MERGE LEFT (RIGHT) (W9-2)	300'	Lane Ends (W4-2) symbol sign	750'	N
Minnesota	LEFT (RIGHT) LANE ENDS (W9-1)[1]	500' to 700'	W9-2 or W4-2	200'	N
Kansas	n/a	n/a	Lane Ends (W4-2) symbol sign	d	N
Arizona	LEFT (RIGHT) LANE ENDS (W9-1)[3]	1000' + 3/4d	Lane Ends (W4-2) symbol sign	d	N
Nevada	LANE ENDS MERGE LEFT (RIGHT) (W9-2)	d/2	Lane Ends (W4-2) symbol sign	d	N
Washington	LEFT (RIGHT) LANE ENDS (W9-1)[4]	n/a[4]	Lane Ends (W4-2) symbol sign[1]	d	N
Wisconsin	LEFT (RIGHT) LANE ENDS (W9-1)	d/2	Lane Ends (W4-2) symbol sign	d/2	W4-2 only
Montana	LEFT (RIGHT) LANE ENDS (W9-1)	200'	Lane Ends (W4-2) symbol sign	d	N
Tennessee	n/a	n/a	Lane Ends (W4-2) symbol sign	d	N
Oregon	LEFT (RIGHT) LANE ENDS (W9-1)[3]	Not defined	Lane Ends (W4-2) symbol sign	d[5]	N
California	LEFT (RIGHT) LANE ENDS (W9-1)	d[5]	Lane Ends (W4-2) symbol sign	d[5]	N
Michigan	LANE ENDS MERGE LEFT (RIGHT) (W9-2)	d	Lane Ends (W4-2) symbol sign	d	N

[1] Sign may be supplemented with distance plaque.
[2] Sign includes supplemental distance plaque.
[3] Sign is optional.
[4] Sign installed if spacing permits. Advance spacing not defined.
[5] Values are extremely close to MUTCD values, but slightly less.

Discussion

The MUTCD states that a LANE ENDS SYMBOL (W4-2) sign or a LANE ENDS MERGE LEFT (RIGHT) (W9-2) sign should be used in advance of a lane reduction and that a LEFT (RIGHT) LANE ENDS (W9-1) sign be used in advance of the recommended sign. While the MUTCD recommends a minimum of one advance sign, the use of two signs is supported by the following:

- Most states(10 of 14 states) are using two signs.
- Using a second advance warning sign in addition to the recommended warning sign results in earlier recognition of the lane termination.
- The MUTCD NPA language includes guidance statements to use both the W9-1 and W4-2 signs.
- KYTC has historically used two advance signs for similar lane reduction scenarios.

The most commonly used sign sequence (9 of 15 states) is the LEFT (RIGHT) LANE ENDS (W9-1) sign for the advance warning sign and the Lane Ends Symbol (W4-2) sign as the primary warning sign. Use of the W4-2 sign is supported by previous research which has found symbol signs perform better than word messages. Based on language in the MUTCD NPA, the W9-2 sign might be eliminated in the next edition of the MUTCD. As such, it is advisable to use this sign sequence.

In terms of spacing for the lane reduction warning sign, a primary concern of KYTC staff is that using *d* from Table 2C-4 of the MUTCD results in broken lane lines being discontinued for too long a distance —
at a distance of ¾ d in advance of the lane taper (see Figure 3B-14 in the MUTCD). At 55 MPH, *d* has a value of 990 feet, leaving approximately 750 feet of full-width pavement with no lane line marking separating the two-lanes of traffic approaching the merge condition.

Staff from KYTC and KTC discussed using smaller values of *d* given that Condition A of Table 2C-4 in the MUTCD is intended for typical conditions where the road user must adjust to speed and change lanes in heavy traffic. Since most 2+1 sections are in rural settings, it was thought Table 3-3 in the AASHTO *Green Book* could be used to establish shorter advance placement distances for signing. Avoidance Maneuver C values are intended for speed/path direction changes on rural roads and are much shorter than values for Condition A in Table 2C-4 of the MUTCD. When the posted speed limit or 85th percentile speed is 55 MPH, this method reduces the advance placement distance from 990 feet (condition A in the MUTCD) to 685 feet (Condition C from Table 3-3 of the *Green Book* minus 180 feet sign legibility).

At the time, it was noted that an explanation could not be provided as to why the value for Condition A was 990 feet instead of 955 feet (1135 feet. from Condition E of Table 3-3 minus 180 feet sign legibility). The National Committee on Uniform Traffic Control Devices (NCUTCD) has noted minor discrepancies in a few of the values in Table 2C-4 and has recommended changes to FHWA. The discrepancies are based on whether a value of 14 seconds or 14.5 seconds was used for perception-reaction time. The NCUTCD recommends that 14 seconds be used for all calculations and that values be rounded to the nearest 25 feet interval. If FHWA approves these modifications, values in Table 2C-4 in the MUTCD will be consistent with values in Column E of Table 3-3 of the *Green Book*.

While the above argument is sound from an engineering perspective, Table 2C-4 is considered by most practitioners to be the minimum standard for advance placement of warning signs. KYTC staff has used these values for decades, and the survey of states found that 12 of 15 states use values of *d* (or values extremely close to *d*) from Table 2C-4. If KYTC wanted to establish different values for *d*, it will require the development of new policies, Standard Drawings, and/or specifications and a significant effort to inform practitioners. Such guidance would likely result in a lack of uniformity with the practices of other states and with local agencies in Kentucky. The standardization of traffic control provides operational and safety benefits, and it is inadvisable to modify advance sign placement to address a pavement marking concern. Other options are available that would more effectively address the pavement marking concern on the approach to the lane reduction taper. Although the values from Condition A of Table 2C-4 are calculated for maneuvers in urban conditions, they are commonly used as the standard for all conditions and would only provide additional advance warning of the lane reduction condition in a rural setting. For these reasons, continued use of the *d* values from Condition A of Table 2C-4 of the MUTCD is the most appropriate approach for advance placement of the primary warning (W4-2) sign.

KYTC currently recommends an advance placement distance of 200 feet for the advance warning sign (optional warning sign in the MUTCD) in a lane reduction scenario. This distance is slightly lower but within a reasonable range of the values used by other states. With the likely changes to lane reduction signing in the next edition of the MUTCD, no change is recommended for this sign placement. Should the proposed language for lane reduction signing in the MUTCD NPA ultimately be approved by FHWA, the W9-2 sign would be placed at the current location of the W4-2 sign and the W4-2 sign would be located closer to the lane reduction taper.

KYTC has traditionally used dual-mounted lane reduction signing in climbing lane scenarios on two-lane roadways. Most states only mount lane reduction signs on the right side of roads with passing lane sections. However, Missouri recommends dual-mounting of both warning signs, and Wisconsin dual-mounts the last sign (W4-2) in the sign sequence. The MUTCD NPA indicates that lane reduction signs should be placed on the left side of the road on one-way road and multi-lane highways if the median width permits when the left-turn lane is the lane merging into the right-lane. 2+1 scenarios would not necessarily fall into those categories but might benefit from dual-mounting when the left-lane is the lane that merges, which would be typical for symmetrical designs. For these reasons, there is no reason to change KYTC's current practice of dual-mounting lane reduction signs on 2+1 facilities and climbing lane sections.

Since lane drop situations could be encountered often on highway projects without signing and/or marking plans, KYTC may want to consider developing Standard Drawings that address the signing and marking of left- and right-lane merges on one-way, two-lane, and multi-lane highways.

2.7.4 Downstream Area

Literature Review

Potts and Harwood (2004) noted that several states use the TWO-WAY TRAFFIC SIGN (W6-3) downstream of the lane drop transition to remind motorists they have returned to a conventional two-lane highway.

2009 MUTCD
Section 2C.44 states that a TWO-WAY TRAFFIC SIGN (W6-3) should be used to warn road users of a transition from a multi-lane divided section of roadway to a two-lane, two-way section of roadway. Some 2+1 designs could fall under this criteria.

W6-3

MUTCD NPA
No significant changes.

Review of State Policies and Standards
Texas and Missouri are the only states that had significant experience with 2+1 roadways. As a result, they were the only states with guidance for signing in the downstream area of a 2+1 corridor. Iowa and Washington have guidance on signing in the downstream area for isolated passing lane scenarios. Relevant policies include:

- Texas — NEXT PASSING LANE X MILES signs may be installed when applicable at the end of the three-lane section. No guidance given on what *when applicable* means.
- Missouri — Use an END PASSING LANES (black-on-white) sign at the last passing lane in series or if the next passing lane is more than 10 miles away. Install a NEXT PASSING LANE X MILES sign at last passing lane in series if the next passing lane is less than 10 miles away.
- Iowa — NEXT PASSING LANE X MILES sign
- Washington — NEXT PASSING LANE X MILES sign

Discussion
Signing of the downstream area does not appear to be as critical an issue as the areas that have been previously discussed. Options were discussed with KYTC's Division of Traffic Operations. The TWO-WAY TRAFFIC (W6-3) sign and Missouri's END PASSING LANES sign, which would acknowledge the change from a 2+1 typical section to a two-lane two-way highway, were not deemed critical as the change in the typical section and associated passing opportunities should be clear based on the markings along the two-lane two-way section. However, support was given for Texas's practice of optional use of a NEXT PASSING LANE X MILES sign at the end of the 2+1 section.

Using the TWO-WAY TRAFFIC SIGN (W6-3) in the downstream area was discussed with KYTC. It was not supported as no other states are using this sign in their guidance, and pavement markings should make it clear when motorists are on a two-lane two-way roadway.

2.7.5 Upstream and Opposing Area
TTI (2001) found that vehicles flowing in the opposite direction of the passing lane must be provided information on whether they may cross into the lane to their left (i.e., the oncoming passing lane) using a combination of both signs and pavement markings.

K-TRAN (1999) found that signing and marking for traffic approaching from the opposite direction has to reflect the passing restriction or permission. Where passing is allowed, signing must clearly show the priority of the opposing, passing lane for traffic in the passing lane direction.

Potts and Harwood (2004) found that agencies that generally provide signing for passing and no-passing zones continue this practice in the opposing direction of travel at passing lane sites using standard passing and no-passing signing and markings. Where passing by vehicles traveling in the opposing direction is permitted, some agencies use a regulatory sign appropriate to passing lanes (e.g., YIELD CENTER LANE TO OPPOSING TRAFFIC).

Harwood and St. John (1984) found no difference in cross-centerline crash rates between passing lane sections where passing in the opposing direction was prohibited and passing lane sections where passing in the opposing direction was permitted if adequate sight distance was available.

Other Countries
According to K-TRAN (1999):

- Ontario, Canada, uses PASS ONLY WHEN CENTERLANE IS CLEAR sign where passing is permitted. The sign is installed where the three lanes are fully developed.
- British Columbia, Canada, uses either a YIELD CENTER LANE TO OPPOSING TRAFFIC or DO NOT PASS sign depending upon whether passing in the opposing direction is permitted or restricted.
- Alberta, Canada, uses a DO NOT PASS WHEN TRAFFIC ONCOMING sign spaced at approximately 500 m when passing is allowed in the opposing lane.
- Australia uses a symbol sign with 3 arrows to indicate proper lane assignment. The sign is located at the beginning of the transition from two to three lanes.

2009 MUTCD
Section 2B.28 allows optional use of the DO NOT PASS (R4-1) sign to supplement no-passing markings.
Section 2B.29 states that the PASS WITH CARE sign should be installed at the downstream end of a no-passing zone if a DO NOT PASS sign has been installed at the upstream end of the zone. Section 2C.45 addresses the optional use of the NO PASSING ZONE (W14-3) sign.

MUTCD NPA
- Incorporates a new Two-Way Traffic on a Three-Lane Roadway symbol sign that may be used on three-lane roadways. When installed along the opposing lane, the sign has the following layout:

Review of State Policies and Standards
Kentucky used to have signing guidance to address passing zones for the opposing single-lane approach in truck-climbing lane sections. Missouri, Wisconsin, and Montana are the only states with guidance for installing signs on Upstream and Opposing Area of passing lane sections.

- Kentucky — Previously used a PASS ONLY WHEN CENTER LANE IS CLEAR sign on the Climbing Lane detail (Exhibit 5 of the TOGM), but the sign was removed in a recent TOGM update.
- Missouri — A ALTERNATING PASSING LANES NEXT XX MILES (graphic, white on green) sign is installed in advance of the first passing lane within the series.
- Wisconsin — On the upstream area approach, a DO NOT PASS WHEN ONCOMING TRAFFIC IN EITHER LANE warning sign is installed when the centerline is marked as passing. It is located where the opposing passing lane reduction taper ends. The sign repeats every mile until passing condition changes. On the upstream area

approach, an ONCOMING TRAFFIC USES CENTER LANE warning sign is installed when the centerline is marked as no-passing. It is located where the opposing passing lane reduction taper ends. The sign is repeated every mile if the passing condition does not change.
- Montana — A DO NOT PASS sign is installed to coincide with a 500 feet no passing zone.

Discussion
Much of the available information regards signing for passing zones that allow passing maneuvers from the single-lane opposing approach. As a no-passing zone is recommended on KYTC's 2+1 corridors, the only signing that is recommended is a NO PASSING ZONE (W14-3) sign 500 feet from the beginning of the 2+1 roadway. This sign would be installed in conjunction with no passing zone markings.

The Upstream and Opposing Area includes the opposing approach to the 2+1 corridor. A PASSING LANE ½ MILE sign is recommended for this approach to identify the existence and location of the first passing lane in a 2+1 corridor. If the Three-Lane Roadway symbol sign is included in a future edition of the MUTCD, it could be considered for installation on the upstream approach where three lanes are fully developed.

2.8 Markings
This portion of the review focuses on pavement markings critical to effective operation of passing lanes, including:

- Centerline Markings and No Passing Zones
- Lane Addition and Transition Markings
- Lane Reduction Markings
- Raised Pavement Markers
- Rumble Strips
- Markings for Common Scenarios

2.8.1 Centerline Markings and No Passing Zones
A fundamental pavement marking decision for a 2+1 corridor is how to stripe the centerline and/or central median separating opposing directions of traffic. A thorough evaluation of this topic includes an examination of passing and no-passing zones in the corridor.

Literature Review
TTI (2001) presented different signing and marking strategies to survey participants to determine their understanding and acceptance of different signing, marking, and related geometric features associated with passing lanes. In terms of passing and no passing markings, they found:

- When presented with a double yellow centerline in the passing lane section, 94 percent of respondents recognized that they could not legally pass in this situation, while 6 percent indicated that they could legally pass provided there was no oncoming traffic.
- When presented with a passing lane marking in the opposing lane of a passing lane section, 79 percent of respondents recognized that passing was legal. One in five survey participants was unclear about whether they could legally pass in the opposing passing lane provided there was no oncoming traffic, even though markings clearly indicate it was legal to do so.

Researchers recommended the gap between a double yellow centerline in a passing lane be increased from 10 inches minimum to 12 inches maximum.

Potts and Harwood (2004) found that the prohibition of passing by vehicles traveling in the opposing direction is particularly appropriate at sites with frequent left-turn movements from the passing lane.

Harwood and St. John (1984) found no difference in cross-centerline crash rates between passing lane sections where passing in the opposing direction was prohibited and passing lane sections where passing in the opposing direction was permitted where adequate sight distance was available

K-TRAN (1999) recommended the whole passing lane be marked by double yellow lines to prohibit passing in opposing lanes when the one-way hourly volume is greater than 400 or when there are sight distance restrictions.

Other Countries
Kirby et al. (2014) referenced New Zealand standards which allow passing in the opposing direction. No passing is continued for a distance beyond the end of the merge condition.

Potts and Harwood (2003) described the following passing zone marking practices from other countries:

- Germany — No passing is established through the entire 2+1 roadway section.
- Finland — A double barrier line is always provided as a separation between opposing travel lanes.
- Sweden — Delineators are placed in a central median so there is no passing.

2009 MUTCD
Figure 3B-3 provides examples of three-lane, two-way marking applications. Condition A is the proper centerline when passing is permitted in the direction of the single lane, while Condition B is the proper centerline with passing prohibited in the direction of the single lane.

Section 3B.02 states that on three-lane roads where the direction of travel shifts from one direction to the other, a no-passing buffer zone should be provided in the center lane. The buffer zone is a flush median island formed by two sets of double yellow centerline markings at least 50 feet in length. The section refers to Figure 3B-5, which provides an example of markings for this scenario. Section 3B.02 establishes diagonal crosshatch markings as optional.

Section 3B.03 states that continuous flush median islands separating travel in opposite directions should be formed with two sets of solid double yellow lines. Section 3B.09 states that no-passing zone markings should be used to prohibit passing in the direction of the convergence and continue through the transition area.

MUTCD NPA
Section 3A.04 states the discernible space separating parallel lines of a double line should not exceed that which is necessary to be recognized as a double line rather than two separate, disassociated single lines.

Section 3B.25 establishes that diagonal crosshatch markings should be used in buffer area. This is optional in the 2009 MUTCD. The NCUTCD has recommended this remain an option in their comments to FHWA on the NPA.

Review of State Policies and Standards
Guidance from other states on centerline markings and passing/no-passing zones is summarized in Table 2.6.

Table 2.6 State Guidance for Centerline Markings and Passing Zones

State	Passing Allowed in Opposing Lane[1]	Beginning of No Passing Zone
Kentucky	Yes for truck climbing Lanes	500' for truck climbing lanes
Texas	Yes	Undetermined
Missouri	No. Use 3' median outlined with two sets of double yellow lines	Undetermined
Minnesota	No	500'
Kansas	Yes	300'
Arizona	Undetermined	500', extending to a point 200' beyond end of 2+1 section
Nevada	No	300', extending to a point 300' beyond end of 2+1 section
Minnesota	No	500' min.
Montana	No	500', extending to 500' beyond end of 2+1 section
Washington	Yes	Undetermined
Wisconsin	Yes	500'
Iowa	Yes	500'
Oregon [2]	Yes	900' for 55 MPH
California [3]	Yes	Undetermined

[1] Determination based on standards and/or review of existing locations.

[2] Passing allowed if there is sufficient sight distance, ADT is less than 3000, passing section is longer than 800 feet, and passing lane is not provided within 2 miles.

[3] No passing is used when ADT exceeds 3,000

Discussion

Most available research suggests that passing from the opposing lane is not necessarily problematic within a passing lane scenario. However, K-TRAN (1999) recommended marking entire length of the passing lane with double yellow lines to prohibit passing in the opposing lanes when the one-way hourly volume is greater than 400 or when there are sight distance restrictions. Most states appear to allow passing from the opposing lane within 2+1 roadways. However, a majority of these state standards are for asymmetrical designs and do not necessarily reflect a continuous 2+1 corridor. Some states, such as California and Oregon, prohibit passing depending on road's average daily traffic (ADT), with 3,000 ADT being the threshold at which passing is prohibited. Since 2+1 corridors provide routine opportunities for passing, there is limited need to permit passing in the opposing lane of 2+1 corridors.

Several states establish 500 feet no passing zone in advance of passing lane sections. The MUTCD requires the no passing zone extend through the convergence of the merge condition. Many states end the no passing zone at the end of the lane reduction taper, but several states extend it downstream of the lane reduction taper. Options were discussed with KYTC's Division of Traffic Operations, and it was decided to extend the no passing zone 500 feet beyond the end of the 2+1 corridor. This will simplify markings by establishing a consistent two-way no passing zone marking 500 feet from either end of the corridor and would ensure reasonable separation from the merge condition and the potential passing opportunities within the two-lane two-way roadway.

The recommended pattern for center line markings is contingent on the presence and width of a central median. In Kentucky, these roadways will likely have 6 in. striping based on KYTC's pavement marking policies. For sections with no median, the recommended striping pattern is a two-direction no-passing zone with 6 in. lines and a 6 in. gap between the lines. The MUTCD includes a standard that continuous flush medians separating opposing directions of two-way traffic should be formed with two sets of solid double yellow lines. The fundamental question is what width of median would facilitate the use of two sets of double yellow lines. Missouri's standards reference a 3 feet median outlined with double yellow lines. However, they utilize 4 in. striping which leaves 12 in. between the interior lines for a 3 feet median. In Kentucky, 6 in. striping is likely to be used on these routes, and a 3 feet median will not provide separation between the two sets of double yellow lines. But a 4 feet median would provide sufficient distance (16 in. if the two sets of lines are located within a rumble strip) between two sets of double lines. For medians less than 4 feet, a single yellow line on either side of the median is recommended, and two sets of double yellow lines are recommended for medians 4 feet or greater. When single yellow lines are used for narrower medians, a transition from single yellow lines to double yellow lines is necessary through transition areas when the flush median becomes greater than 4 feet.

Passing zones for the opposing lane of climbing lanes has been debated within KYTC for many years. Many of the roads that have climbing lanes likely have ADTs greater than the thresholds established in the K-TRANS (2009) research and in the policies of states like Oregon and California. KYTC may want to evaluate the safety performance of climbing lanes with opposing lane passing zones and/or establish thresholds that warrant the establishment of no-passing zones on these roadways.

2.8.2 Lane Addition and Transition Markings

K-TRAN (1999) referenced the following research:

- Staba et al. (1991) who found that lane use depends on the pavement marking within the lane addition. When the passing lane flows directly from a single channel entrance, 80 percent of all directional traffic choses the passing lane as opposed to 20 percent for a design in which the entering traffic is channeled to the basic lane. There was no significant difference in the amount of passing with channelized and unchannelized markings.
- Fong and Rooney (1990) found that without channelization, 36 percent of vehicles were in the inner lane at the beginning of the passing lane. With channelization, this dropped to 22 percent. There was no significant difference in the amount of passing with channelized and unchannelized markings.
- Batz (1989) found that 41 percent of platoon leaders flowed to the passing lane of an unchannelized case, whereas only one percent flowed to the passing lane of a channelized case. It was inconclusive as to whether channelization impacts the number of passes of platoon leaders.
- All passing lane sections should be provided with clear channelization to the outer lane with appropriate pavement markings.

TTI (2001) presented different signing and marking strategies to survey participants to determine their understanding and acceptance of signing, marking, and related geometric features associated with passing lanes. In terms of markings at the lane addition taper, they found:

- No entrance marking
    - If following a slower vehicle, 98 percent of people would use the passing lane to pass.
    - If not following or followed by a vehicle, 87 percent of people would use the outer slow lane. A field study revealed the number of vehicles selecting the passing lane was almost twice that indicated from the survey, with approximately 25 percent of drivers choosing the passing lane.
- Dotted lane line entrance marking
    - If following a slower vehicle, 68 percent of people would use the passing lane to pass.
    - If not following or followed by a vehicle, 80 percent of people would use the outer slow lane while 20 percent would use the passing lane. While these results might suggest the dotted line is less effective than no markings at encouraging drivers to use the outer slow lane, a field study indicated that the opposite is true.
- A field review of in-service performance of the dotted line taper marking was inconclusive as to whether the line performed better when vehicles were platooned. However, the marking treatment significantly

affected lane selection when vehicle headways were greater than 5 seconds (i.e., single vehicles). As a result, TTI recommended that a dashed white line (3 feet lines with 17 feet gap) should be provided in the transition area extending from near the highway center line to the beginning of the white dashed line that separates the passing lane from the right lane.

- An analysis of the Minnesota treatment (channelization using median with double-yellow lines) resulted in the highest percentage of both lead/trailing vehicles entering the right lane. This arrangement had the lowest percentages of lead vehicles entering the right lane with trailing vehicles entering the left-lane at a point 500 ft from the end of the lane taper.

Potts and Harwood (2004) noted that passing lanes work most effectively if most drivers enter the right lane at the lane addition transition and use the left lane only to pass a slower vehicle. They identified two marking patterns that have been used to encourage drivers to enter the right lane of the passing lane section, including a white diagonal dotted line marking and a yellow median island marking (Figure 2.4). They found no general agreement among state highway agencies on the value of lane addition transition markings and encouraged further testing of markings.

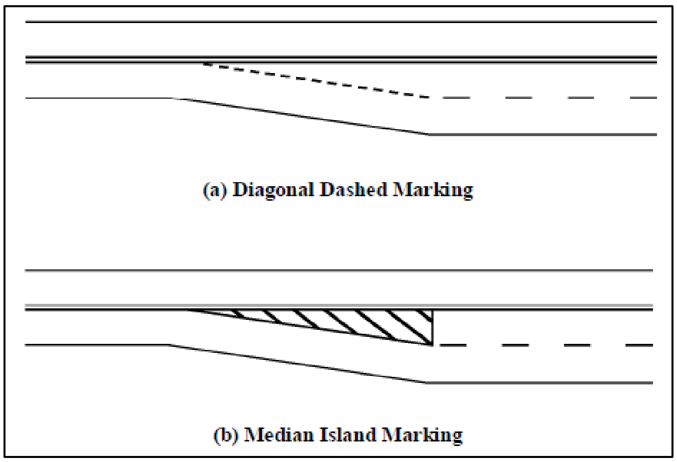


Figure 2.4 Marking Patterns That Encourage Motorists to Use the Right Lanes of Passing Lane Sections

Other Countries
Kirby et al. (2014) referenced New Zealand standards, which include a diagonal dotted line to direct motorists into the slow lane. For non-critical transitions, they recommended tapers between 70 m (230 feet) and 100 m (330 feet) with no buffer separation. For critical transitions, they recommended tapers from 115 m (375 feet) to 160 m (525 feet) with a 80 m (260 feet) buffer (3 seconds of travel). Ireland's *Department of Traffic Signs Manual* (2019) requires use a crosshatched median within the lane addition taper to direct motorists into the slow lane.

Potts and Harwood (2003) noted the following practices for critical and non-critical transitions:

Germany:	Non-critical transitions	100 feet minimum and 160 feet maximum, tapers at 45 degrees
	Critical transitions	590 feet, tapers at 45 degrees
Finland:	Non-critical transitions	160 feet including tapers (80 feet tapers, back to back)
	Critical transitions	1640 feet including tapers (656 feet tapers and 328 feet buffer)
Sweden:	Non-critical transitions	330 feet long
	Critical transitions	1000 feet long

2009 MUTCD
Relevant material from Section 3A.06:

- Dotted lines provide guidance or warning of a downstream change in lane function.
- Dotted lines used as lane lines should consist of 3-foot line segments and 9-foot gaps.

Section 3B.02 lists formulas for calculating the lane transition taper:

$L = W \times S$ when posted or statutory speed is 45 MPH or greater
$L = (W \times S^{2)})/60$ when posted or statutory speed is 40 MPH or less

Under both formulas, L equals the taper length in feet, W equals the width of the offset in feet, and S equals the 85th percentile speed or the posted or statutory speed limit (whichever is higher). While Part 3 of the MUTCD never clarifies how the value of L relates to a lane addition taper, Section 6C.08 on temporary traffic control acknowledges that a shifting taper should have a length of approximately ½ L.

MUTCD NPA
Section 3A.04 includes an addition to the general functions of lines. It states that dotted lines are used as an edge line or lane line extension guide vehicles through an intersection, a taper area, or an interchange ramp area.

A new version of Figure 2D-28 shows an example of Signing for an Intermittent Passing Lane that includes a dotted line across the entering taper.

Review of State Policies and Standards
Guidance from other states on lane addition and transition pavement markings is summarized in Table 2.7.

Table 2.7 State Guidance for Lane Addition and Transition Markings

State	Lane Addition Marking	Transition Markings
Kentucky	No standards for passing lanes. No dotted line extension used through the lane addition taper of truck climbing lanes. Crosshatching is typically 2' lines at 20' spacing	N/A
Texas	Dotted line extension used through lane addition tapers of both symmetrical and asymmetrical passing lanes to direct motorists into the rightmost lane.	Buffer for Transition areas: Critical: 50' (min.), Stopping Sight Distance (des.) Non-critical: 1/2 L taper with no buffer
Missouri	Double yellow line installed through the lane addition taper of both symmetrical and asymmetrical passing lanes to create median that forces motorists into the rightmost lane. Crosshatching is 2' lines with 50' spacing with a minimum of 3 lines.	Buffer for Transition Areas: Critical: 1500' or more Non-critical: 500'
California	No dotted line extension through the lane addition taper. Broken line starts 50' beyond the end of the lane addition taper.	N/A
Iowa	Dotted line extension used through lane addition taper to direct motorists into the rightmost lane	N/A
Minnesota	Double yellow line installed through the lane addition taper of passing lanes to create median that forces motorists into the rightmost lane. Includes a lane entry taper once passing lane has been added.	N/A
Kansas	Dotted line extension used through the lane addition taper, but marking directs motorists into the leftmost lane	N/A
Arizona	No dotted line extension through the lane addition taper	N/A
Nevada	Double yellow line (left line- solid, right line - broken) installed through the lane addition taper of passing lanes to create median that forces motorists into the rightmost lane. Broken line is marked once passing lane is added. No gap or taper for lane entry.	N/A
Washington	No dotted line extension through the lane addition taper	N/A
Wisconsin	Dotted line extension used through lane addition taper to direct motorists into the rightmost lane. Not included if taper is less than 700' or if shoulder in passing lane section is less than the adjacent highway.	N/A
Montana	No dotted line extension through the lane addition taper	N/A
Tennessee	No dotted line extension through the lane addition taper	N/A
Oregon	No dotted line extension through the lane addition taper	N/A

Discussion

Based on a review of state practices and research, five potential marking patterns were identified for lane addition markings within passing lane sections (see Figure 2.5). Option A does not include any markings through the lane addition taper (similar to KYTC's climbing lane detail) and is the most common method used in other states. Research by TTI (2001) revealed that this marking pattern resulted in high rates of passing lane usage but also higher percentages of isolated vehicles using the central passing lane. Option B includes the use of a dotted line extension through the lane addition taper to direct motorists into the outer slow lane. While three states use this method, the TTI (2001) participant survey suggested this marking was less effective, although their field study suggested it had positive impacts with larger headways. Option C includes the creation of a central median using double yellow markings and is the standard in Missouri. TTI (2001) found that Option C resulted in the highest percentage of both lead-trailing vehicles entering the right lane, but had a low percentage of passing lane usage 500 feet from the end of the lane addition taper. Nevada has a similar treatment (Option D) that includes a broken line for the rightmost double yellow marking to permit passing through the taper. Option E is from Minnesota and includes a flush median with double yellow lines but also a striped lane entry taper for the passing lane.

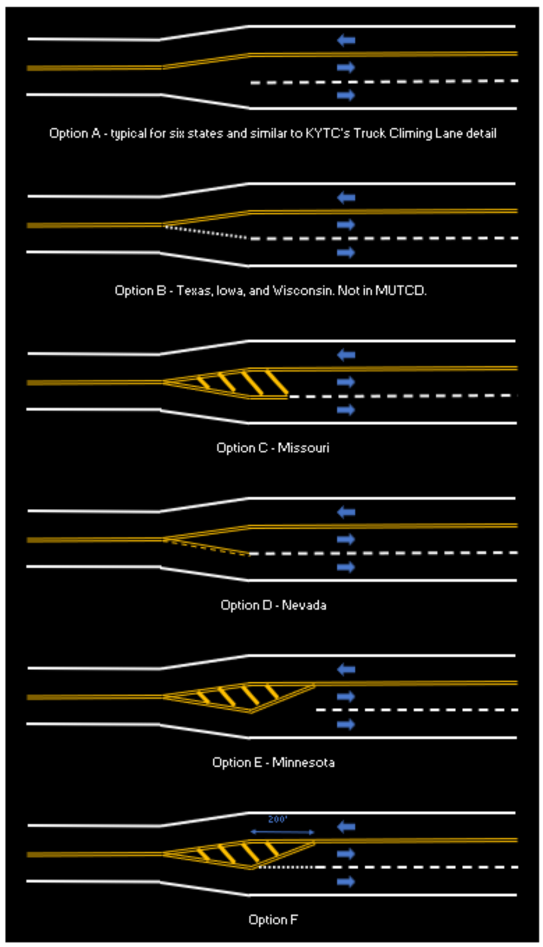


Figure 2.5 Six Options for Lane Addition and Transition Markings

These options were discussed with KYTC's Division of Traffic Operations, and the recommended marking pattern (Option F) combines Option E with the inclusion of a dotted line extension across the lane entry taper. This option is the most effective at getting motorists into the outer slow lane and provides clear warning (through the central median) to motorists of a change in roadway configuration and operations. The passing lane entry taper of 200 feet was selected as this is the minimum taper recommended for rural areas in the Green Book. Longer entry tapers reduce the available length for passing maneuvers within the passing lane section. Including a dotted line extension across the passing lane entry taper supports lane assist technology in modern vehicles and provides uniform markings of auxiliary lanes throughout the corridor. A similar dotted line marking pattern is recommended for lane entries into auxiliary turning lanes.

A critical transition occurs where opposing passing lanes merge with opposing vehicles in the central lane travelling towards each other. A non-critical transition occurs where opposing passing lanes diverge with opposing vehicles in the central lane travelling away from each other (see Figure 2.6). The MUTCD states that a minimum buffer of 50 feet should be used for critical transitions. For critical transitions, Texas uses a minimum buffer zone of 50 feet with a desirable buffer zone of stopping sight distance. It does not have a buffer zone for non-critical transitions and stripes entry tapers back-to-back. Missouri's *Engineering Policy Guide* indicates that buffer zones for critical transitions are typically 1,500 feet or more, and buffer zones for non-critical transitions are typically 500 feet or more. Figure 3-29 and 3-30 the Green Book include schematics for adjacent lane drop and lane addition tapers on 2+1 roads, which include a 320 feet buffer zone for critical transitions and no buffer zone for non-critical transitions.

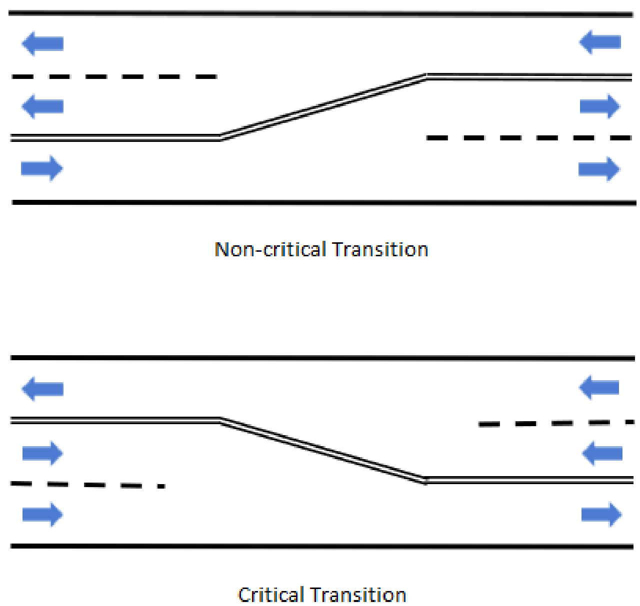


Figure 2.6 Layouts for Non-Critical and Critical Transitions

Options for buffer zones between non-critical and critical transitions were discussed with KYTC's Division of Traffic Operations. For non-critical transitions (Figure 2.7), Option A is from Texas, which uses a shared lane taper. Option B is from the Green Book and does not have a buffer zone, but lane tapers begin at the same point to provide a striped flush median. Option C is like Option B but includes a buffer zone. Missouri uses a 500 feet minimum buffer zone is such situations and a 150 feet buffer zone was included on a recent 2+1 project in District 4. Based on discussions with the Division of Traffic Operations, we do not feel a buffer zone is necessary. However, something more than Texas's shared taper is needed. As a result, the option of using adjacent lane tapers (Option B) was selected as it provides a minimal median that could be crosshatched to warn of the change in lane use while maximizing the available length for passing maneuvers.

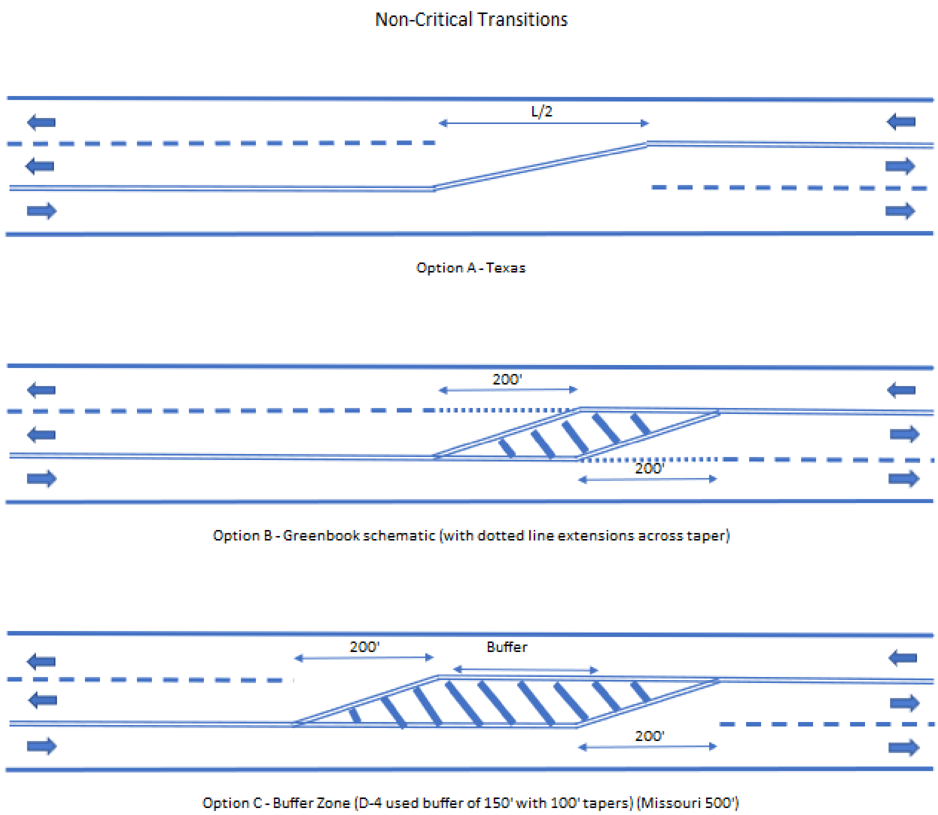


Figure 2.7 Layouts for Buffer Zones in Non-Critical and Critical Transitions

For critical transitions, a 200 feet minimum buffer zone was selected to provide adequate warning and stopping distance in the unlikely event that opposing vehicles cross their lane reduction taper at the same time [660 feet taper plus ½ buffer zone = 760 feet], while maximizing the available length for passing maneuvers (Figure 2.8). The 200 feet distance is also consistent with other marking features that are recommended later in this document and should improve uniformity of marking applications.

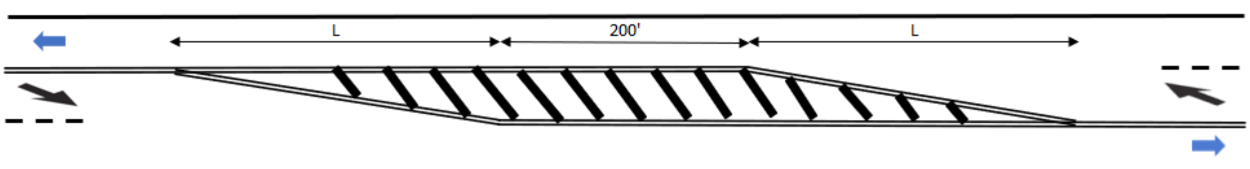


Figure 2.8 Striping Pattern for Critical Transitions

When the central median is outlined by two sets of double yellow lines, the MUTCD states that diagonal crosshatching may be installed in the buffer area. For states with 2+1 traffic control standards, Texas does not show crosshatching while Missouri uses 2 feet lines at 50 feet spacing with a minimum of 3 lines within each transition area. KYTC's Standard Drawings show crosshatching at turning lanes composed of 2 feet lines at 20 feet spacing. While this crosshatching is optional in the current MUTCD, the MUTCD NPA includes language to elevate it to a guidance statement. However, the NCUTCD has recommended this language remain an option statement in the next edition of the MUTCD. Photos of crosshatching with 20 feet spacing and 50 feet spacing were reviewed with KYTC's Division of Traffic Operations, and it was determined that 50 feet spacing is preferred as it provides adequate delineation while minimizing the amount of material requiring maintenance.

Lane addition pavement markings for climbing lanes were also discussed with KYTC. It was recognized climbing lanes function differently than passing lane sections and various options were reviewed (Figure 2.9).

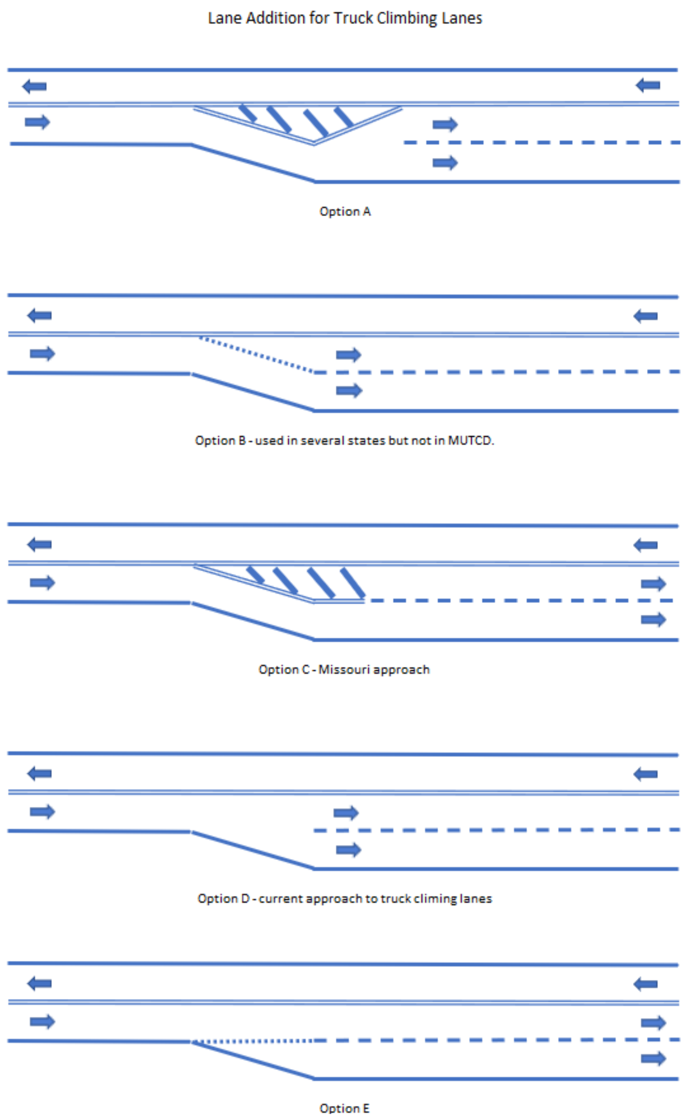


Figure 2.9 Pavement Marking Options for Climbing Lanes

For climbing lanes, the rightmost slow lane is the auxiliary lane, and motorists have no need to enter it unless they are moving slower than trailing vehicles. KYTC's current climbing lane striping detail does not include pavement markings in the lane addition taper area. Based on discussions with KYTC's Division of Traffic Operations, they liked Kansas' method of striping a dotted line extension across the lane addition taper to direct motorists into the leftmost lane (Option E) and to support lane assist technology in modern vehicles.

2.8.3 Lane-Reduction Transition Markings

Balk and Jackson (2016) explored driver comprehension of six lane reduction markings without signing. Markings varied in terms of their incorporation and length of dotted and broken lines. The study found:

- A supplemental solid white line on left-side of the lane line improved driver understanding that the rightmost lane would end, had earlier reported lane changes, and garnered the highest preference ratings

- Dotted lines resulted in better driver understanding of an upcoming necessary lane change than did standard broken lane lines
- Marking combinations involving dotted lines to the taper generated the most driver understanding that the rightmost travel lane would end and that a lane change was required.
- Combinations that terminated ¾ *d* in advance of the lane taper generated the fastest response times.
- In terms of participant preference, markings with the solid white line were ranked higher than those without the solid white line. Markings that extended to the taper were preferred over those which ended ¾ *d* in advance of the lane reduction taper.

Marchese and Gonzales (2019) built on Balk and Jackson (2016) by exploring how sign-marking combinations impacted merging behavior prior to lane reduction transitions and driver understanding and time of comprehension of the intended message conveyed at lane reduction transitions. They developed a survey that evaluated combinations of four warning signs, two advanced warning signs, and two-lane line transition markings. In terms lane reduction markings, they found:

- Including a solid white line with a dotted lane line yields better lane reduction recognition and encourages earlier lane changes than a single dotted lane line.
- Lane reduction arrow markings had no significant effects on response time or time between responses. This finding should not be interpreted as evidence for not using lane reduction arrows as they could still be necessary in high traffic density or short transition scenarios.

Potts and Harwood (2004) recommended that drop transition markings at the downstream end of a passing lane conform with the MUTCD.

Other Countries
Kirby et al. (2014) referenced New Zealand standards, which continue the broken lane line to the start of the lane reduction taper and include edge marker posts along the taper. In Ireland's *Department of Traffic Signs Manual* (2019), the broken lane is continued to the beginning of the lane reduction taper and include three advance lane deflection (merge) arrows.

Potts and Harwood (2003) found the following lane reduction marking practices from other countries:
- Germany — Three lane reduction arrows are used to warn motorists that they must merge, and broken lines extend to the beginning of the lane reduction taper.
- Finland — One merge arrow is used at the end of the passing lane, and broken lines extend through the lane reduction taper.
- Sweden — Three merge arrows are used in advance of the lane taper, and the broken lane line continues through the lane taper for a distance until a specific width is reached. Delineators are placed through the taper at 33 feet spacing.

2009 MUTCD
Section 2B.02 establishes guidance for calculating the lane transition taper:
- $L = W \times S$ when the posted or statutory speed is 45 MPH or greater
- $L = (W \times S^{2})/60$ when the posted or statutory speed is 40 MPH or less
    - Under both formulas, L equals the taper length in feet, W equals the width of the offset in feet, and S equals the 85th percentile speed or the posted or statutory speed limit (whichever is higher).
    - The minimum lane transition taper length should be 100 feet in urban areas and 200 feet in rural areas.

Section 3B.04 does not list dotted white lines as an option for lane reduction situations. Dotted line applications are specific to intersections and interchanges.

Relevant material from Section 3B.09 on lane reduction transition markings includes:

- Where pavement markings are used, lane reduction transition markings shall be used where the number of lanes is reduced. Refers to Figure 3B-14.
- No-passing markings are required through the transition area in direction of convergence.
- The taper formulas (addressed earlier in this document) should be used. The lane reduction taper length should be L.
- Where observed speeds exceed posted or statutory limits, longer tapers should be used.
- Lane lines should be discontinued one-quarter of the distance between the LANE ENDS sign and the point where the transition taper begins.
- Edge lines should be used through transition area.
- Edge lines may be omitted on certain low-speed urban roadways.
- Minimum tapers are 100 feet in urban areas and 200 feet rural areas.

Section 3B.20 states that lane reduction arrows should be used if the speed limit is 45 mph or greater and if speed the limit is 40 mph or less if supported by engineering judgment. Section 3F.03 indicates that delineators through the taper are optional.

MUTCD NPA
Section 3A.04 includes the following additions:
- States that dotted lines provide warning of a downstream change in lane function. Eliminated that they provided as guidance.
- Under general functions of longitudinal lines, establishes that dotted lines are also used as a lane line or edge line extension to guide vehicles through an intersection, a taper area, or an interchange ramp area.

Section 3B.12 includes the following additions/changes:
- Use of edge lines within the transition area is elevated from guidance to a standard.
- Use of delineators in taper areas elevated from option to guidance, except for certain low-speed urban roads.
- Delineators may be omitted in tapers on certain low-speed roads.
- Lane reduction arrows may be used on roadways with a speed limit less than 45 mph. This is a change from 2009 MUTCD, where use on lower-speed roads is based on engineering judgment and established in a guidance statement.
- Tapers shorter than 100 feet may be used for roadways with speeds less than 25 mph.

Review of State Policies and Procedures
Guidance from other states on lane reduction pavement markings is summarized in Table 2.8.

Table 2.8 State Guidance for Lane Reduction Pavement Markings

State	Broken Line Marking	# of Lane Reduction Arrows	Arrow Placement	Delineators in lane reduction taper
Kentucky	Ends 3/4 d in advance of taper	3	At warning signs and near taper	Optional. Refer to MUTCD for spacing.
Texas	Ends 3/4 d in advance of taper with dotted line extended to taper	2	Within d	N/A
Missouri	Ends 1/4 d in advance of taper	N/A	N/A	N/A
Iowa	Ends 550' in advance of taper	N/A	N/A	N/A
Minnesota	Ends 200' in advance of taper	2	At d and near end of broken line)	N/A
Kansas	Ends 3/4 d in advance of taper with dotted line extended through the taper	N/A	N/A	N/A
Arizona	Ends 3/4 d in advance of taper	2	At d and near taper	Installed at 100' spacing. May be eliminated in urban areas with curb.
Nevada	Ends 3/4 d in advance of taper	2	At 1/2 d and 1/4 d	N/A
Washington	Note to install in accordance with MUTCD	N/A	N/A	N/A
Wisconsin	Ends 1/4 d in advance of taper	N/A	N/A	N/A
Montana	Ends at the beginning of lane taper	9	Within d	Installed at 100' spacing.
Tennessee	Ends 3/4 d in advance of taper	N/A	N/A	N/A
Oregon	Ends 3/4 d in advance of taper	3	Near end of broken line and the other two within 3/4 d	N/A
California	Ends 3/4 d in advance of taper	3	Near d, 1/2d, and near taper	N/A
Michigan	Ends 3/4 d in advance of taper	2	Near the end of broken line and 50' in advance of lane taper	Installed at 100' spacing. May be eliminated if inner lane is merging.

A primary concern of KYTC is MUTCD guidance, which leaves a long distance (3/4 *d*) of full-width pavement in advance of lane reductions with no lane line marking. KYTC previously considered modifying the advance placement distance (*d*) of warning signs, addressing a pavement marking issue through sign placement is inadvisable. Of the 14 states surveyed, six states discontinue the broken lane line a distance of ¾ *d* in accordance with the MUTCD. Two other states discontinue the broken line at ¾ *d* but include a dotted line extension to the beginning of the lane reduction taper (Texas) or to the end of the lane reduction taper (Kansas). Other states extend the broken lane line to the lane reduction taper or to a point closer to the beginning of the lane reduction taper (e.g., ¼ *d*, 200 feet and 500 feet). A review of current MUTCD language does not indicate there is an allowance for using the dotted line extension on the approach to lane reductions. This position was confirmed in discussions with FHWA's MUTCD Team.

If KYTC were to consider extending the broken line marking, the question remains as to at what point the broken line would be terminated. The *Human Factors Guidelines for Roadway Systems* (2012) recommends providing a 5 second preview time when possible and a 3 second preview time as an absolute minimum. Assuming an approach speed of 55 mph, the recommended preview distance is 403 feet (less than the ½ *d* value of 495 feet) for 5 seconds preview time and 242 feet (slightly less than the ¼ *d* value of 248 feet) for a 3 second preview time. Both options were discussed with KYTC's Division of Traffic Operations. Since the ¼ *d* option designs toward an absolute minimum condition, extending the broken lane line to a point ½ *d* in advance of the lane taper was the preferred option.

Of the surveyed states using lane reduction arrows, most use two arrows. The MUTCD does not specify the number of arrows to use, but Figure 3B-14 (Examples of Applications of Lane-Reduction Transition Markings) shows two arrows. While KYTC does not have Standard Drawings for lane reduction signing and/or markings, there are signing and marking examples in the TOGM for climbing lanes (Exhibit 5) and for transitions from four to two lanes (Exhibit 6) which include three lane reduction arrows spaced 500 feet apart. To minimize the number of arrows that need to be maintained in a 2+1 corridor, KYTC should use a minimum of two lane reductions arrows with one arrow placed at the LANE ENDS (W4-2) sign (distance of *d* in advance of the lane reduction taper) and the other arrow placed at the end of the broken lane line (at a distance of ½ *d* in advance of the lane reduction taper). Consistent with standards in certain states and the MUTCD, using lane reduction arrows would be optional when the speed limit is less than 45 mph.

Using delineators along the taper of lane reduction tapers is optional in the current MUTCD. Optional use is referenced in Exhibit 5 and Exhibit 6 of the TOGM. It is advisable to allow the optional use of delineators through the lane reduction tapers on asymmetrical 2+1 corridors. The use of delineators in the lane reduction tapers of symmetrical designs would be problematic as the inner lane is typically merging, and the placement/maintenance of delineators in the central area would be difficult, if not impossible. A delineator spacing of 100 feet is common for states that use delineators in lane reduction tapers, so this spacing is recommended for KYTC.

KYTC may want to consider developing Standard Drawings that address the signing and marking of left- and right-lane merges on one-way, two-lane, and multi-lane highways since lane drop situations could be commonly encountered on highway projects without a signing and/or marking plan.

2.8.4 Raised Pavement Markers

Literature Review

Bahar et al. (2004) found:

- Nonselective implementation of permanent raised pavement markers (PRPMs) on two-lane roads does not significantly reduce total or nighttime crashes, nor does it significantly increase these crash types.
- Nighttime safety performance of PRPMs improved as traffic volume increased.
- Safety performance of PRPMs was negatively impacted by higher degrees of road curvature.
- Drivers are likely to stay better centered in lanes delineated on both sides. Delineating the lane line will decrease the number of lane line encroachments. Therefore, the potential for sideswipe crashes decreases. The safety benefits of reduced lane-line encroachments are expected to be greater than the potential negative safety impact of increased shoulder encroachments, where there are wide shoulders and shoulder rumble strips.
- On two-lane roadways with centerline PRPMs, drivers move away from the centerline toward the shoulder, which may reduce the incidence of opposing head-on crashes.

Agent and Green's (2009) analysis of crash data on rural, two-lane roads found that the crash rate was lower on roads on the Pavement Marker System then other roads. The type of rural, two-lane roads included in KYTC's Pavement Marker System typically had better roadway geometrics than the overall roadway system. They found that continued use of pavement markers could be justified if properly installed and maintained.

2009 MUTCD

Use of raised pavement markers is optional in the 2009 MUTCD.

MUTCD NPA

No significant changes.

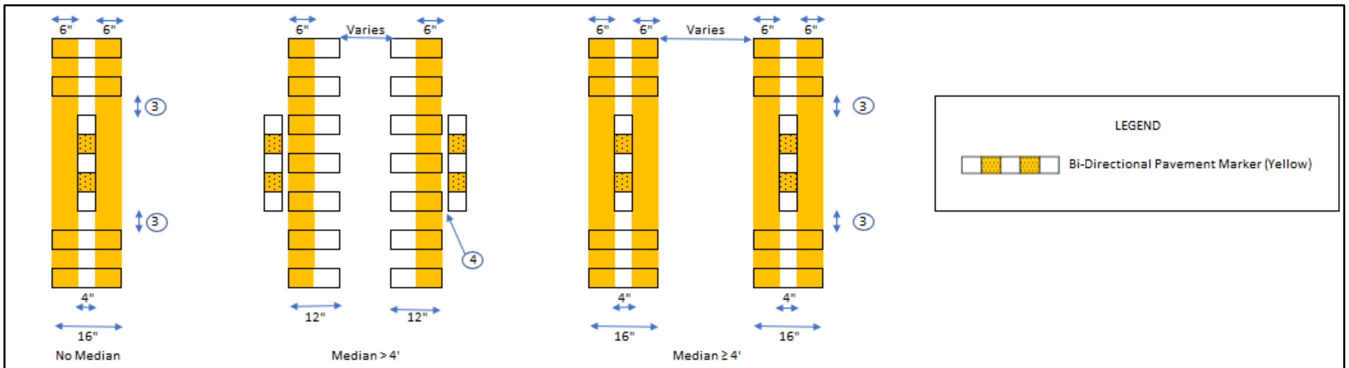
Review of State Policies and Procedures

Texas does not recommend pavement markings on dotted white extensions. Otherwise, no significant information was found on the use of raised pavement markers in passing lanes or 2+1 corridors.

Discussion

KYTC established a Pavement Marker System — a list of highways eligible for the installation of pavement markers. Approximately 15 years ago, KYTC started to question the use of pavement markers due to isolated installation failures and national crash modification factors suggesting they could negatively impact safety on some two-lane highways. At the same time, there was interest in reducing the system's size to minimize maintenance costs. Upon completion of pavement marker research by KTC, the Cabinet determined that pavement markers were primarily positional guidance devices that are most beneficial on multi-lane roadways. As a result, most two-lane highways were removed from the Pavement Marker System in 2010. In the following years, KYTC experimented with and expanded the use of inlaid markers (lenses set within a recessed groove) as an alternative to Type V (metal snowplowable) pavement markers. In 2019, KYTC established inlaid pavement markers as the standard pavement marker.

Based on the available information, 2+1 corridors appear to be good candidates for inclusion on KYTC's Pavement Marker System. 2+1 corridors are likely to be limited in number so their inclusion should not significantly impact maintenance costs. They are also likely to have higher volumes and better geometry, which typically correlate with better safety performance for pavement markers. Furthermore, 2+1 roads include multiple lanes and lane reductions which would benefit from the enhanced positional guidance provided by pavement markers. The recent transition to inlaid markers also eliminates safety concerns with pavement markers becoming dislodged on two-lane highways. Suggested locations for pavement markers are provided in Figure 2.10.



1 Drawings are only intended to show the relative positions of pavement markers and rumble strips in relation to the recommended pavement marking arrangements. Refer to Pavement Marker and Rumble Strip standard drawings for additional details on placement, dimensions, and spacing of rumble strips and pavement markers.

2 Rumble strips should be omitted where the posted speed limit is 45 MPH or less, or where lane widths are less than 11'.

(3) Discontinue the centerline rumble strips (6" min./ 12 max.) before and after the groove for each inlaid pavement marker. Install as many rumble strips as possible between adjacent pavement markers while maintaing the 24" cycle.

(4) Markers placed along edge lines should be placed so that the near edge of the groove is no more than 1" from the near edge of the line. Inlaid pavement markers with bi-directional yellow lenses.

Figure 2.10 Recommended Placement of Pavement Markers

2.8.5 Rumble Strips

Review of State Policies and Procedures

Missouri discontinues centerline rumble strips through the limits of all left-turn lanes. Otherwise, no significant information was found on the use of rumble strips in passing lanes or 2+1 corridors.

Discussion

Based on KYTC policy, 2+1 roadways are likely to require centerline rumble strips. One issue is the preferred width and location of the rumble strip relative to centerline markings and pavement markers. A 16 inch rumble strip is preferred for double no-passing markings as the entire marking could fit within the rumble strip by reducing the gap between lines to 4 in. A 12 inch rumble strip is recommended for single lane lines.

During our review, it was noted that KYTC Standard Drawing TPR-100 does not show centerline rumble strips through both sets of double yellow centerlines on the approach to intersections with turning lanes. The decision to have rumble strips along only one centerline marking was made early in KYTC's deployment of centerline rumble strips when there was uncertainty about contractors' ability to install rumble strips in transition areas where rumble strips would be so closely spaced. This should no longer be a concern, and rumble strips along both edges of flush medians would be advisable in transition areas, especially in 2+1 corridors. Including rumble strips along both sets of lines will reduce crossover events and could be accommodated with minor adjustments to the rumble strip layout through transition areas when the centerline marking/median is modified. As a result, KYTC should consider modifying Standard Drawing TPR-100 to show rumble strips through both sets of double yellow centerlines.

2+1 roadways are likely to have a shoulder width that would require installation of a shoulder rumble strip. Placement of the edge line within the rumble strip (rumble stripe application) could be an additional safety feature if deemed appropriate based on engineering judgment.

2.8.6 Markings for Common Scenarios

Discussion

During a field review of 2+1 corridors and analysis of marking plans for future projects, several common scenarios were identified considered worthy of a pavement marking detail. Most the scenarios involve transitions near at-grade intersections. Buffer zones (typically 200 feet) are recommended in most cases to separate merge/diverge conditions and/or provide additional distance for the placement of signing for intersections.

Transition to Intersection, Passing Lane Approaching Left-Turn Lane

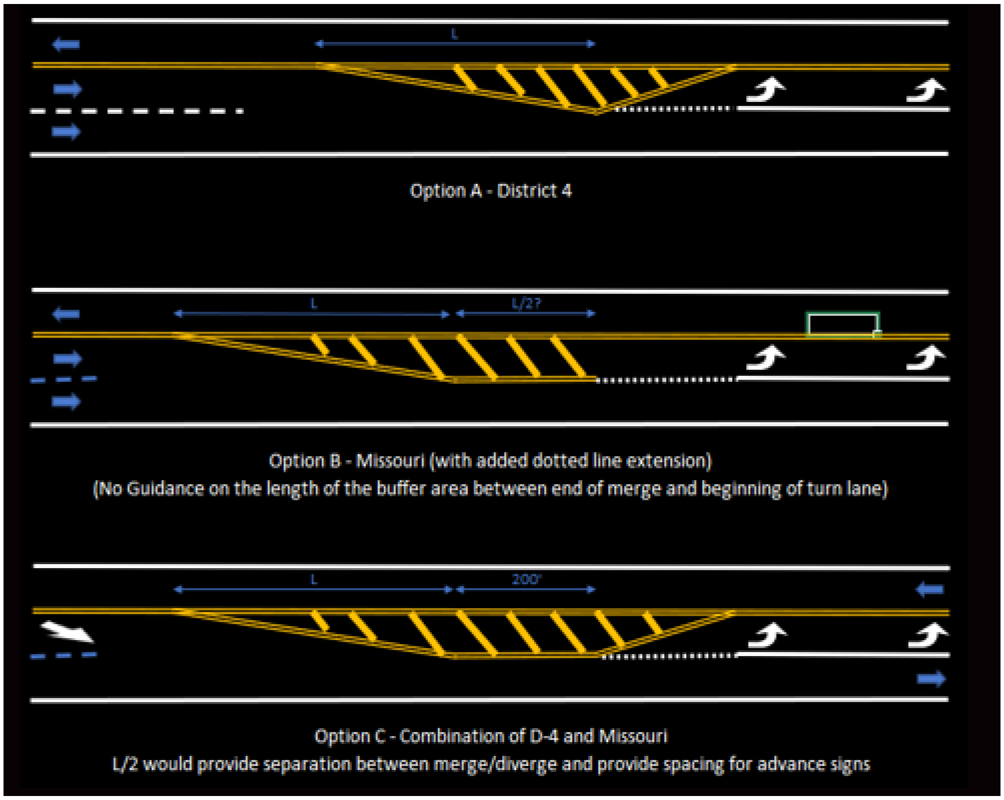


Figure 2.11 Markings for Transitions to Intersection, Passing Lane Approaching Left-Turn Lane

- Option A has been used on some KYTC projects. Option B is from Missouri, although we could find no discussion on recommended buffer zone length.
- Option C was developed with input from KYTC's Division of Traffic Operations and is recommended for KYTC applications. It includes a 200 foot buffer zone to separate merge/diverge movements and provide additional space for sign placement, which could be extensive at major intersections. To achieve consistency with other recommendations, it incorporates a dotted line extension across the lane entry taper to support lane assist technology in newer vehicles.

Transition to Intersection, Single Lane Approaching a Left-Turn Lane

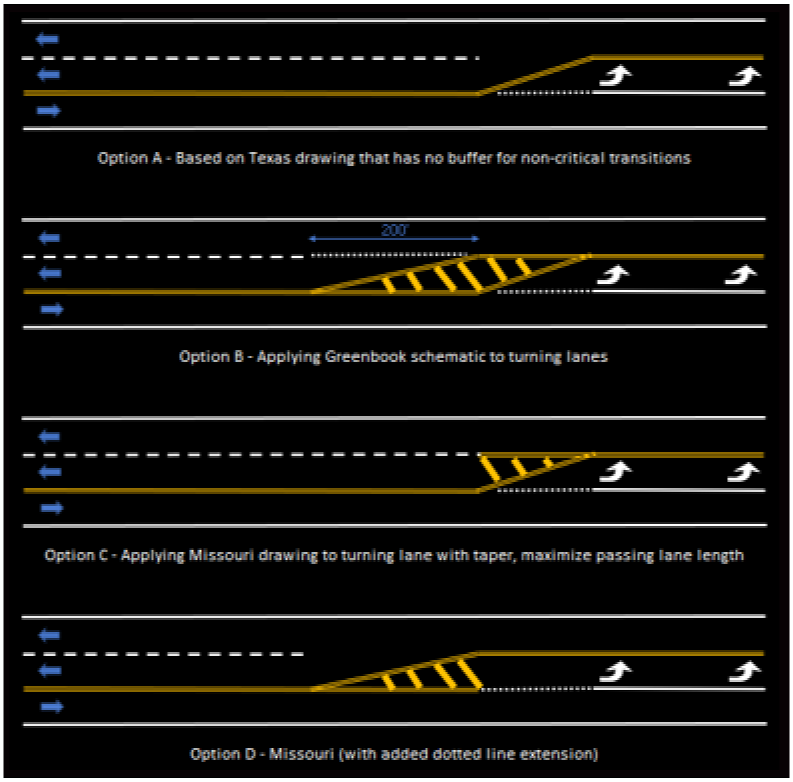


Figure 2.12 Marking Options for Transition to Intersection, Single Lane Approaching a Left-Turn Lane

- Option A was developed based on Texas's approach to non-critical transitions. Option B is based on the Green Book schematic for non-critical transitions. Option C was developed using Missouri's approach to lane addition tapers. Option D is similar to Option C but includes a lane entry taper.
- Based on discussions with KYTC's Division of Traffic Operations, Option B is recommended for KYTC applications due to its similarity with non-critical transitions.

Transition to T-Intersection — Passing Lane on Approach with No Left-Turn Lane

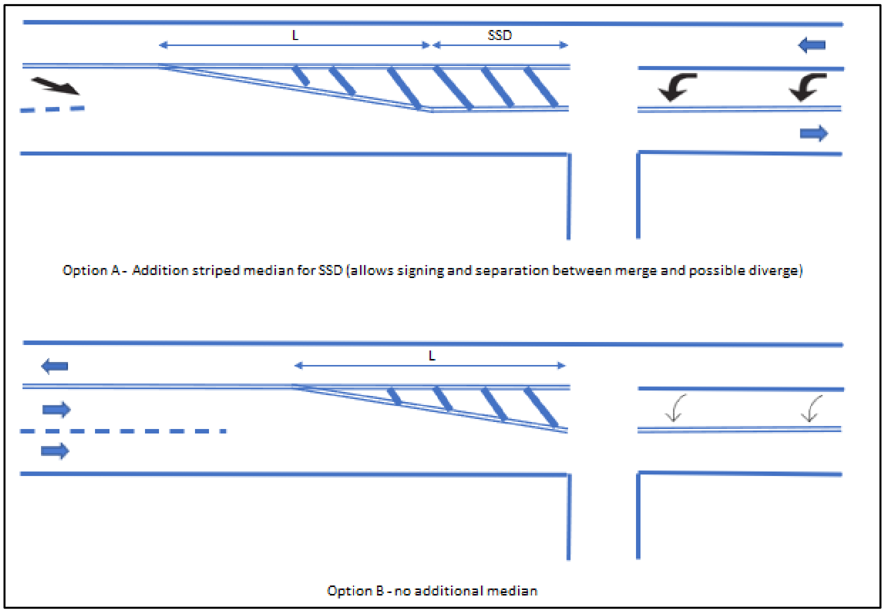


Figure 2.13 Marking Options for Transition to T-Intersection — Passing Lane on Approach with No Left-Turn Lane

- The primary decision with this scenario was whether to include a buffer zone between the end of the lane reduction taper and downstream intersection. Option A includes a buffer zone; Option B does not.
- Based on discussions with KYTC's Division of Traffic Operations, Option B is recommended, with a buffer zone length equal to stopping sight distance. This buffer zone separates decision points, offers additional space for sign placement, and simplifies the decision-making process for motorists on the side street approach by improving visibility of approaching traffic.

Transition to T-Intersection — Single Lane on Approach with No Left-Turn Lane

- For this scenario, a minimum buffer zone is needed to (1) establish an adequate flush median on the approach to the intersection and (2) separate the intersection and the lane entry taper for the opposing passing lane.

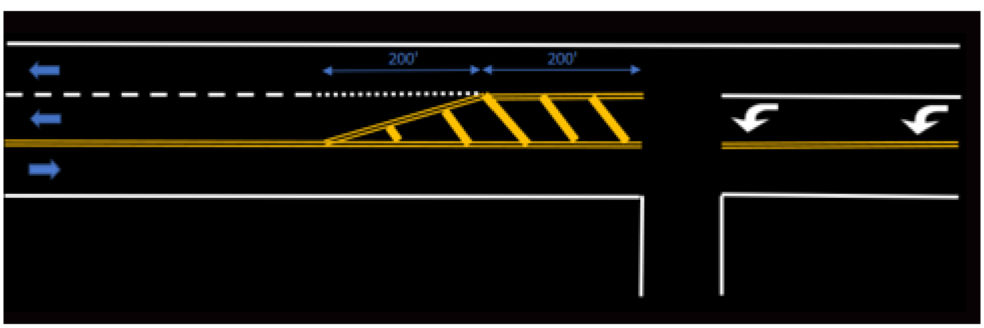


Figure 2.14 Recommended Marking for Transition to T-Intersection — Single Lane on Approach with No Left-Turn Lane

- This option has a 200 foot transition for common 2+1 scenarios, which should improve uniformity in pavement marking plans. Consistent use of dotted line extensions across a 200 foot lane entry taper is maintained.

Passing Lane Approaching End of 2+1 Corridor

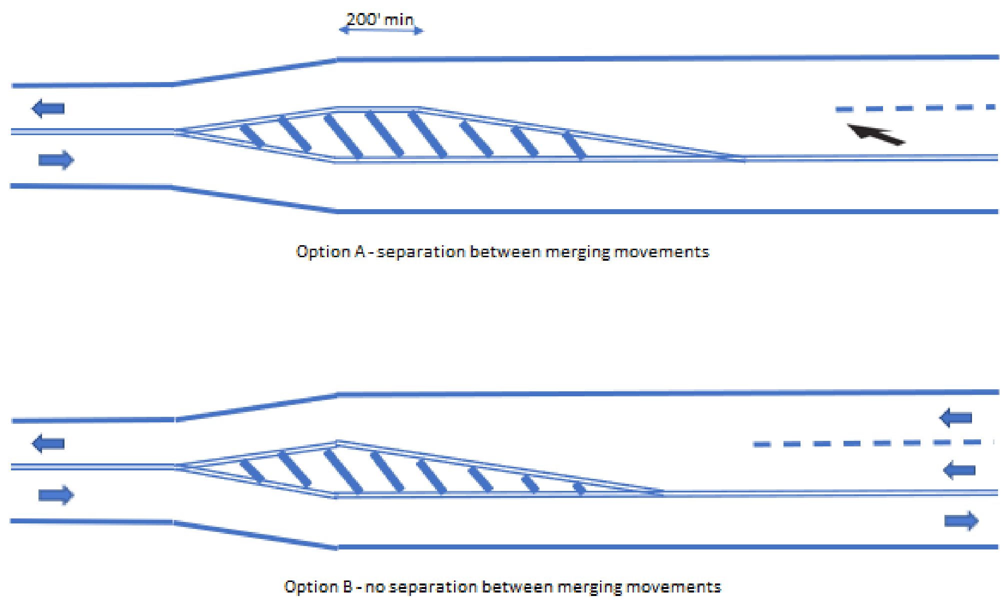


Figure 2.15 Marking Options for Passing Lane Approaching End of 2+1 Corridor

- The primary decision with this scenario was whether to include a buffer zone between the end of the lane reduction taper and the downstream lane shift. Option A includes a buffer zone; Option B does not.
- Based on discussions with KYTC's Division of Traffic Operations, Option A is recommended with a buffer zone of 200 feet to provide minimal separation between the merging and lane shift conditions.

Chapter 3 Highway Safety Summary on Kentucky's Existing 2+1 Roadway

3.1 Background on Kentucky's Existing 2+1 Roadways

Since 2013 KYTC has built several 2+1 roads. Once each segment opened, KYTC and KTC began monitoring their performance, paying special attention to highway safety statistics. The Cabinet has many other 2+1 projects in the design stage, however, we focus here on the KY 55 corridor in central Kentucky.

An approximately six-mile stretch of KY 55 in Adair County was the first to adopt a 2 + 1 configuration in Kentucky. KYTC gradually added more 2 + 1 segments following the existing KY 55 route. Table 3.1 lists six 2+1 road locations in Kentucky and the date they opened to traffic. Taken together, these segments create a 2+1 corridor beginning in Columbia and running north to Campbellsville. In Campbellsville the 2+1 segment follows the US 68-KY 55 common route to Lebanon. North of Lebanon, the 2+1 segment follows KY 55 to Springfield. Eventually KYTC plans to build a 2+1 road on KY 55 north of Springfield, completing a nearly 60-mile corridor of 2+1 roadway stretching from the Cumberland Parkway to the Bluegrass Parkway.

Table 3.1 Location of Existing 2+1 Roadways in Kentucky

County (Item #)	Route	Mile Point Range	Date Opened as a 2+1 Roadway
Adair (8-8851)	KY 55	15 to 20.9	• Fall 2016
Taylor (4-8920)	KY 55	Adair 20.9-21.3 and Taylor 0.0 to 7.8	• Oct 2020
Marion (4-8916.10)	KY 55	Marion 1.8 to 4.7 and Washington 0-0.15	• July 2019 • (This section was a construction zone with adjacent 4-8916.20 through most of 2021.)
Marion (4-8917)	US 68	Taylor 7.404-13.531 and Marion 0 to 9.339	• Under Construction • (Sept 2022 anticipated complete)
Washington (4-8916.20)	KY 55	0.15-4.55	• Sept 2021 completion

3.2 Plausibility of a Crash Reduction Factor Based on Kentucky Data

Because 2 + 1 designs are relatively new in Kentucky, we lack enough data draw definitive conclusions about their safety performance. Crash reduction factors (CRFs) cannot be appropriately defined using Kentucky data. But our literature review documented a number of studies that show 2+1 roadways elsewhere have been very effective in making highways safer. As more data are collected it will be important to develop robust statistical models to analyze the performance of 2 + 1 roads (e.g., D'Agostino et al. 2019).

3.3 Crash Numbers on KY 55's 2+1 Roads

To evaluate the safety performance of 2 + 1 configurations, we compared crash rates for segments before and after their conversion to a 2 + 1 layout across time periods of equal duration. Because post-2020 crash data are not yet available, our analysis is restricted to 2 + 1 segments of KY 55 that opened before 2021. We adopted the KABCO Injury Classification Scale (Table 3.2) to categorize crash severity. For fatal and serious injury crashes on 2+1 configurations we examined police reports (Section 3.4). Tables 3.3 – 3.5 summarize before-and-after crash data for 2 + 1 segments in Adair County, Taylor County, and Marion/Washington County, respectively. The segments in Adair and Taylor counties saw significant reduction in crash numbers, providing good preliminary evidence that 2 + 1 designs improve safety. The Marion/Washington County segment recorded a slight uptick in crashes, although this could have been due to the area being an active construction zone throughout most of 2019 and 2020. Figures 3.1 – 3.3 map the locations of crashes on each segment following 2 + 1 implementation.

Table 3.2 KABCO Injury Classifications

Classification	Definition
K	Fatal Injury
A	Suspected Serious Injury
B	Suspected Minor Injury
C	Possible Injury
O	Property Damage Only

Table 3.3 Crash Numbers Before and After 2 + 1 Implementation (KY 55 Milepoints 15.0 – 20.9 in Adair County)

KABCO Crash Type	2011 – 2015 (Before 2 + 1)	2016 – 2020 (Post 2 + 1)
K	0	0
A	0	1
B	3	4
C	6	10
O	73	41

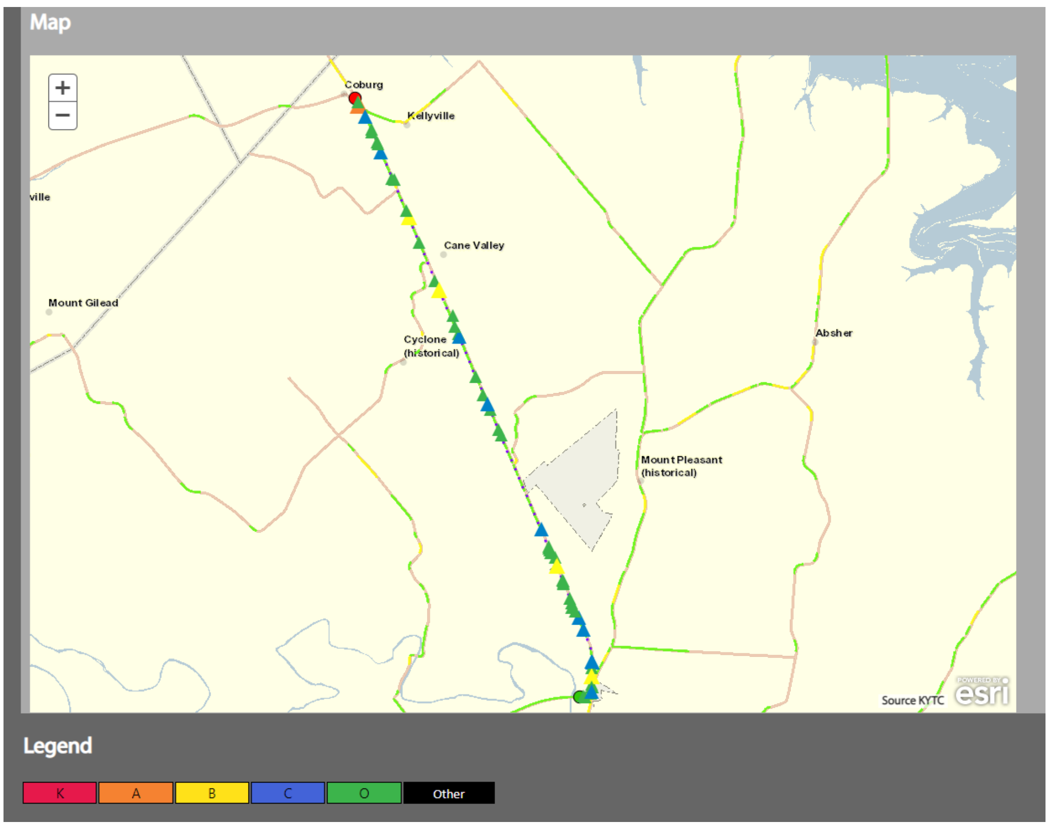


Figure 3.1 Crashes on KY 55 milepoints 15.0 to 20.9 in Adair (2016 – 2020)

Table 3.4 Crash Numbers Before and After 2 + 1 Implementation (KY 55 Milepoints 0.0 – 7.8 in Taylor County)

KABCO Crash Type	2015 (Before 2 + 1)	2020 (Post 2 + 1)
K	0	0
A	1	1
B	1	1
C	2	1
O	47	18

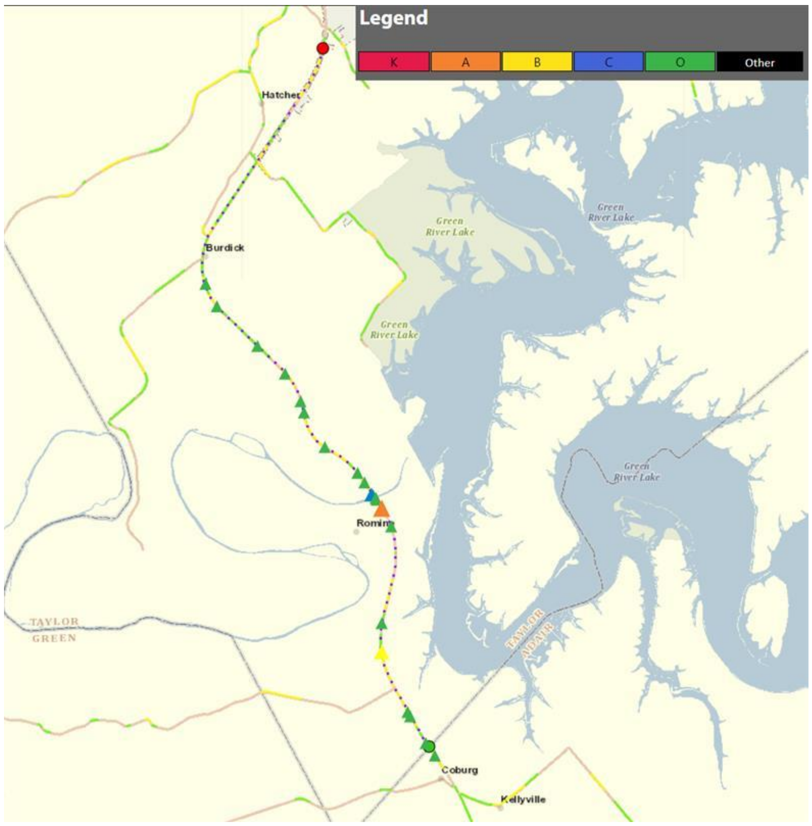


Figure 3.2 Crashes on KY 55 in Taylor County (2020)

Table 3.5 Crash Numbers Before and After 2 + 1 Implementation (KY 55 Milepoints 1.8 – 4.7 in Marion County and Milepoints 0.0 – 0.15 in Washington County)

KABCO Crash Type	2014 – 2015 (Before 2 + 1)	2019 – 2020 (Post 2 + 1)
K	0	1
A	0	0
B	1	3
C	2	0
O	17	20

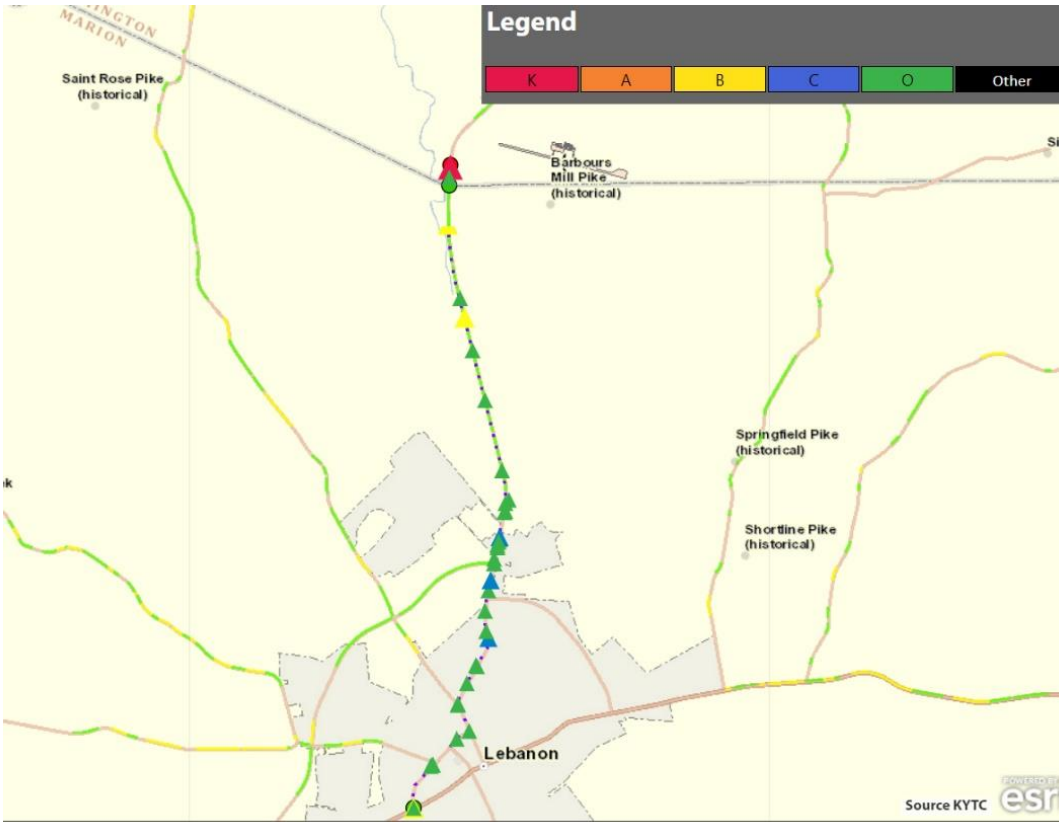


Figure 3.3 Crashes on KY 55 from milepoints 1.8 to 4.7 in Marion County and 0.0 to 0.15 in Washington (2019 – 2020)

3.4 Summaries of Severe Crashes on Kentucky's 2+1 Roads

We looked at police reports for the three fatal and serious injury crashes reported on KY 55 following conversion to a 2 + 1 configuration.

3.4.1 Fatal Crash in 2020 on KY 55 in Washington County

A fatal crash involving three vehicles occurred in February 2020 during heavy rain and limited visibility. Vehicle 1 was traveling southbound on KY 55 toward Marion County and was behind several vehicles as it entered the passing lane section. Vehicle 1 and at least one more vehicle attempted to enter the passing lane to go around slower moving vehicle that moved to the right-hand lane. The vehicle in front of Vehicle 1 executed a successful passing movement, but Vehicle 1 lost control. The vehicle's rear end drifted into the oncoming lane of travel and struck the driver's side of Vehicle 2. After striking Vehicle 2, Vehicle 1 rotated counter clockwise at least 180 degrees and began traveling southward in the northbound lane. The back end of Vehicle 1 then struck the front end of Vehicle 3. After the collision, an off duty EMT attempted to help vehicle occupants involved in the incident and found the driver of Vehicle 3 dead on arrival. The crash report listed the following factors as contributing to the collision:

- Human Factors
    - Exceeded Stated Speed Limit
    - Failed To Keep Proper Lane
    - Too Fast For Conditions
- Vehicular Factors
    - Tires
- Environmental Factors
    - Slippery Surface
    - Water Pooling

3.4.2 Serious Injury Crash in 2017 on KY 55 in Adair County

A serious injury crash involving two vehicles occurred in November 2017. As Vehicle 1 and Vehicle 2 traveled northbound, Vehicle 2 stopped in the roadway waiting for a clear gap in southbound traffic to turn left into private business parking lot. Vehicle 1 then struck the rear end of Vehicle 2. Vehicle 1's driver stated they did not see that Vehicle 2 had stopped. The crash report listed the following factor as contributing to the collision:

- Human Factors
    - Inattention

3.4.3 Serious Injury Crash in 2020 on KY 55 in Taylor County

A serious injury crash involving two vehicles traveling in opposite directions occurred in September 2020. Vehicle 1 was traveling southbound on KY 55 and Vehicle 2, a semi-trailer truck, was traveling northbound. As Vehicle 1 attempted to pass another vehicle in a no passing zone it collided with Vehicle 2 in the northbound lane. The driver of Vehicle 2 attempted to avoid Vehicle 1 but could not get off the road before Vehicle 1 sideswiped its trailer. Vehicle 1 came rest on the shoulder of the southbound lane against a guardrail, facing south. The driver of Vehicle 1 reported they had been drinking. Due to their injuries, the driver was flown to the University of Louisville Hospital. The crash report listed the following factors as contributing to the collision:

- Human Factors
    - Improper Passing
    - Inattention
    - Not Under Proper Control

3.5 Summary

Without additional data, we cannot draw definitive conclusions about the safety performance of Kentucky's new 2 + 1 roadways. Based on available crash records, roadway operations and safety are similar to other rural Kentucky highways, although crash rates fell on two of the three segments we looked at. KYTC will benefit from continued observation and study of the safety performance of Kentucky's 2+1 roadways.

Chapter 4 2+1 Roadway Design Guidance

In August 2013 KYTC's Division of Highway Design released design guidance on 2+1 roadways that covered design principles, location guidelines, passing lane layouts, and geometrics. Since 2013 KYTC has learned a great deal about 2+1 roads through project development and observing traffic operations in Kentucky and elsewhere. The updated guidance proposed in this report draws on research, guidelines, and policies from other DOTs and from KYTC's experience with 2+1 roads over the past decade. This chapter summarizes key updates in the refreshed guidance.

4.1 2+1 Roadway Design Comparisons

We compared KYTC's 2013 2+1 guidance to policies and practices in other publications and research reports as well as those adopted by other state DOTs. We examined the following documents:

- 2018 Green Book — A Policy on Geometric Design of Highways and Streets, 7th Edition
- Missouri Department of Transportation Engineering Policy Guide, *233.3 Passing Lanes*
- Texas Department of Transportation Roadway Design Manual, Section 6 *Super 2 Highways*
- Colorado Department of Transportation 2018 Roadway Design Guide, *3.3.6 Passing Lanes* and *3.3.7 2+1 Roadways*
- Sarchet et al., 2+1 ROAD WITH BARRIER; Evaluation of the Feasibility of Deployment of Swedish 2+1 Road with Barrier in Colorado (2020)
- Minnesota Department of Transportation 2012 Road Design Manual, *Chapter 4 Passing Lanes*
- Minnesota Department of Transportation, *Technical Memorandum No. 98-08-ES-01* (1998)
- Washington State Department of Transportation 2021 Design Manual, *Chapter 1270.03 Passing Lanes*

The results of this comparison are reproduced below.

KYTC Design Guidance for 2+1 Roadways

Agency	Traffic Volume for Recommended Use (ADT)	Passing Lane Length	
Kentucky Transportation Cabinet	5,000 to 20,000 ADT (design year volumes of 15,000 to 20,000 -2 +1 Roadway Initial, 4-lane Ultimate)	**Directional Flow Rate (pc/h)** <400 <700 ≥700	**Directional Flow Rate (pc/h)** ≥0.5-0.75 ≥0.75-1.00 >1.00-2.00
AASHTO Green Book 2018	Should not be used where current or projected flow rates exceed 1,200 veh/h in one direction.	**One-Way Flow Rate (veh/h)** 100-200 201-400 401-700 701-1200	**Passing Lane Length (mi)** 0.5 0.50-0.75 0.75-1.00 1.00-2.00
Missouri DOT	Level of service for a two-lane highway is defined in terms of two primary service measures: Percent time spent following and Average travel speed. Appropriate for two-lane roadways carrying relatively high traffic volumes where nearly continuous passing lanes are needed to achieve the desired level of service.	**Directional Flow Rate (pc/h)** Less than 100 100 - 400 400 - 700 ≥700	**Passing Lane Length (mi)** ≤0.5 ≥0.5-0.75 ≥0.75-1.00 >1.00-2.00
Texas DOT	A Super 2 project can be introduced on an existing two-lane roadway where there is a significant amount of slow moving traffic, limited sight distance for passing, and/or the existing traffic volume has exceeded the two-lane highway capacity, creating the need for vehicles to pass on a more frequent basis.	**Minimum** 1 mi	**Desirable** 1.5 -2 mi
Colorado DOT	May be suitable for corridors with traffic volumes higer than can be served with isolated passing lanes, yet not high enough to require a consistent four lane cross section. Should not generally be considered where the volume exceeds 1,200 vehicles per hour in one direction.	Uses the Green Book guidance.	
CDOT-2020-05 Research Report	Not specifically mentioned. They used a B/C analysis focused upon reducing crashes and the cost to implement the 2+1.	Passing lane lengths preferred length is between ½-mile and 1-mile. •The absolute minimum length for a passing lane is ¼ mile. •Lengths over 1-mile lose efficiency, but are permissible.	
Minnesota DOT	Considers passing lanes using five methods: operational criteria, level of service criteria, cost effectiveness analysis, benfit-cost analysis and safety methods. *Project volume of 6000 ADT is minimum. No max volume noted.	**One-Way Flow Rate (veh/h)** 100 200 400 700 or higher	**Passing Lane Length (mi) (They have good guidance on length. See their Manual.)** 0.5 0.50-0.75 0.75-1.00 1.00-2.00
Washington State DOT	See traffic flow rates in the table.	**One-Way Flow Rate (veh/h)** 100 200 400 700 or higher	**Passing Lane Length (mi) (They have good guidance on length. See their Manual.)** 0.5 0.50-0.75 0.75-1.00 1.00-2.00

	Flush Median	Centerline Rumble Strips
Kentucky Transportation Cabinet	Preferred - 4ft	Recommended regardless of median width
AASHTO Green Book 2018	Preferred - 4ft KYTC guidance used the Green Book guidance	Not mentioned.
Missouri DOT	Preferred - 4ft	Must be addressed.
Texas DOT	Not mentioned.	Not mentioned.
Colorado DOT	Not mentioned.	Not mentioned.
CDOT-2020-05 Research Report	6-foot median (including cable barrier)	Not mentioned.
Minnesota DOT	Not mentioned, however, based on context, they did suggest wider lanes (14ft) could be utilized next to the centerline striping	Recommended regardless of median width
Washington State DOT	Not mentioned.	See Chapter 1600 for shoulder rumble strip criteria and considerations.

	Location of the Crown	Superevation
Kentucky Transportation Cabinet	Retrofit Existing Road: May Be Placed within the Traveled Way New Construction: Placed at a Lane Boundary	Handled no differently on a 2+1 roadway than on a comparable two- lane or four-lane undivided road
AASHTO Green Book 2018	KYTC guidance used the Green Book guidance.	KYTC guidance used the Green Book guidance.
Missouri DOT	Not mentioned.	Not mentioned.
Texas DOT	Not mentioned.	Not mentioned.
Colorado DOT	Not mentioned.	Not mentioned.
CDOT-2020-05 Research Report	Not mentioned.	Not mentioned.
Minnesota DOT	The grade line should coincide with the highway centerline on 2-lane and multi-lane undivided highways.	Not mentioned.
Washington State DOT	Widening symmetrically to maintain the roadway crown at the centerline is preferred, including in continuous passing lane configurations. However, the roadway crown may be placed in other locations as deemed appropriate. Considerations for crown locations might include: costs, constructability, right of way, environmentally sensitive roadsides, or other factors.	When designing the addition of passing lanes, make sure existing curves at the desired location have adequate superelevation to provide speeds suitable for passing.

	Minimum Recommended Typical Section (Used to retrofit existing super two-lane roadways)	Ideal Typical Section (Used on new construction and high-speed/high volume designs)
Kentucky Transportation Cabinet	**Lane Width:** 11 feet **Paved Shoulder Width:** 2 feet **Flush Median Width:** 1 foot **Total Pavement Width:** 38 feet	**Lane Width:** 12 feet **Paved Shoulder Width:** 8 feet - Single Lane Side 4 feet - Passing Lane Side **Flush Median Width:** 1 foot **Total Pavement Width:** 52 feet
AASHTO Green Book 2018	**Lane Width:** Determined from volumes, speeds, and functional classes in Green Book Chapters 5, 6, and 7. From Table 6-5 for Rural Collector, over 2000 ADT, and 55+ mph. Also from 7.2.11.2 (reconstruction) 11 feet **Paved Shoulder Width:** 6 feet (both sides) **Flush Median Width:** Retrofit median width not mentioned. Use 1 foot. **Total Pavement Width:** 46 feet	**Lane Width:** Determined from volumes, speeds, and functional classes in Green Book Chapters 5, 6, and 7. From Table 7-3 for Rural Arterial,over 2000 ADT, and 55+ mph. Also from 7.2.11.4 12 feet **Paved Shoulder Width:** 8 feet (both sides) **Flush Median Width:** 4 feet **Total Pavement Width:** 56 feet
Missouri DOT	**Lane Width:** Typical lane widths of 12 ft. are to be used throughout the length of the passing lane unless a reduced lane width would substantially reduce costs. In general, the lane width is to be the same as the lane width on the adjacent sections of two-lane highway. (MODOT does use 11ft lanes on retrofits.) **Paved Shoulder Width:** Whenever practical, the shoulder width in a passing lane section is not to be narrower than the shoulder width on the adjacent sections of two-lane highway. In no case shall the shoulder width be less than 4 ft. **Flush Median Width:** Passing lanes can operate effectively with no separation between opposing lanes of travel. MODOT has used 0 feet for the median. **Total Pavement Width:** 41 feet	**Lane Width:** Same as Minimum Recommended Typical Section **Paved Shoulder Width:** Typical shoulder widths are to be used throughout the length of the passing lane unless a reduced shoulder width would substantially reduce costs. Whenever practical, the shoulder width in a passing lane section is not to be narrower than the shoulder width on the adjacent sections of two-lane highway. 8 feet. **Flush Median Width:** A flush separation of 4 ft. between the opposing directions of travel is preferred if at all possible. 4 feet. **Total Pavement Width:** 56 feet
Texas DOT	**Lane Width:** Minimum 11ft, Desirable 12ft **Paved Shoulder Width:** Minimum 3ft, Desirable 8 - 10ft Consider providing full shoulders (8'-10') in areas with high driveway density. **Flush Median Width:** Not mentioned. **Total Pavement Width:** Minimum 39ft, Desirable 56ft	**Lane Width:** Not mentioned for new construction. **Paved Shoulder Width:** Not mentioned for new construction. **Flush Median Width:** Not mentioned for new construction. **Total Pavement Width:** Not mentioned for new construction.

Agency	Minimum Recommended Typical Section (Used to retrofit existing super two-lane roadways)	Ideal Typical Section (Used on new construction and high-speed/high volume designs)
Colorado DOT	**Lane Width:** Uses the Green Book guidance. **Paved Shoulder Width:** Uses the Green Book guidance. **Flush Median Width:** Uses the Green Book guidance. **Total Pavement Width:** Uses the Green Book guidance.	**Lane Width:** Uses the Green Book guidance. **Paved Shoulder Width:** Uses the Green Book guidance. **Flush Median Width:** Uses the Green Book guidance. **Total Pavement Width:** Uses the Green Book guidance.
CDOT-2020-05 Research Report	**Lane Width:** 12-foot single lane, two 11-foot lanes **Paved Shoulder Width:** 4-foot outside shoulders **Flush Median Width:** 6-foot median (including cable barrier) **Total Pavement Width:** 46 feet	**Lane Width:** Not mentioned for new construction. **Paved Shoulder Width:** Not mentioned for new construction. **Flush Median Width:** Not mentioned for new construction. **Total Pavement Width:** Not mentioned for new construction.
Minnesota DOT	**Lane Width:** The passing lane width shall be 12 ft **Paved Shoulder Width:** The shoulder width should be 6 ft (minimum). When a composite shoulder is used on the highway, the passing section should also use a composite shoulder. An example would be a highway which has 2 ft bituminous and 4.0 ft gravel (minimum). **Flush Median Width:** Not mentioned. **Total Pavement Width:** 48 feet	**Lane Width:** The passing lane width shall be 12 ft **Paved Shoulder Width:** The shoulder width should be 10 ft (desirable). When a composite shoulder is used on the highway, the passing section should also use a composite shoulder. An example would be a highway which has a 10 ft composite shoulder comprised of 2 ft bituminous and 8.0 ft gravel (desirable). **Flush Median Width:** Not mentioned. **Total Pavement Width:** 56 feet
Washington State DOT	The shoulder may be reduced to 4 feet. If the shoulder width is reduced to 4 feet, document the reason for the decision on the design parameter sheets. If the shoulder width is reduced to less than 4 feet, a design analysis is required.	Where practicable provide shoulder width in a passing lane section equal to the shoulder width on the adjacent segments of a two-lane highway.

	Critical Lane Transition	Non-Critical Lane Transition
Kentucky Transportation Cabinet	320 foot buffer (No Man's Land) L = WS for S ≥ 45mph (Green Book Equation 3-38) or L = (WS2)/60 for S < 45mph (Green Book Equation 3-39)	Taper 100ft (along centerline) minimum in urban areas Taper 200ft (along centerline) minimum in rural areas
AASHTO Green Book 2018	KYTC guidance used the Green Book guidance.	KYTC guidance used the Green Book guidance.
Missouri DOT	MODOT guidance used the Green Book guidance.	MODOT guidance used the Green Book guidance.
Texas DOT	Minimum 50 foot buffer, Stopping Sight Distance Desirable (No Man's Land) Taper length from each direction based on L = WS	Length for opening a passing lane is L = WS/2, and for closing a passing lane is L = WS.
Colorado DOT	CODOT guidance used the MUTCD/Green Book guidance. They do not discuss critical vs. non-critical transitions. Adequate sight distance should be provided at both the add and drop lane tapers. A minimum sight distance of 1000 feet on the approach to each taper is recommended.	
CDOT-2020-05 Research Report	Critical tapers will be standard merging tapers of S:1 (where S is the Speed Limit or 85th percentile Speed) (tapering from 22-feet to 12-feet the taper will be 10 x S feet long) (Due to observed operational difficulties at left-lane drops in Colorado, at critical (merging) transitions the right lane should be dropped (using the S:1 merging taper) and then redirection transition (also S:1, so length = 10 x S again) should move traffic from the left (center) lane to the right.)	Non-Critical (Diverging) Tapers: Non-critical tapers should be 100 feet.
Minnesota DOT	Minimum 50 foot buffer, Stopping Sight Distance Desirable (No Man's Land) Taper length from each direction based on L = WS	Length for opening a passing lane is L = WS/2, and for closing a passing lane is L = WS.
Washington State DOT	The recommended minimum transition distance between passing lanes in opposing directions is 500 feet for "tail-to-tail" and 1,500 feet for "head-to-head" (see Exhibit 1270-8).	**1270.03(3)(c) Intersection-Related Considerations:** Consider a corridor evaluation of potential passing lane locations for each direction, avoiding placement of passing lanes near intersections. Avoid or minimize turning movements on a road section where passing is encouraged. Avoid locating passing lanes near high-volume intersections, existing structures, railroad crossings, areas of dense development, and two-way left-turn lanes.

	Access Control Recommendations	Right of Way
Kentucky Transportation Cabinet	• No Left Turns within first 1000 feet of the start of the passing lane • Major intersections or access points be placed at the passing zone transition zones so that auxiliary turn lanes may be provided • Special provisions for turning vehicles, such as exclusive left-turn lanes are to be considered at higher-volume intersections and driveways.	The purchase of access rights from adjacent properties should be considered; this creates full control of access between major intersections.
AASHTO Green Book 2018	• Major intersections should be located in the transition areas between opposing passing lanes and conventional left-turn lanes provided at the intersection. • Low-volume intersections and driveways may be accommodated within the passing lance sections.	Not mentioned.
Missouri DOT	The number, type, and location of entrances are to be considered.	Not mentioned.
Texas DOT	• Consider providing a left turn lane if a significant traffic generator falls within the limits of a Super 2. • When evaluating the termination of a passing lane at an intersection, consideration should be given to traffic operations turning and weaving movements, and intersection geometrics. If closure of the passing lane at the intersection would result in significant operational lane weaving, then consideration should be given to extending the passing lane beyond the intersection.	Existing ROW width considerations must be analyzed to determine feasibility of upgrading to a Super 2.
Colorado DOT	Intersection locations should be considered when determining passing locations to minimize turning movements within passing lanes or to provide dedicated left turn lanes at intersections	Not mentioned.
CDOT-2020-05 Research Report	• Intersections with significant volumes (500+ side road ADT) will include widening to accommodate auxiliary lanes so no turning traffic needs to decelerate in a thru or passing lane. • The center lane may serve as left turn lanes if both passing lanes can be tapered out and redirected before the intersection (right lane drop, then redirect to the right, then open a left turn auxiliary lane), barrier ends where auxiliary lane begins. • While breaks in the center cable rail will generally be necessary to retain the existing level of functionality, some accesses may be sufficiently minor or may have a sufficient degree of redundancy as a result of being very close to another access point, that they needn't be specifically accommodated.	Not mentioned.
Minnesota DOT	• The passing section shall be located where a minimal number of entrances are present. On the lane drop side, entrances are prohibited in the area of a lane drop transition and 170 ft (50 m) beyond unless approved by the Geometrics Engineer. On the two lane side, entrances are undesirable over the same distance. • Public road intersections are undesirable anywhere within the passing lane section. If a public road intersection cannot be avoided, it should have a very low ADT and good sight distance. Exclusive left turn lanes should be considered. Public road intersections are extremely undesirable near the end or beginning of a passing lane section. If such an intersection cannot be avoided near the end (beginning) of a passing lane section, the passing lane should be extended a minimum of 900 ft (270 m) past (prior to) the intersection. • Districts are strongly encouraged to acquire access control throughout the passing lane section to prevent new entrances from being built.	Not mentioned.
Washington State DOT	• Consider providing a left turn lane if a significant traffic generator falls within the limits of a Super 2. • When evaluating the termination of a passing lane at an intersection, consideration should be given to traffic operations turning and weaving movements, and intersection geometrics. If closure of the passing lane at the intersection would result in significant operational lane weaving, then consideration should be given to extending the passing lane beyond the intersection. • Provide right- and left-turn lanes in passing lane sections where they would be provided on a conventional twolane highway. Left turns within the first 1,000 feet of a passing lane are undesirable. Strategies to address the turning movement could include left-turn lanes, right-in/right-out access, beginning the passing lane after the entrance, and so on.	Not mentioned.

Other Recommendations

	Other Recommendations
Kentucky Transportation Cabinet	• Typical section elements may be reduced or the passing lane eliminated for short sections such as structures or extensive cut sections, where doing so would provide significant cost savings. • A symmetrical 2+1 Roadway design maintains a continuous three-lane cross section, utilizing the center lane to provide a passing lane in alternating directions along the highway. An asymmetrical 2+1 Roadway adds the third lane for passing on the outside of a consistent two-lane roadway.
AASHTO Green Book 2018	• Should only be used in level or rolling terrain. • Stopping sight distances should be provided continuously along a 2+1 Roadway. • Decision sight distance should be considered at intersections and lane drops.
Missouri DOT	• Particularly appropriate over an extended section of roadway where a wide pavement is already available. • May use either a two-lane cross-section with added pavement for passing lanes (asymmetrical) or a three-lane cross-section with the middle lane used for alternating passing lanes (symmetrical). • Signing and delineation are essential to the operation of passing lanes. • Safe and effective passing lane operations require adequate sight distance on the approach to lane addition and lane drop tapers.
Texas DOT	• The location of large drainage structures and bridges should be evaluated when considering the placement of passing lanes. • Evaluate traffic operations including truck volumes if consideration is given to terminating passing lanes on significant uphill grades. Coordinate passing lanes with climbing lane needs to improve operating characteristics. • Avoid closing a passing lane over a hill or around a horizontal curve where the pavement surface at the end of the taper isn't visible from the beginning of the taper. • Allow adequate distance (recommend stopping site distance) between the end of a lane closure taper and a constraint such as metal beam guard fence, a narrow structure, or major traffic generator. • Consider providing the passing lane in the direction leaving an incorporated area for potential platoons generated in the urban area.
Colorado DOT	• The 2+1 roadway concept has been found to improve operational efficiency and reduce crashes for select two-lane highways • Should be used on level or rolling terrain; mountainous terrain or steep grades should consider climbing lanes as an alternative. • The selection of the location should consider the location of intersections and high-volume driveways as well as physical constraints such as bridges and culverts that could restrict provision of a continuous shoulder.
CDOT-2020-05 Research Report	• The cross section may revert to 2-lane (with barrier) in constrained locations, approaching intersections, where driveway access density is high, etc.. • Observational before and after studies conducted in Sweden over more than 20 years, show that a 75% crash reduction in fatalities and a 50% reduction in injuries can be expected
Minnesota DOT	• *To fully appreciate the value of the concept it is desirable to apply it to segments of at least 30 kilometers (18.6 miles) in length. • A 10 ft bituminous shoulder shall be used in the lane drop area and 500 ft (desirable) beyond to provide a recovery area for drivers who may encounter a conflict. A 1:25 taper transition should be used from the 10 ft shoulder to the normal shoulder. • Safe and effective passing lane operations require adequate sight distance on the approach to both the lane addition and lane drop tapers. A minimum sight distance of 1,000 ft (300 m) on the approach to each taper is required. • Passing lanes are much more effective if the majority of drivers enter the right lane at the lane addition transition and use the left lane for passing slower vehicles. Therefore, the geometric design of the lane addition transition should encourage drivers to enter the right lane. Signing and markings will also provide guidance for drivers to enter the right lane.
Washington State DOT	• See 1270.03(1) Passing Lane Benefits • See 1270.03(3) Passing Lane Location. • See 1270.03(4)(a) Alternative Configurations

4.2 KYTC Roadway Design Guidelines For 2+1 Roadways

Using the comparisons presented above as a baseline, the project's study advisory committee discussed and selected guidelines that address Kentucky's needs. The guidelines and their justifications are discussed below.

4.2.1 – 2+1 Roadways Definition

The guidance provides clearer definitions of 2+1 roadways and adds material on their objectives and drawbacks. NCHRP Project 20-7 comments were removed. The term *shared four lane* is replaced by the industry-standard terms *2+1 road* or *2+1 roadway*.

4.2.2 – 2+1 Roadway Passing Lanes Definition

This section describes symmetrical and asymmetrical designs and illustrates both configurations. Optimal passing lane lengths for traffic operational efficiency were updated to reflect the 2018 Green Book. The guidance specifies one-way flow rates (vehicles/hour) and recommended passing lane lengths (miles). Vehicle merging behaviors at the end of a passing lane can be problematic at high traffic flow rates and when heavy vehicles make up a high percentage of traffic. Higher flow rates reduce the average gap between vehicles, forcing drivers to merge into smaller gaps. Drivers merging into smaller gaps disrupts traffic flow as following vehicles must decelerate for the merging vehicles. Eventually, a threshold is reached at which point the passing lane's performance degrades below that of a non–passing lane segment. The maximum recommended one-way flow rate for a 2+1 facility is 1,200 vehicles/hour.

Recommendations for traffic volume thresholds remain unchanged. While flow rate is a better measure for operational analysis of 2+1 roads, average daily traffic (ADT) is a useful metric when considering a 2+1 roadway alternative. The guidance recommends that 2+1 configuration should be considered as the ultimate design for roads with a design year volume of 15,000 ADT or less. For design year volumes of 15,000 – 20,000 ADT, a 2+1 configuration may be used as the initial design, but KYTC should purchase right of way to accommodate expansion to a four-lane facility.

4.2.3 – 2+1 Roadway Design Considerations

The guidance adds more information on key design considerations, including passing lane length, operational direction, and the location of transitions. Designers have the flexibility to choose passing lane locations to maximize a facility's operational effectiveness and minimize construction costs. Guidance also emphasizes that 2+1 concepts must be developed throughout the roadway corridor by a design team carefully examining geometric, operational, and site-specific factors.

4.2.4 – Passing Lane Transitions

The guidance provides expanded detail on passing lane transitions. The terms *head-to-head* and *tail-to-tail* are substituted for *critical transition* and *non-critical transition*, respectively. KYTC will continue using equations from the *Green Book* to calculate lane-drop taper lengths — Equation 3-38 for speed limits ≥ 45 mph and Equation 3-39 for speed limits < 45 mph. Taking a cue from how other states lay out transitions, the guidance provides a range for head-to-head buffers:

A minimum buffer of 200 feet should provide adequate warning and stopping distance to accommodate opposing vehicles that cross their lane reduction taper and enter the transition area. For example, where the pavement markings establish a lane drop, a 12-foot lane and 55 mph speed limit would require a taper distance of 660 feet. Adding one-half the buffer zone length (100 feet) means the distance from the start of the passing lane transition to the middle of the head-to-head transition should be 760 feet. In this scenario, a vehicle traveling 55 mph would need more than nine seconds to proceed from the beginning of the lane reduction taper to the middle of the buffer zone. Taper distance, pavement markings, and centerline rumble strips should be adequate to alert errant drivers and give them enough time to take corrective action. The *Green Book* recommends a 320-foot buffer between the end of each lane drop, which may be more appropriate for higher ADT routes or those with higher percentages of truck traffic.

4.2.5 – 2+1 Roadway Access Management
The guidance offers an expanded treatment of 2+1 roadway access management. It discusses intersection placement as well as considerations for adding right-turn-lanes, left-turn lanes, and two-way left-turn lanes. A turn lane can be one of the lanes in a three-lane section (i.e., transition to single-lane operations in each direction and use the third lane as the auxiliary lane). Or a turn lane can be added by widening a road (i.e., build four lanes to create the extra pavement width needed for an auxiliary lane).

Designers need to consider reduced turning-lane warrants when the road context calls for extra safety measures (e.g., adequate sight distance is not available at an intersection, several entrances are in close proximity, or there is a high posted speed (≥ 45 mph) and high flow rate).

4.2.6 – 2+1 Roadway Typical Section
Guidelines on 2+1 roadway typical sections remain largely unchanged. Lane and shoulder widths are calculated using the same procedures as for conventional two-lane highways — by considering functional class, volumes, and speeds. The guidance directs users to the *Highway Design Manual* (HD-702.10) for more information. Where feasible, a flush median separation of 4 feet between the opposing directions of travel is preferred. Centerline rumble strips and pavement markers are recommended on all 2+1 facilities. Lane pavement crown point and superelevation guidelines are consistent with the 2013 guidance.

4.2.7 – Signing and Pavement Markings
The guidance addresses signing and pavement markings, which are essential to the safe and effective operation of 2+1 passing lanes. It references the *Traffic Operations Guidance Manual* and the latest edition of the *Manual on Uniform Traffic Control Devices*. Chapter 5 of this report (*2+1 Roadway Signing and Markings*) has more information on this topic.

4.2.8 – Public Involvement
The guidance encourages additional public involvement activities to inform residents and businesses of the 2+1 configuration's benefits and intended use. The guidance directs users to the Highway Design Manual (HD-601) and KYTC's Public Involvement Toolbox for more information.

Chapter 5 Recommendations for Signing and Marking 2+1 Roads

Agencies communicate critical information to motorists about road configurations and driving operations through signs and pavement markings. While the MUTCD establishes the minimum traffic control needed along highways, 2+1 roads warrant an expanded set of traffic control devices. This chapter presents recommendations for signing and marking 2+1 roads. Recommendations are based on the literature review, state guidance, survey results, and the MUTCD.

5.1 Summary of Recommendations

Approach to Passing Lane
Recommended signing criteria for the Approach to the Passing Lane area:

- Install a PASSING LANE ½ MILE sign in advance of the **first** passing lane on a 2+1 corridor.
- Install a NEXT PASSING LANE X MILES sign at the beginning of the passing lane approach or interior passing lanes on a 2+1 corridor. Place the sign approximately 500 feet from the end of taper for the previous passing lane.

Recommended signing criteria for the Approach to the Passing Lane area of a truck climbing lane:

- Install a TRUCK LANE ½ MILE sign in advance of truck climbing lanes.
    - The Traffic Operations Guidance Manual (TOGM) has two options for advance signing on the existing Truck Climbing Lane detail (500 feet and ½ mile). We recommend deleting the option to place the sign at 500 feet.

Lane Addition Taper and Passing Lane
Recommended signing criteria for the Lane Addition Taper and Passing Lane area:

- Install a KEEP RIGHT EXCEPT TO PASS (R4-16) sign after the passing lane has been added. Place the sign 200 feet beyond the end of the lane addition taper.

Recommended signing criteria for the Lane Addition Taper and Passing Lane area of a truck climbing lane:

- On two-lane highways, install a SLOWER TRAFFIC KEEP RIGHT (R4-3) sign at the beginning of the lane addition taper.
- On multi-lane highways, install a TRUCKS USE RIGHT LANE (R4-5) sign after the truck climbing lane has been added. Place the sign 200 feet beyond the end of the lane addition taper.

Approach to Lane Reduction
Recommended signing criteria for the Approach to Lane Reduction area:

- Place a Lane Reduction Symbol (W4-2) sign a distance “d” in advance of the lane reduction taper.
- Place a LEFT (RIGHT) LANE ENDS (W9-1) sign 200 feet in advance of the W4-2 sign.
- Adopt dual-mounted Lane Reduction warning signs.

Note: These criteria match those shown in TOGM Exhibit 5 (truck climbing lane detail).

KYTC may want to consider developing Standard Drawings that show recommended signing and markings for lane reductions on one-way, two-lane, and multi-lane highways. These should address both left- and right-lane merges. The drawings should incorporate criteria similar to the signing/markings recommended for 2+1 lane reductions. On one-way streets or divided highways where median width permits, mount Lane Reduction signs on the left side of the roadway where the left lane is the lane which is ending.

Downstream Area
Recommended signing criteria for the Upstream and Opposing area:

- Install a NO PASSING ZONE (W14-3) sign 500 feet in advance of either end of a 2+1 corridor to supplement other no-passing zone markings.
- Install a PASSING LANE ½ MILE sign for the first passing lane on both approaches to a 2+1 corridor.

Centerline Markings and No Passing Zones
Recommended signing criteria for center line markings:

- Establish no passing in advance of and throughout 2+1 corridors.
- Establish no passing with a two-way no passing zone marking that begins 500 feet in advance of each corridor and extends to a point 500 feet beyond the 2+1 corridor.
- Use the patterns in Table 5.1 for center line pavement markings:

Table 5.1 Centerline Pavement Markings According to Median

No median	• Two-way no passing marking
Median < 4 ft.	• Single solid line on either side • Use double yellow lines in transition areas where flush medians become ≥ 4 ft.
Median ≥ 4 ft.	• Double yellow center line on either side of the median

KYTC should evaluate the safety performance of truck climbing lanes with opposing lane passing zones and/or set thresholds that would warrant the establishment of no-passing zones on these roads.

Lane Addition and Transition Markings
Recommended marking criteria for lane additions and lane transitions:

- Include the creation of a central median with a double yellow no passing line through the lane addition taper to direct motorists into the rightmost lane.
- Include a marked taper (200 foot minimum) for entry into passing lane entry tapers. Use a minimum buffer zone of 200 feet for critical transitions where opposing vehicles merge while travelling towards each other (at 55 MPH, the total length of the central median is 660 ft. taper + 200 ft. buffer zone + 660 ft. taper = 1,520 ft.).

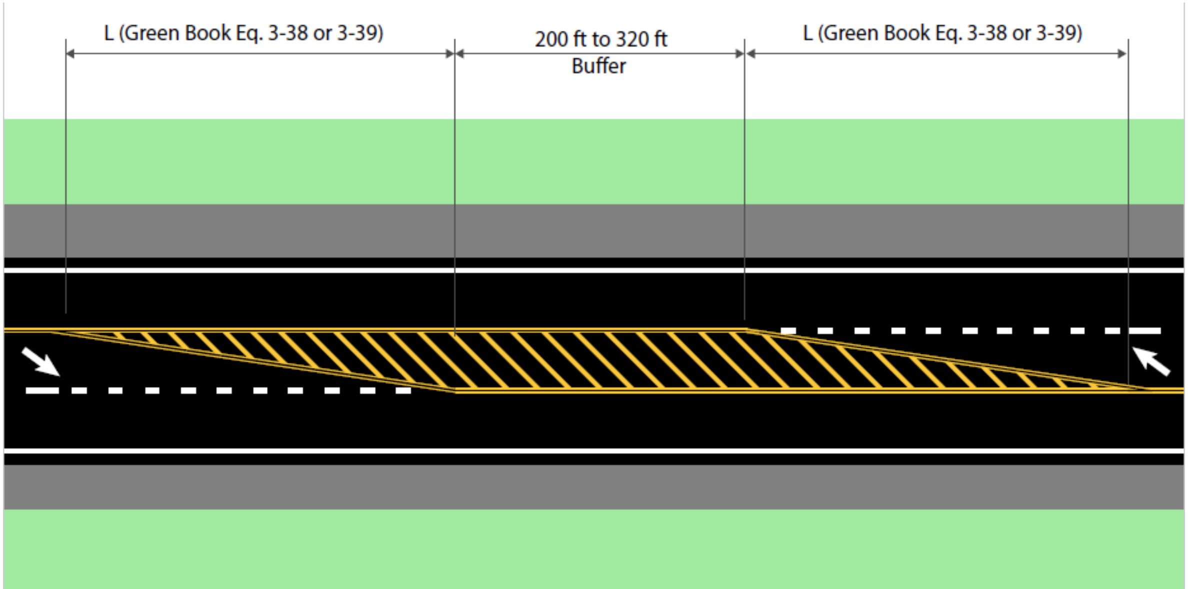


Figure 5.1 Recommended Striping for Critical Transitions

- Do not require a buffer zone for non-critical transitions where opposing vehicles diverge as they travel away from each other. In these areas, provide a central median by marking opposing lane entry tapers adjacent to each other (the total length of the median is 200 ft. taper + 200 ft. taper = 400 ft.).

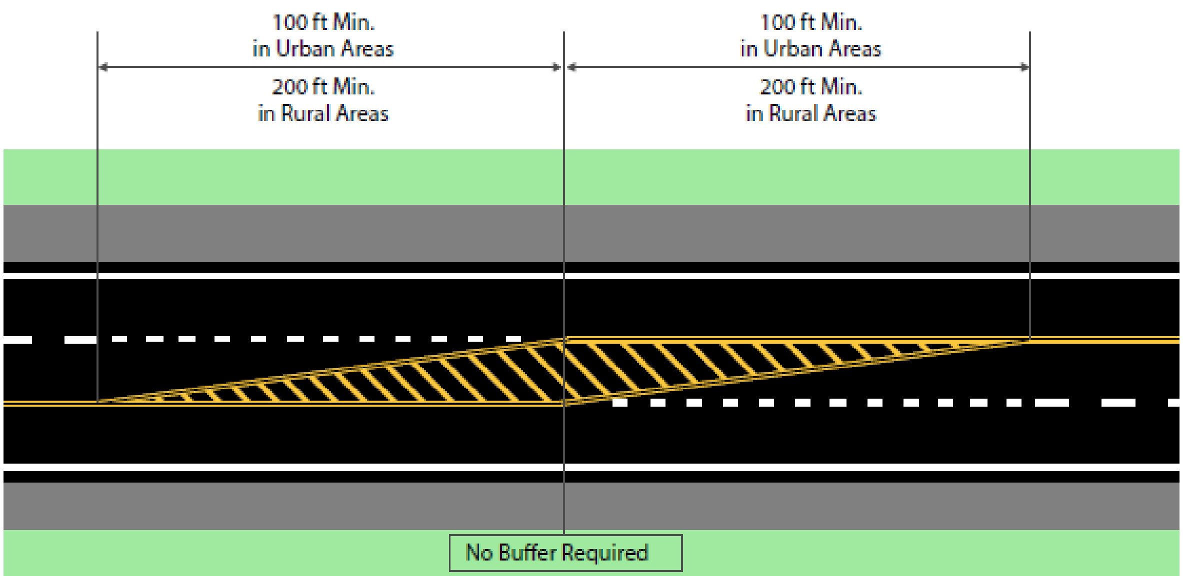


Figure 5.2 Recommended Striping for Non-Critical Transitions

- Install diagonal crosshatching with yellow lines (2 foot lines at 50 foot spacing) through lane additions, lane transitions, and buffer zones.
- Install white dotted line extensions across entry tapers to passing lanes and auxiliary turning lanes. Dotted lines consist of 3 foot segments with 9 foot gaps that are the same width as the edge line and center line markings.
- For truck climbing lanes, paint a dotted line across the entry taper to direct motorists into the center lane.

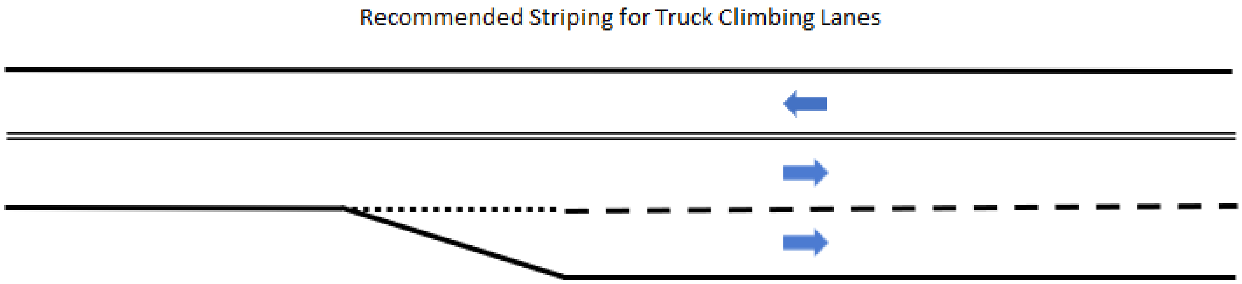


Figure 5.3 Recommended Striping for Truck Climbing Lanes

Lane-Reduction Transition Markings
Recommended criteria for lane reduction markings:

- Discontinue broken lane lines at a distance of ½ d in advance of the lane reduction taper.
- Use a minimum of two lane-reduction arrows on the approach to lane reductions. Install the first lane reduction arrow near the Lane Ends (W4-2) symbol sign (distance of d in advance of the lane reduction taper) and the second arrow at the end of the broken lane line (distance of 1/2 d from the lane reduction taper). Lane reduction arrows may be eliminated if the speed limit is < 45 MPH.
- Delineators may be installed along the lane reduction taper for passing lanes on asymmetrical 2+1 corridors. Spacing should be approximately 100 feet throughout the taper.

Recommendations for truck lane and two-to-four lane transition signing details should be incorporated into the TOGM.

KYTC should consider developing Standard Drawings that show recommended signing and markings for lane reductions on one-way, two-lane, and multi-lane highways. Drawings should address left- and right-lane merges and incorporate lane reduction signing/markings previously recommended in this report.

Raised Pavement Markers
KYTC should consider including 2+1 roads on its Pavement Marker System. Since pavement marking plans do not typically address the placement of pavement markers, the Cabinet should consider developing a Standard Drawing that shows the recommended placement of pavement markers relative to centerline striping and centerline rumble strips.

Rumble Strips
- Modify Standard Drawing TPR-100 to show rumble strips through both sets of double yellow centerlines.
- Use an edge line rumble stripe in 2+1 corridors based on engineering judgment.

Markings for Common Scenarios
Figure 5.4 illustrates recommended markings and marking locations for common scenarios.

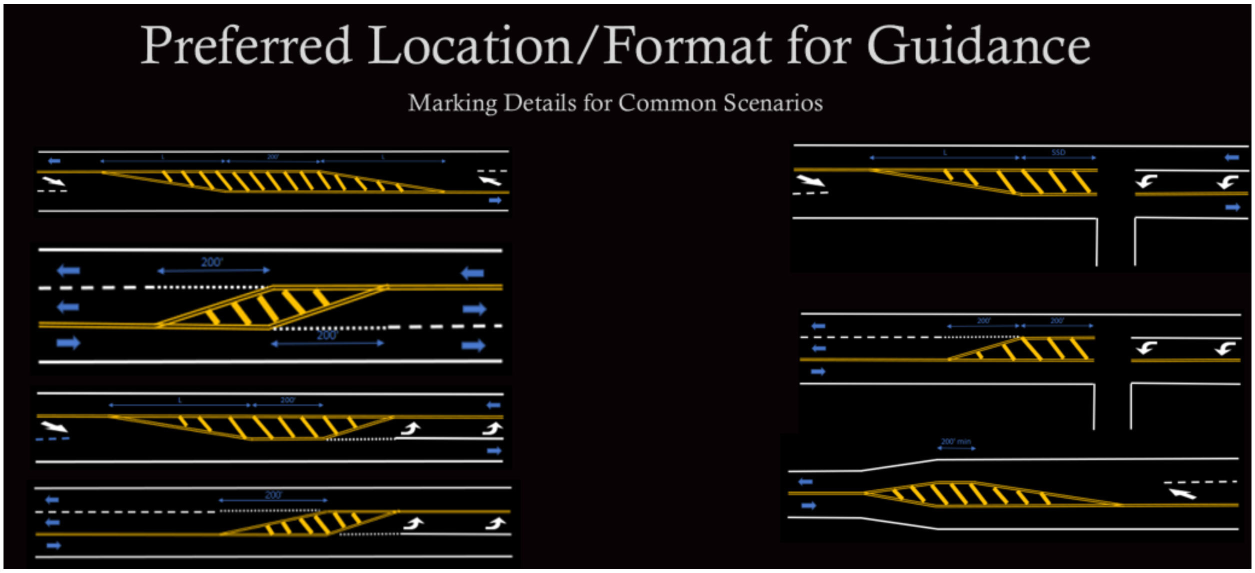


Figure 5.4 Preferred Marking Locations for Common Scenarios

Signing and Marking Details
Detailed drawings are provided for the following:

- Typical signing scenarios for 2+1 roadways (Figure 5.5)
- Typical markings scenarios for 2+1 roadways (Figures 5.6 and 5.7)
- Centerline markings and rumble strip arrangements for 2+1 Roadways (Figure 5.8)

Because 2+1 roads typically have a striping and/or signing plan, a Standard Drawing for signs and markings would provide limited benefit as the information's main purpose is to aid the designer developing the striping and/or signing plan. Practitioners would be better served by including this information in the TOGM and referencing it in the *Highway Design Manual's* 2+1 design guidance. KYTC's Highway Knowledge Portal is another platform where practitioners can access these details.

A similar argument applies to signing and marking truck climbing lanes. Exhibit 5 in the TOGM addresses these issues, while Exhibit 6 focuses on two to four-lane transitions. These exhibits should be modified to incorporate details and recommendations outlined this report. The *Highway Design Manual's* section on to truck climbing lanes should reference TOGM Exhibit 5.

Lane reductions are much more likely to be encountered on a project with no striping or marking plans. As such, construction staff will benefit from a Standard Drawing for signing and marking lane reductions on one-way, two-way, and multi-lane highways. This drawing should incorporate recommendations in this report.

5.2 2022 Updated *Traffic Operations Guidance Manual* for 2+1 Roadways
The *Traffic Operations Guidance Manual* is being updated to include instruction and exhibits on 2+1 roadway's pavement markings and signing. A copy of the proposed 2+1 Traffic Operations guidance, including detailed drawings, is shown below.

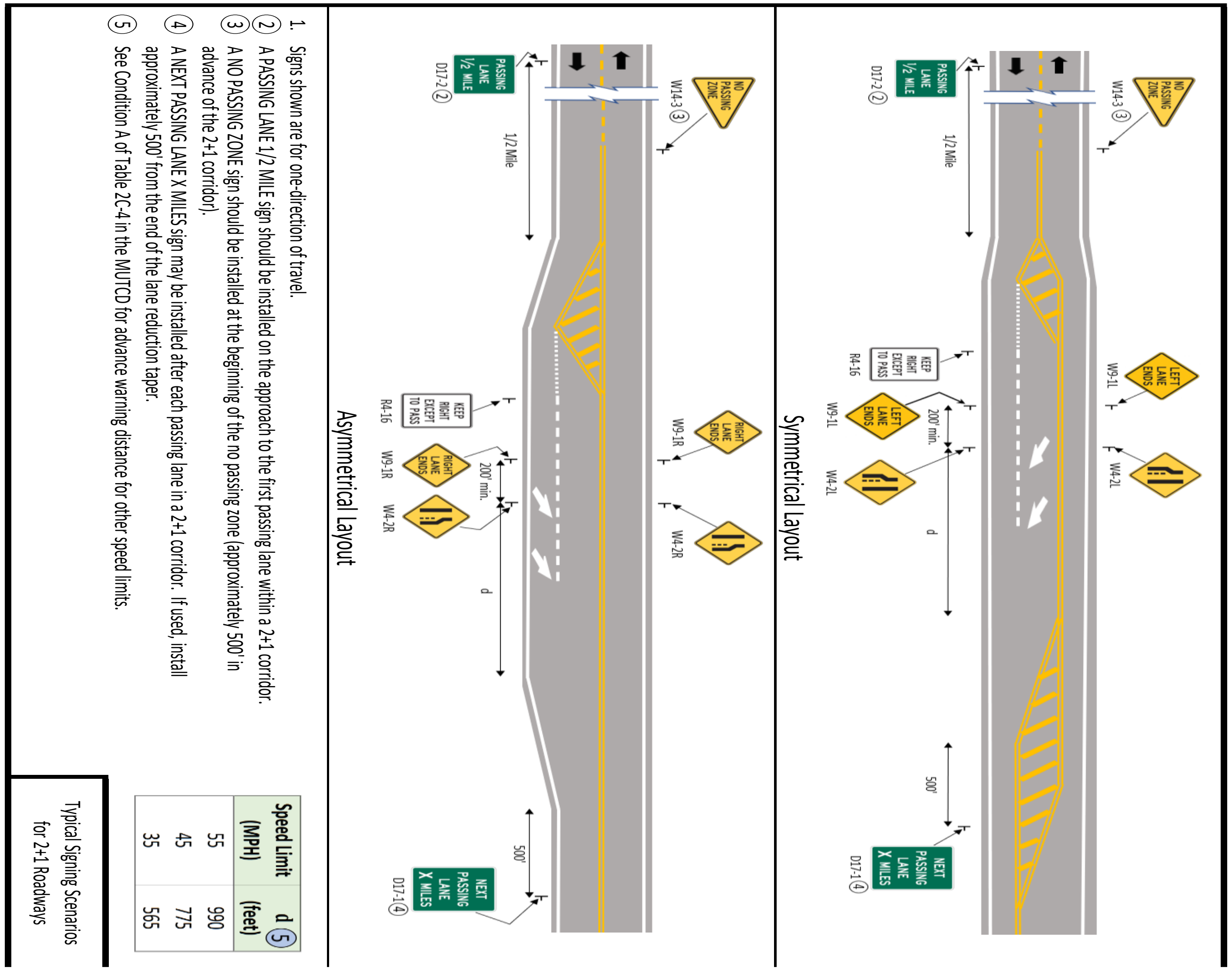
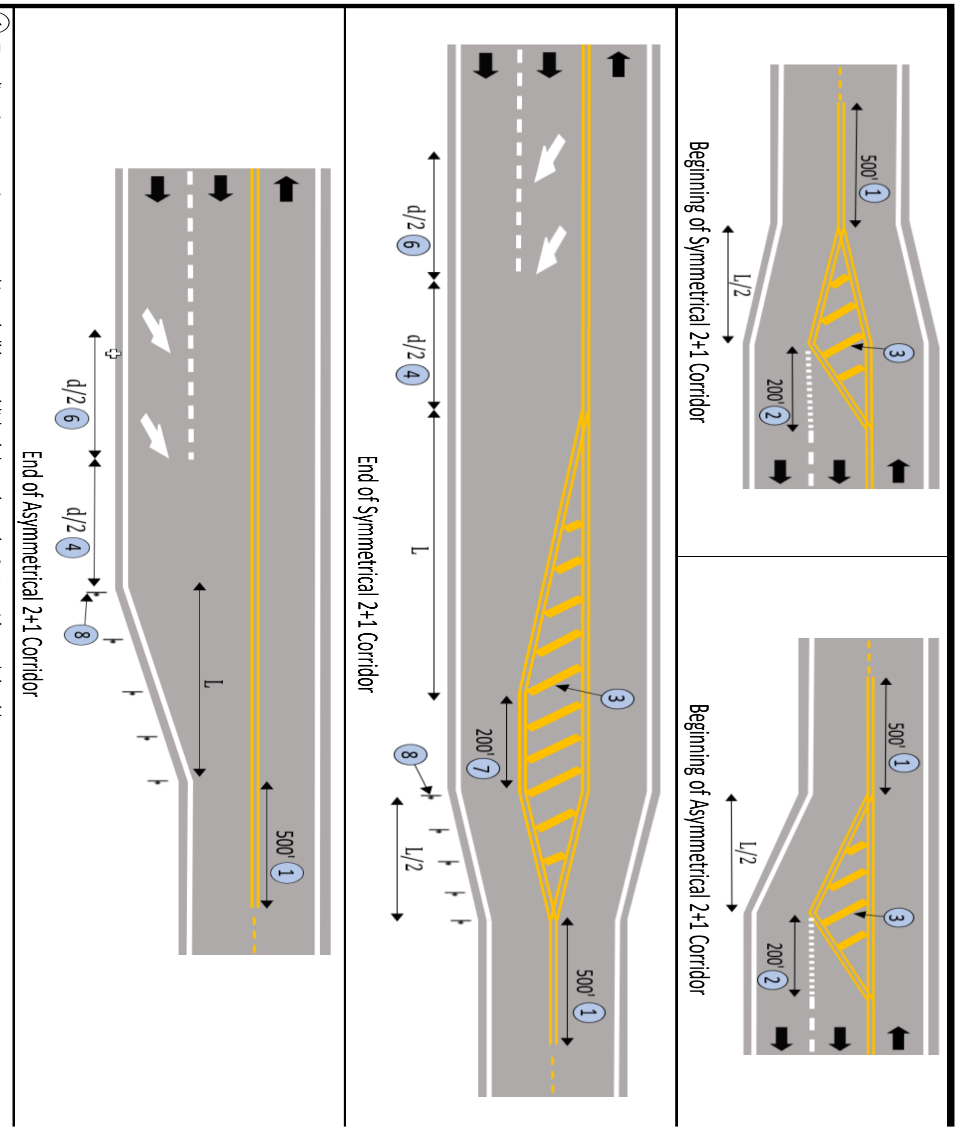


Figure 5.5 Typical Signing Scenarios for 2+1 Roadways



(1) Two-direction no-passing zone markings shall be established throughout the 2+1 corridor and should extend 500' (min.) from the beginning and end of the 2+1 corridor.

(2) Lane entry tapers for passing lanes should be 200' (min.) in rural areas and 100' (min.) in urban areas. Dotted lines (2' lines with 6' gaps) should be installed across entry tapers to passing lanes.

(3) Diagonal crosshatching should be used in flush medians of transition areas. See TPM-204 for dimensions.

(4) Broken lane lines should be discontinued at a distance of 1/2 d in advance of the lane reduction taper.

(5) See Condition A of Table 2C-4 in the MUTCD for values of d for other speed limits.

(6) Two lane reduction arrows (min.) should be installed on approaches to lane reductions. Arrows should be located at the positions shown but may be eliminated if speed limit is less than 45 MPH.

(7) Buffer zone of 200' (min.) should be used between separate tapers.

(8) Delineators may be installed along lane reduction tapers (approx. spacing of 100').

Speed Limit	L (feet)
40 mph or less	$L = \frac{WS^2}{60}$
45 mph or more	L = WS

Where: W = width of offset in feet
S = posted speed limit

Speed Limit (MPH)	d (5) (feet)
55	990
45	775
35	565

Page 1 of 2

Typical Markings Scenario for 2+1 Roadways

Figure 5.6 Typical Markings Scenarios for 2+1 Roadways (1/2)

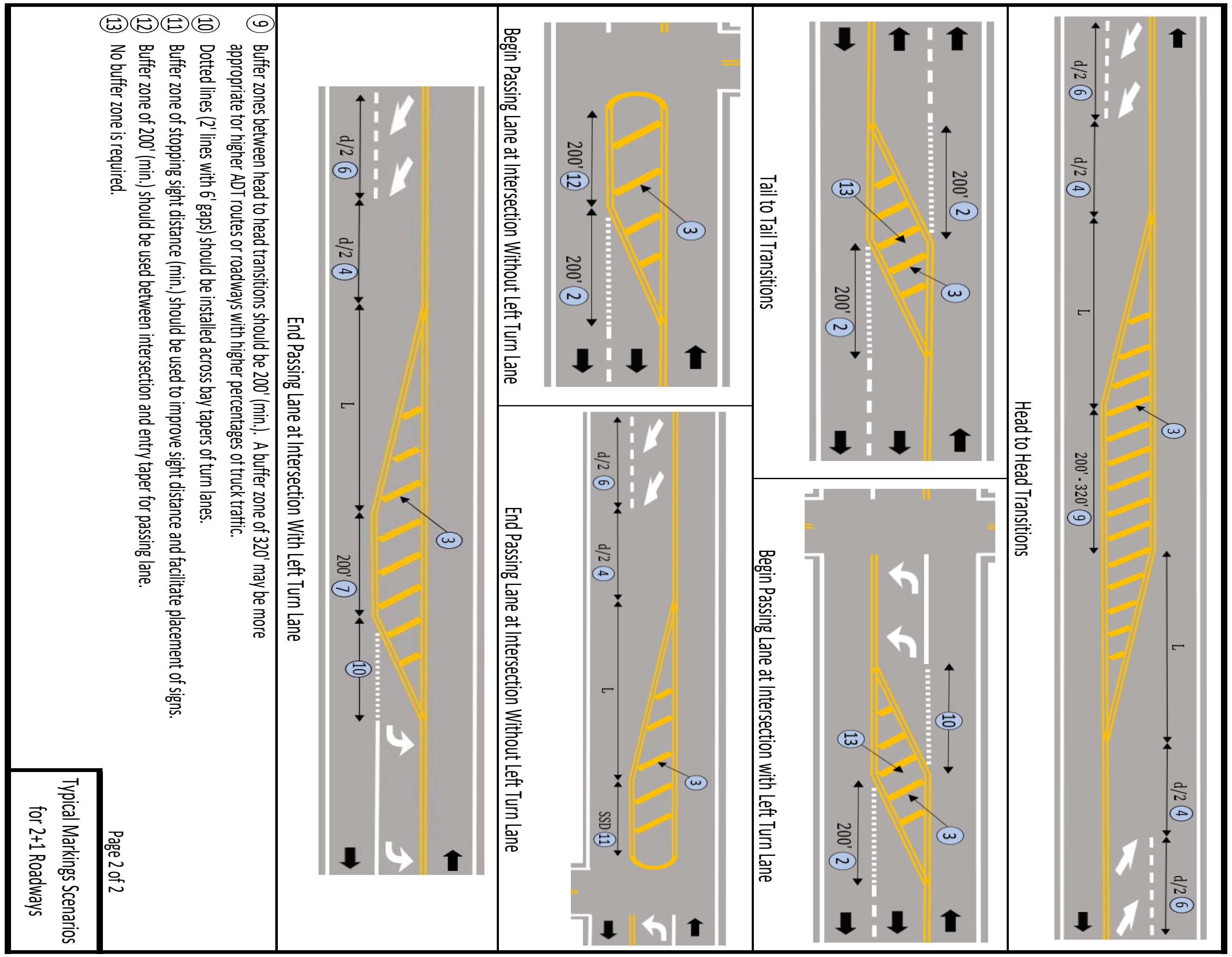


Figure 5.7 Typical Markings Scenarios for 2+1 Roadways (2/2)

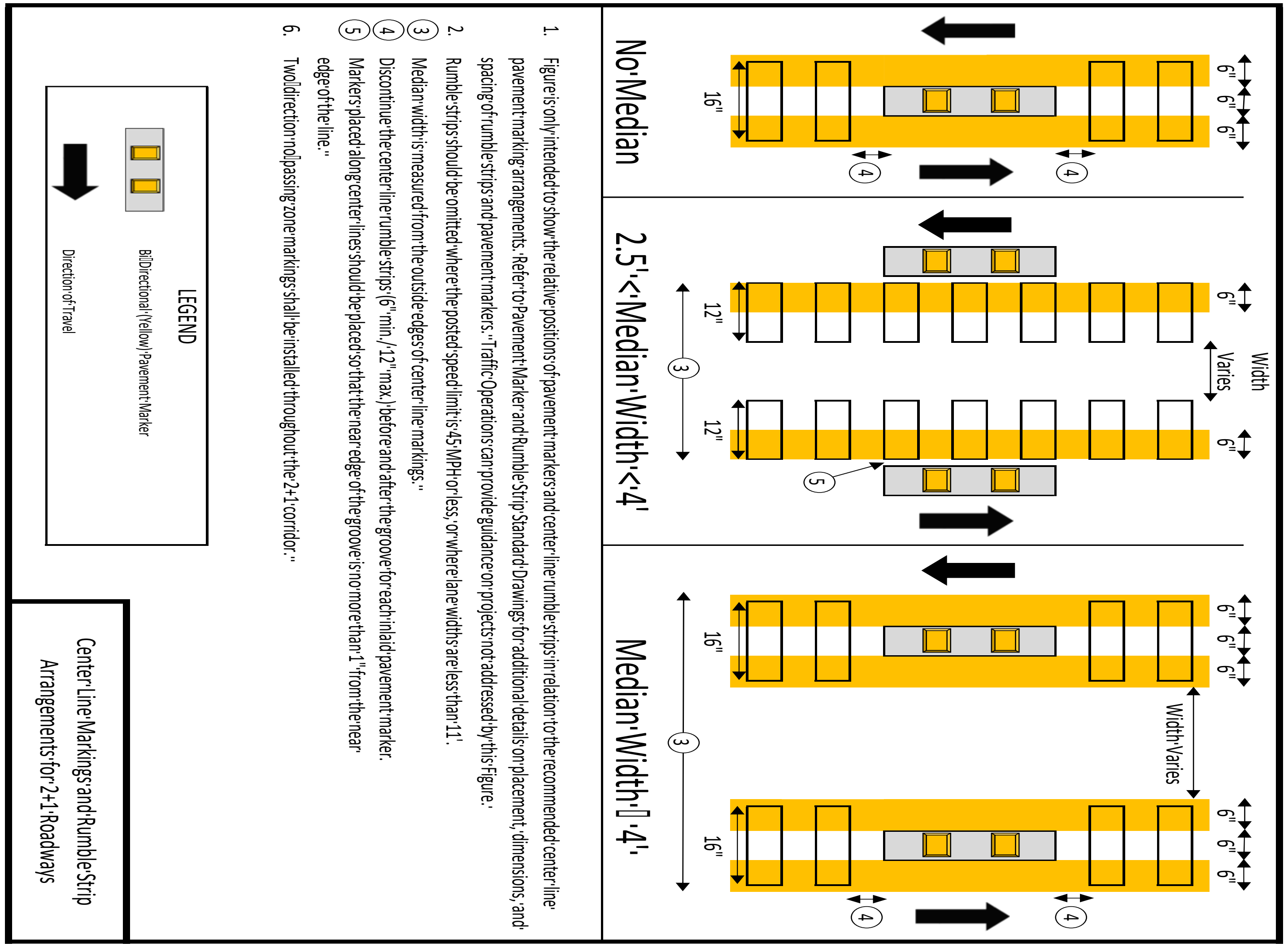


Figure 5.8 Centerline Markings and Rumble Strip Arrangements for 2+1 Roadways

Chapter 6 Conclusion

KYTC continues to support the use of innovative, context-adapted facility designs that improve the mobility and safety of Kentucky motorists. Extensive experience with deployment of 2+1 roadways by highway agencies around the world has shown that this configuration has many applications in Kentucky. The 2+1 concept may be used to address operational deficiencies on rural, two-lane roadways with traffic volumes higher than can be served by isolated passing lanes, but which are not high enough to justify a four-lane roadway. Compared to two-lane roads, 2+1 configurations improve traffic operations and reduce crashes; they also cost less to build than four-lane roadways. Updated guidance documented in this report will help KYTC Project Managers and Project Development Teams develop and deliver practical, quality 2+1 roadway alternatives.

The Division of Highway Design adopted the updated 2+1 roadway design guidance created as part of this study. This guidance draws on research, guidelines, and policies from other DOTs and KYTC's experience with 2+1 roads over the past decade. 2+1 design principles, location guidelines, passing lane layouts, and geometrics are documented in the revised guidance.

From the outset of this study, signing and pavement markings have been a primary focus. 2+1 facilities cannot operate properly without implementing sound traffic control principles. Prior to this study, KYTC has had no formal guidance for 2+1 signings and markings. KYTC's Division of Traffic Operations has collaborated with the research team to create instructions and exhibits on 2+1 roadway's pavement markings and signing. KYTC released the guidance through a joint Design Memorandum 01-22 and Traffic Operations Memorandum 03-22. This information is also presented as an article on the online Highway Knowledge Portal (See Appendix 1). Once this guidance is published in the *Traffic Operations Guidance Manual*, designers and engineers throughout the state will be able to apply uniform standards for signing and pavement markings on 2+1 roadways.

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Appendix A KYTC's 2+1 Roadway Design Guidance

Commonwealth of Kentucky
Transportation Cabinet
transportation.ky.gov

Andy Beshear
Governor

Jim Gray
Secretary

DESIGN MEMORANDUM NO. 01-22; TRAFFIC OPERATIONS MEMORANDUM 03-22

TO: Chief District Engineers
Highway Design Engineers
Engineering Support Engineers
Active Consultants

FROM: William T. Layson, P.E.
Director
Division of Highway Design

Tim Tharpe, P.E.
Director
Division of Traffic Operations

DATE: September 21, 2022

SUBJECT: 2+1 Roadway Design Guidance Update with Signing and Pavement Markings

A 2+1 roadway is a three-lane highway that has two travel lanes in one direction – one of which is used for passing maneuvers – and one lane in the opposite direction. The passing lane alternates every few miles. The 2+1 concept is used to improve operations on rural, two-lane roads that do not have the volume to warrant a four-lane facility. *KYTC's 2+1 Roadway Design Guidance* (attached) updates and supersedes the guidance in Design Memorandum No. 04-13 *Design Guidance for Shared Four-Lane (2+1) Roadways*.

Clear signage and pavement markings are essential to the operation of 2+1 passing lanes. Attached to this memorandum are figures to assist with typical signing and markings for these facilities. The Traffic Operations Guidance Manual (TOGM) will be updated to include these figures in a future update.

The updated guidance may be used on any 2+1 roadway project and shall be applied on new projects and projects with 2+1 roadway alternates that have not progressed past Preliminary Line and Grade (PL&G).

Attachments

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2+1 Roadways

A 2+1 road is a three-lane highway that has two travel lanes in one direction – one of which is used for passing maneuvers – and one lane in the opposite direction. The passing lane alternates every few miles. On some highways, traffic volumes are insufficient to justify a four-lane highway but are too great to be served by a two-lane configuration with permitted passing (when a vehicle can safely pass another) or a two-lane configuration which has occasional added-on passing lanes. In these conditions, a continuous passing lane whose directionality alternates is less stressful for drivers than finding a passing gap in oncoming traffic and minimizes the likelihood of head-on collisions with opposing vehicles. 2+1 roadways can be a good option in these situations.

2+1 configurations have several objectives:

- Provide systematic passing opportunities along a highway corridor. Improve traffic operations on two-lane highways by breaking up traffic platoons.
- Increase average travel speed along a corridor. Average travel speed in the passing lane is increased, and the speed benefits of passing lanes continue downstream of the lane.
- Reduce delays resulting from the inability to pass, either due to passing restrictions or limited gaps in the opposing traffic stream. Passing lanes typically reduce the *percent time-spent-following* (PTSF). PTSF is the average percentage of total travel time vehicles travel in platoons behind slower vehicles because they cannot execute passing maneuvers on a two-lane highway. This benefit can persist for some distance downstream of the passing lane and improve level of service.
- Improve safety by providing passing opportunities that do not require a passing driver to use the opposing traffic lane. This reduces the risk of head-on collisions and improves road safety relative to two-lane highways.
- Reduce costs and environmental impacts compared to adopting a four-lane configuration.

Disadvantages of 2+1 configurations include:

- Increased potential of high-speed differential conflicts with vehicles leaving or entering the roadway at intersections and access points.
- Compared to two-lane highways, greater risk of sideswipe crashes where vehicles merge at transitions from two-lanes to one.
- Possible safety concerns at traffic volumes close to capacity. Higher flow rates reduce the average gap between vehicles, which forces drivers to merge into smaller gaps.
- When transitioning from two lanes to one lane with high traffic volumes, merging is difficult and capacity goes down.
- Opportunities to pass slow vehicles are prohibited in single-lane sections.

2+1 Roadway Passing Lanes

Symmetrical 2+1 roadways maintain a continuous three-lane cross section. The road's center lane uses pavement markings to establish a passing lane which changes directionality throughout the corridor. Asymmetrical 2+1 roadways add a third lane for passing on the outside of a two-lane roadway. Either configuration can be used to improve traffic flow. Compared to a two-lane highway with the same traffic volume, 2+1 roads generally operate at least two levels of service higher and have lower crash rates. They are a cost-effective option for reconstructing two-lane highways with high traffic volumes but which are not sufficient to warrant a full four-lane facility. Figure 1 shows conceptual drawings of symmetrical and asymmetrical 2+1 configurations.

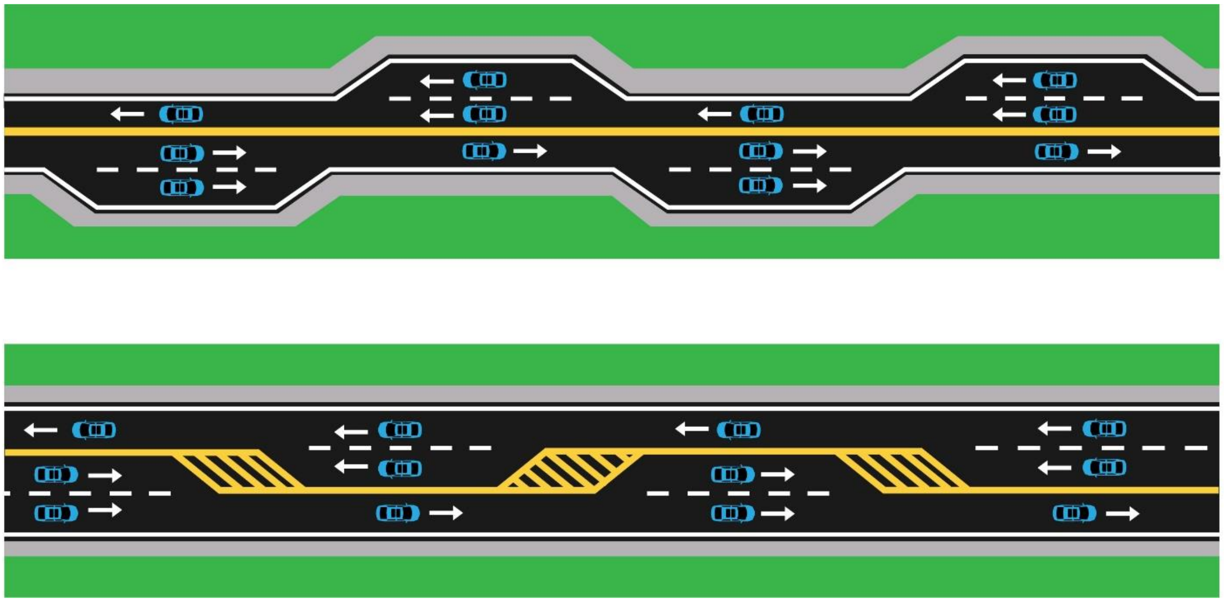


Figure A1 Asymmetrical and Symmetrical 2+1 Configurations

When a passing lane is added to a two-lane, two-way rural highway, its operational effectiveness depends on the length of the passing section and spacing between passing sections. It is desirable to have a passing lane section that can convert platoon flow at its upstream end to free-flowing single vehicles at its downstream end.

For any passing lane application, a minimum passing lane length of 0.5 miles is recommended — a shorter lane is not effective at reducing vehicle platooning. The maximum recommended passing lane length is 2 miles — a longer lane is less effective and has a lower benefit/cost ratio. Table A1 lists the optimal passing lane lengths based on one-way flow rates. **These lane lengths do not include passing lane tapers at the beginning or end of passing lanes.** Designers may need to vary lengths to account for site-specific factors (e.g., addressing safety-related issues).

Table A1 Optimal Passing Lane Lengths for Traffic Operational Efficiency

One-Way Flow Rate (veh/h)	Recommended Passing Lane Length (mi)
100 – 200	0.5
201 – 400	0.50 – 0.75
401 – 701	0.75 – 1.00
701 – 1,200	1.00 – 2.00

Source: AASHTO *Green Book*

2+1 configurations provide a viable design alternative for high-speed rural highways that have moderate traffic volumes. They can be used on a new alignment or retrofitted on an existing alignment. A 2+1 configuration should be considered the ultimate design for roads with a design year volume of 15,000 ADT (Average Daily Traffic) or less. If the design year volume is 15,000 – 20,000 ADT, a 2+1 configuration may be used as the initial design, but right of way should be purchased to accommodate expansion to a four-lane facility. If the large increase in the forecasted traffic volume never materializes, a four-lane section need not be built. Typically, roads with a design year volume less than 5,000 ADT will not benefit from a 2+1 configuration.

A 2+1 configuration is generally not recommended if flow rates exceed 1,200 veh/h in one direction of travel — effective merging operation is maintained at lane drops when flow rates are equal to or less than 1,200 veh/h. A four-lane roadway is generally more efficient at high traffic flow rates. To decide whether an existing two-lane highway should be converted to a 2+1 configuration or a four-lane facility, a traffic engineering analysis should be performed. This analysis should determine the number of lanes required to achieve a targeted volume-to-capacity ratio. The *Highway Capacity Manual* outlines procedures for performing operational analysis and assessing roadway capacity.

Even though a 2+1 road is expected to be a consistent three-lane facility, it may be narrowed along the corridor based on project needs and constraints. For example, the three-lane section may be reduced to two-lanes along a short distance when passing over bridges or through deep cuts where a three-lane full-width cross section would significantly increase project costs. A two-lane configuration may also be used on a section to avoid environmental impacts.

2+1 Roadway Design Considerations

Key design considerations for 2+1 roads include passing lane length, operational direction, and the location of transitions. It is unlikely passing lanes will simply alternate directions every other mile. Instead, the design team must carefully examine geometric, operational, and site-specific factors when developing a 2+1 concept throughout the roadway corridor. Designers should be flexible when choosing passing lane locations. Ideally, their placement should maximize operational effectiveness and minimize construction costs. Factors to consider when designing a 2+1 road are listed below.

- A 2+1 configuration should only be used in level or rolling terrain. In mountainous terrain and on isolated steep grades, the most appropriate placement is climbing lanes on uphill grades.
- When choosing the passing lane's operational direction, pay close attention to grades. Uphill grades are preferred but not required. As the highway grade lengthens and steepens, traffic operation benefits from having the two-lane operation on the uphill grade. Evaluate traffic operations including truck volumes if consideration is given to terminating passing lanes on uphill grades.
- Safe and effective passing lane operations require adequate sight distance on the approach to lane additions and lane drop tapers.
- Provide stopping sight distance continuously along a 2+1 roadway.
- Consider decision sight distance at intersections and lane drops.
- Avoid closing a passing lane over a hill or around a horizontal curve where the pavement surface at the end of the taper is not visible from the beginning of the taper.
- Preference for passing is normally given to traffic departing an incorporated area. Providing access in this manner accords passing opportunities as vehicles leave congested areas and can serve as a traffic calming measure as vehicles enter the town through the one-lane section.
- Passing lanes should be located away from major intersections and high-volume driveways to decrease the probability of speed differentials between turning and passing traffic. Major intersections should be located in the transition area between opposing passing lanes, and conventional left-turn lanes should be provided at the intersection. Low-volume intersections and driveways may be accommodated within passing lanes sections but not within taper transition areas. See *2+1 Roadway Access Management* for more information.
- Exercise caution when applying the 2+1 concept to an existing roadway with low-speed curves. Because the 2+1 configuration increases travel speeds and encourages passing, review geometric factors (e.g., horizontal curve radius, superelevation) to determine whether they are adequate for the anticipated operation, or if improvements are needed to match the facility's design speed.
- Passing lanes are most effective when drivers enter the right lane at the lane transition and only use the left lane when passing a slower vehicle. Therefore, geometric design and pavement markings along the transition should encourage drivers to enter the right lane.
- When ending a 2+1 section and transitioning from three lanes to two lanes, allow adequate distance (recommend stopping sight distance) between the end of a lane closure taper and obstacles such as guardrail or guardrail end treatments, narrow bridges, or high-traffic intersections.

Passing Lane Transitions

Transitions between passing lanes in opposing directions require careful design. Intersections, bridges, auxiliary turn lanes, and appropriate pavement markings in medians can be used to establish a buffer between opposing passing lanes.

Transitions which begin or end the passing lane should be located where drivers have full view of the change. A *head-to-head* transition is located immediately downstream of a lane drop. It is called head-to-head because vehicles in the middle lane head toward each other before merging into the right lane. Therefore, a buffer between vehicles traveling in opposite directions is needed. A minimum buffer of 200 feet should provide adequate warning and stopping distance to accommodate opposing vehicles that cross their lane reduction taper and enter the transition area. For example, where the pavement markings establish a lane drop, a 12-foot lane and 55 mph speed limit would require a taper distance of 660 feet. Adding one-half the buffer zone length (100 feet) means the distance from the start of the passing lane transition to the middle of the head-to-head transition should be 760 feet. In this scenario, a vehicle traveling 55 mph would need more than nine seconds to proceed from the beginning of the lane reduction taper to the middle of the buffer zone. Taper distance, pavement markings, and centerline rumble strips should be adequate to alert errant drivers and give them enough time to take corrective action. The *Green Book* recommends a 320-foot buffer between the end of each lane drop, which may be more appropriate for higher ADT routes or those with higher percentages of truck traffic.

A *tail-to-tail* transition is located immediately upstream of a lane addition. With tail-to-tail transitions, vehicles in the middle lane head away from each rather than toward each other.

Lane drops (Figure A2) and additions (Figure A3) are illustrated below.

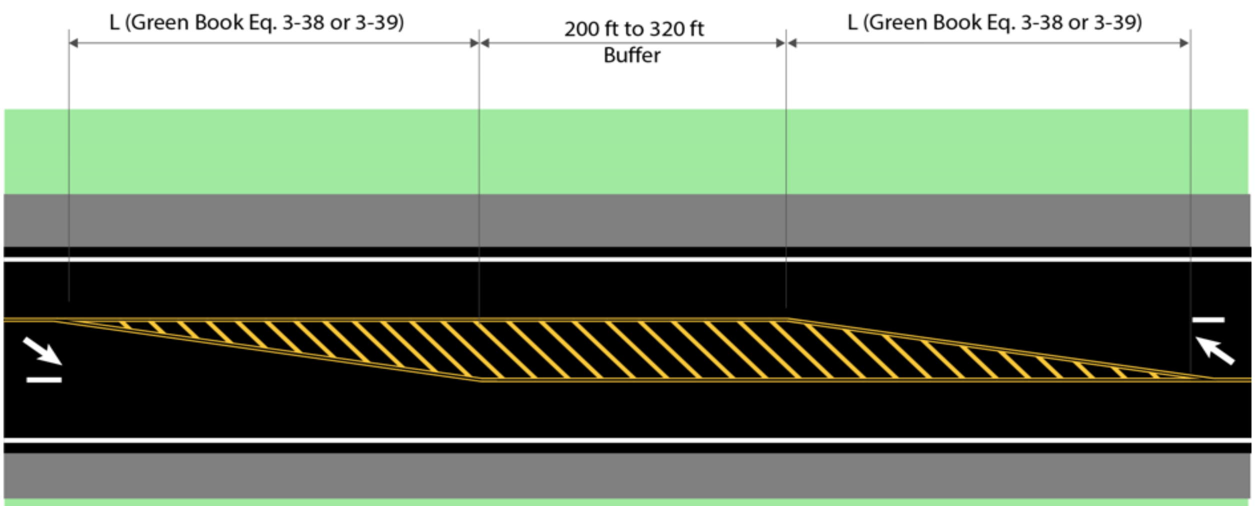


Figure A2 Schematic for Head-to-Head Transitions on a 2+1 Roadway

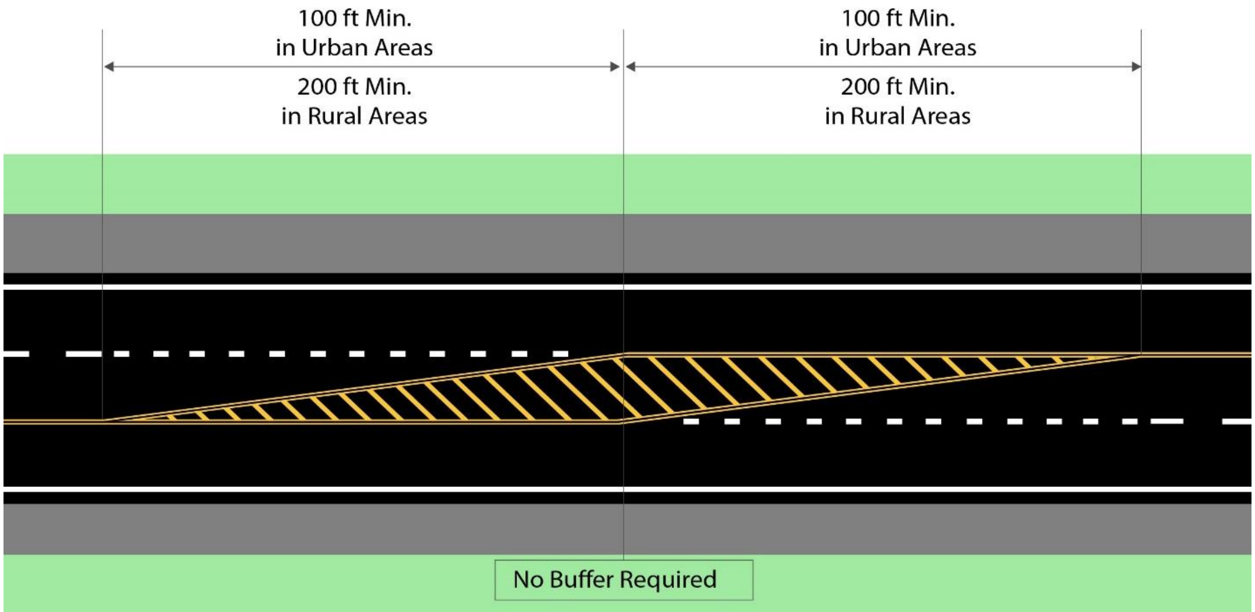


Figure A3 Schematic for Tail-to-Tail Transitions on a 2+1 Roadway

The *Green Book* provides equations to compute lane-drop taper length. Equation 3-38 from the *Green Book* is applied where the posted or statutory speed limit is greater than or equal to 45 mph, while Equation 3-39 is used if the posted or statutory speed limit is less than 45 mph.

(3-38) $L = WS$ for $S \geq 45$ mph
(3-39) $L = (WS^2) / 60$ for $S < 45$ mph

where:
L = Length of lane-drop taper (ft)
W = Width (ft)
S = Speed (mph)

The recommended length for the lane addition taper is one-half of the lane-drop length.

2+1 Roadway Access Management
Intersection placement should (1) minimize turning movements within passing lanes or (2) provide dedicated right- or left-turn lanes (see the *Highway Design Manual* HD-902). Access management considerations for 2+1 configurations are listed below.

- Provide right- and left-turn lanes in passing lane sections in the same locations they would be provided on a conventional two-lane highway.
- Low-volume intersections and driveways may be accommodated within passing lane sections.
- Reduced turning-lane warrants should be considered when the road context calls for extra safety measures (e.g., adequate sight distance is not available at an intersection, several entrances are close together, or there is a high posted speed (≥45 mph) and high flow rate).

For example, when these situations exist, the project team might decide to add left-turn lanes for any access with a projected peak hour left-ingress turning volume greater than 10 vehicles per hour (veh/h). Right turn lanes could be added for any access with a projected peak hour right-ingress turning volume greater than 25 veh/h.

One strategy for the provision of turn lanes is using one lane in the three-lane section (i.e., transition to single-lane operations each direction and use the third lane as the auxiliary lane). Another strategy is to widen the road (i.e., build four lanes to create the extra pavement width needed for an auxiliary lane).

Along a three-lane section, intersections with conventional left-turn lanes should be located in the transition areas between opposing passing lanes. This minimizes turning traffic volume in passing lanes (Figure A4) and allows the passing lane to switch direction. (See the *Traffic Operations Guidance Manual* for details on pavement markings.)

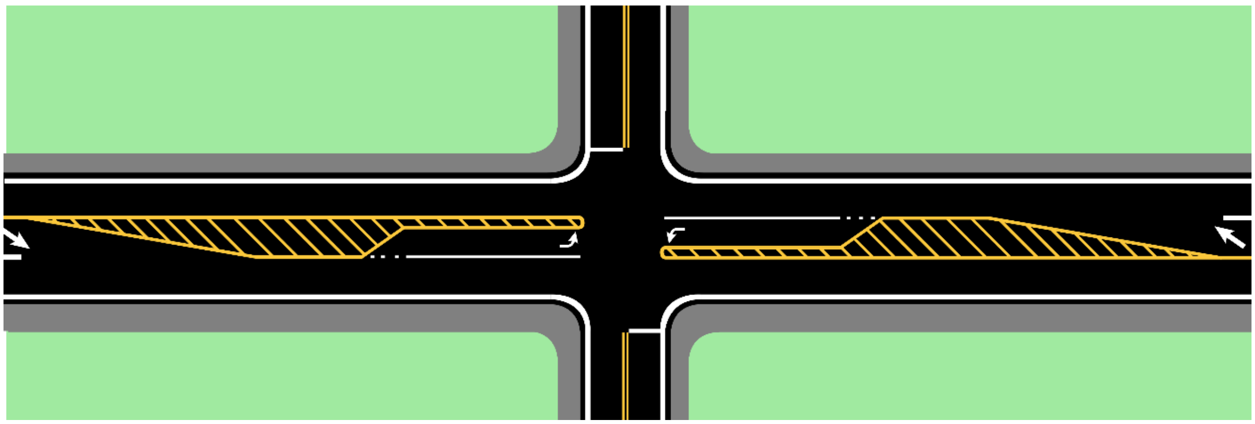


Figure A4 Schematic for Four-Leg Intersections on a 2+1 Roadway

In some circumstances, designers can select a two-way left-turn lane (TWLTL) to address left turns from the mainline. For example, in short sections where a 2+1 configuration passes through a rural town or area with multiple driveways on both sides of the road, a TWLTL could be provided in the middle lane (Figure A5).

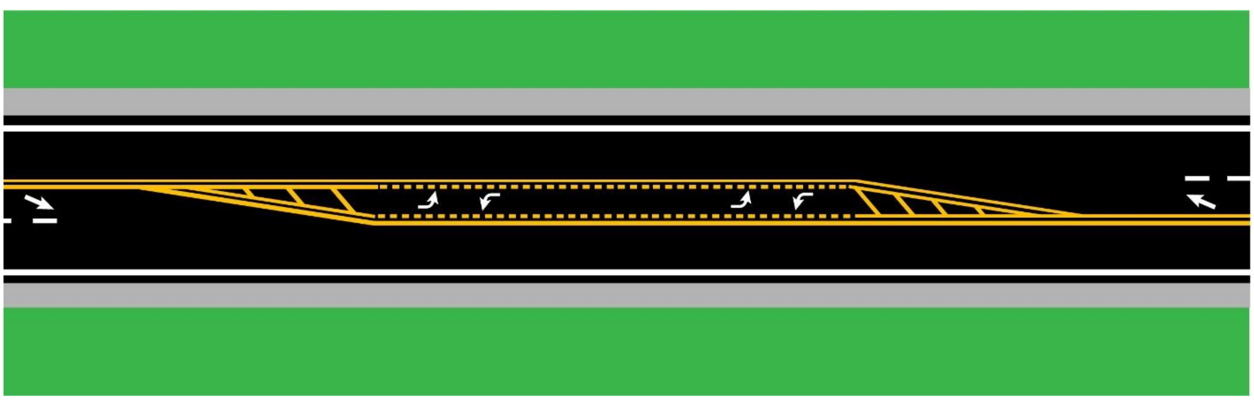


Figure A5 Schematic for Two-Way Left-Turn Lane on a 2+1 Roadway

- Placing entrances that require left-turns within the first 1,000 feet of a passing lane is sub-optimal because higher speeds and overtaking maneuvers are most common in this area.
- Do not locate entrances in areas with lane drops, tapers, or transitions.
- An alternative strategy for turning movements is permitting only right-in/right-out access. Section 9.9 (Indirect Left Turns and U-turns) of the *Green Book* reviews alternatives to left-turn lanes.

Where growth and development are expected, 2+1 road designs should include an area concept plan for future land development. Prospective frontage roads and their intersections with a 2+1 road can be planned and indicated on highway plans as future construction. In this case, purchasing access rights from adjacent properties should be considered. This approach can be used to create full access control between major intersections, improving the corridor's long-term safety. If access rights are purchased, alternative access points to the public street system should be provided to affected properties.

2+1 Roadway Typical Section – Lane and Shoulder Widths
Appropriate lane and shoulder widths are determined in the same manner as for conventional two-lane highways — through a consideration of functional class, volumes, and speeds. For more information, see the *Highway Design Manual* (HD-702.10).

- In general, a 2+1 road's lane width should match the lane width on adjacent sections of a two-lane highway.
- When site or budget constraints dictate a narrower cross section, the project team should determine where to reduce cross section elements based on traffic volumes, roadside conditions, geometric alignments, and crash data.
- Use typical shoulder widths throughout the length of the passing lane unless a reduced shoulder width would substantially reduce costs or avoid significant impacts. Shoulder widths may differ between the passing lane and the single lane side. For example, the paved shoulder width could be 8 feet on the single lane side and 4 feet on the passing lane. If the typical section has to be narrowed, the single lane side should have the wider shoulder.
- Whenever practical, the shoulder width in a passing lane section should not be narrower than the shoulder width on adjacent two-lane sections.
- Consider providing full shoulders (8 feet – 10 feet) in areas with high driveway density.

2+1 Roadway Flush Median
Passing lanes can operate effectively with no separation between opposing lanes of travel. However, some separation is preferable. A flush median separation of 4 feet between the opposing directions of travel is preferred (where feasible). Center line rumble strips and pavement markers are recommended on all 2+1 roadways.

2+1 Roadway Lane Pavement Crown Point and Superelevation
Locating the pavement's crown is one of the more complicated design issues on 2+1 roadways. Where an existing two-lane highway is restriped or widened to a 2+1 configuration, the crown may be placed within the traveled way. An existing highway may also be widened on one side only, resulting in the crown being located at a lane line. For new construction, the crown should be placed at a lane boundary. If it is necessary to transition the crown point along the roadway, it should be done along the lane drop or lane addition tapers. Figure 5 illustrates recommended crown locations.

Issues related to superelevation should be handled the same on a 2+1 road as on a comparable two- or four-lane undivided road.

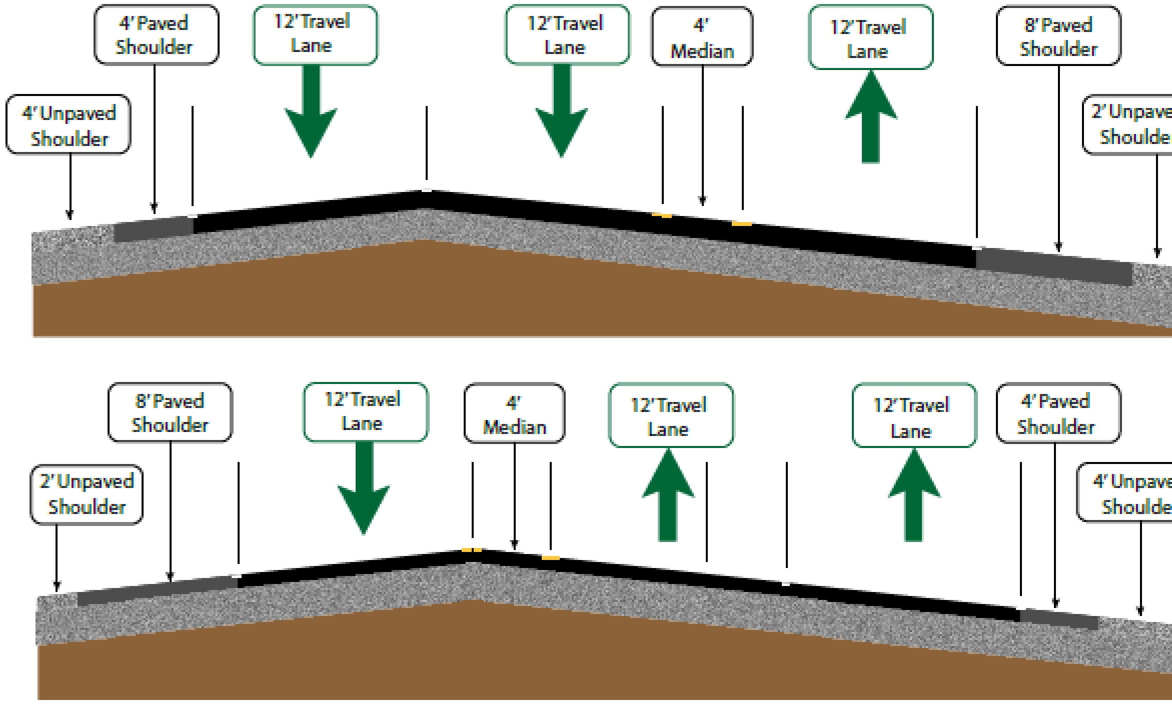


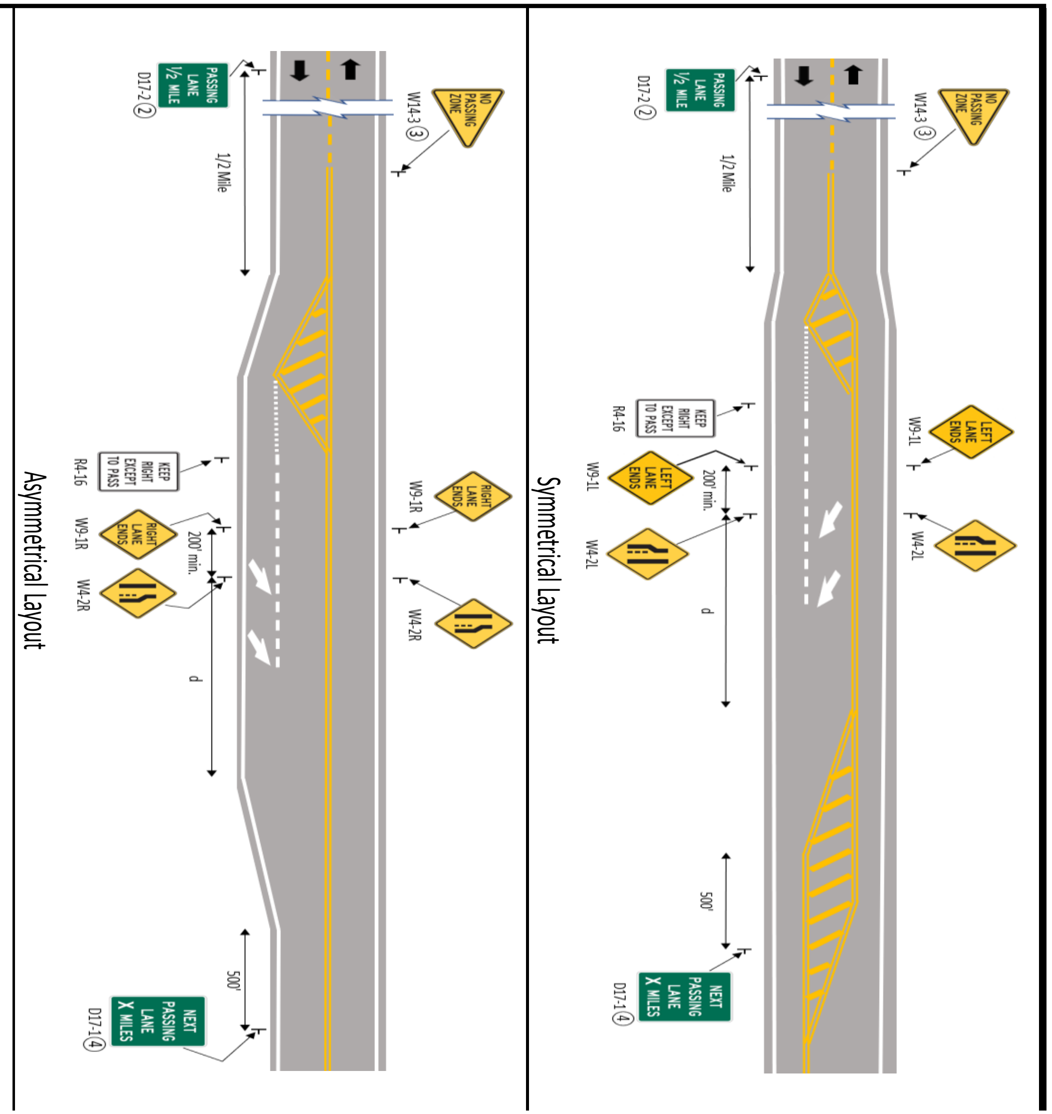
Figure A6 Example 2+1 Road Typical Sections

Signing and Pavement Markings

Clear signage and pavement markings are essential to the operation of 2+1 passing lanes. Signing and marking plans should be developed for 2+1 facilities. The plans should be coordinated with the Division of Traffic Operations and be developed in compliance with the Traffic Operations Guidance Manual and the latest edition of the *Manual on Uniform Traffic Control Devices*.

Public Involvement

Due to the unique design features of a 2+1 facility, additional public involvement activities are encouraged to inform residents and businesses of the proposed design's benefits and intended use. For more information and ideas on public involvement, see the Highway Design Manual (HD-601) and KYTC's Public Involvement Toolbox: https://transportation.ky.gov/PublicInvolvementToolbox/Pages/default.aspx.

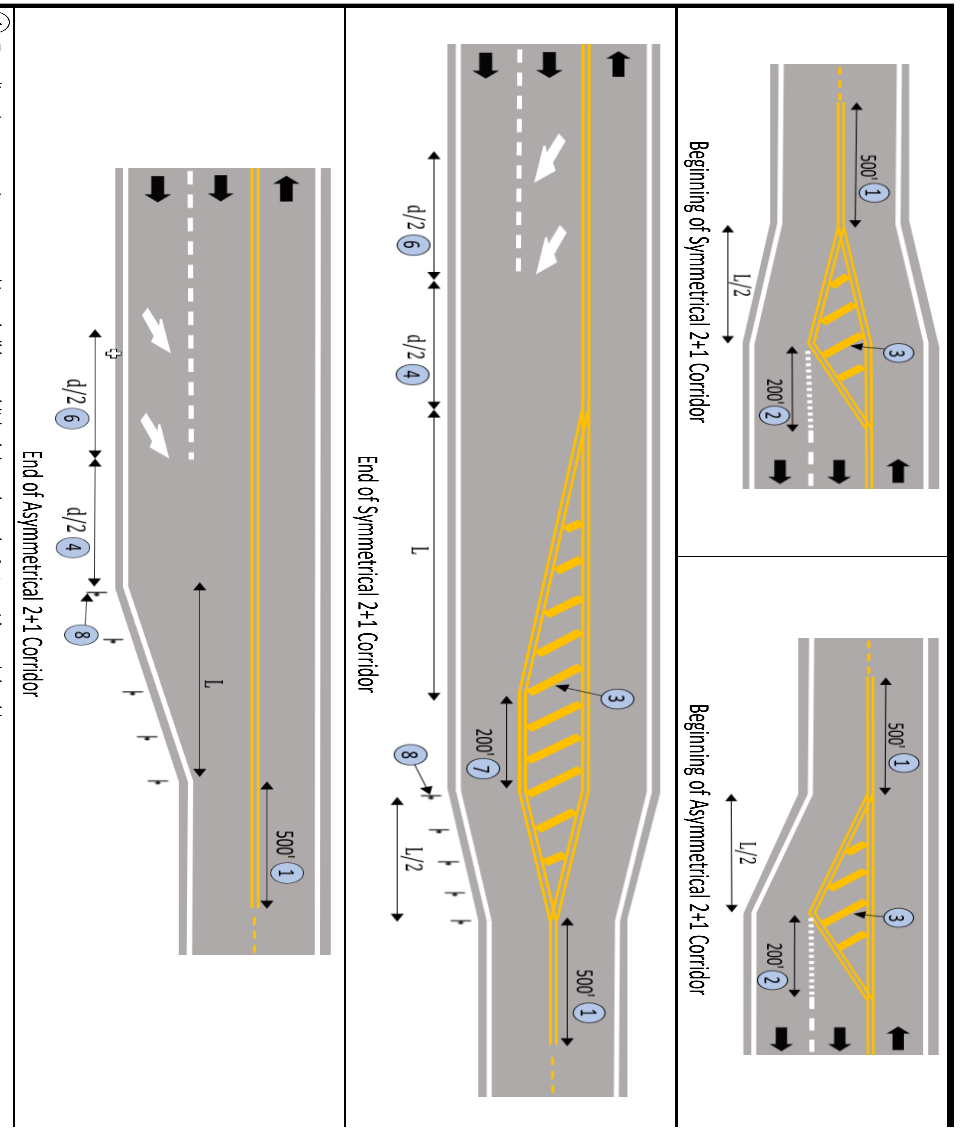


1. Signs shown are for one-direction of travel.
(2) A PASSING LANE 1/2 MILE sign should be installed on the approach to the first passing lane within a 2+1 corridor.
(3) A NO PASSING ZONE sign should be installed at the beginning of the no passing zone (approximately 500' in advance of the 2+1 corridor).
(4) A NEXT PASSING LANE X MILES sign may be installed after each passing lane in a 2+1 corridor. If used, install approximately 500' from the end of the lane reduction taper.
(5) See Condition A of Table 2C-4 in the MUTCD for advance warning distance for other speed limits.

Speed Limit (MPH)	d (5) (feet)
55	990
45	775
35	565

Typical Signing Scenarios for 2+1 Roadways

Typical Signing Scenarios for 2+1 Roadways



(1) Two-direction no-passing zone markings shall be established throughout the 2+1 corridor and should extend 500' (min.) from the beginning and end of the 2+1 corridor.

(2) Lane entry tapers for passing lanes should be 200' (min.) in rural areas and 100' (min.) in urban areas. Dotted lines (2' lines with 6' gaps) should be installed across entry tapers to passing lanes.

(3) Diagonal crosshatching should be used in flush medians of transition areas. See TPM-204 for dimensions.

(4) Broken lane lines should be discontinued at a distance of 1/2 d in advance of the lane reduction taper.

(5) See Condition A of Table 2C-4 in the MUTCD for values of d for other speed limits.

(6) Two lane reduction arrows (min.) should be installed on approaches to lane reductions. Arrows should be located at the positions shown but may be eliminated if speed limit is less than 45 MPH.

(7) Buffer zone of 200' (min.) should be used between separate tapers.

(8) Delineators may be installed along lane reduction tapers (approx. spacing of 100').

Speed Limit	L (feet)
40 mph or less	$L = \frac{WS^2}{60}$
45 mph or more	L = WS

Where: W = width of offset in feet
S = posted speed limit

Speed Limit (MPH)	d (5) (feet)
55	990
45	775
35	565

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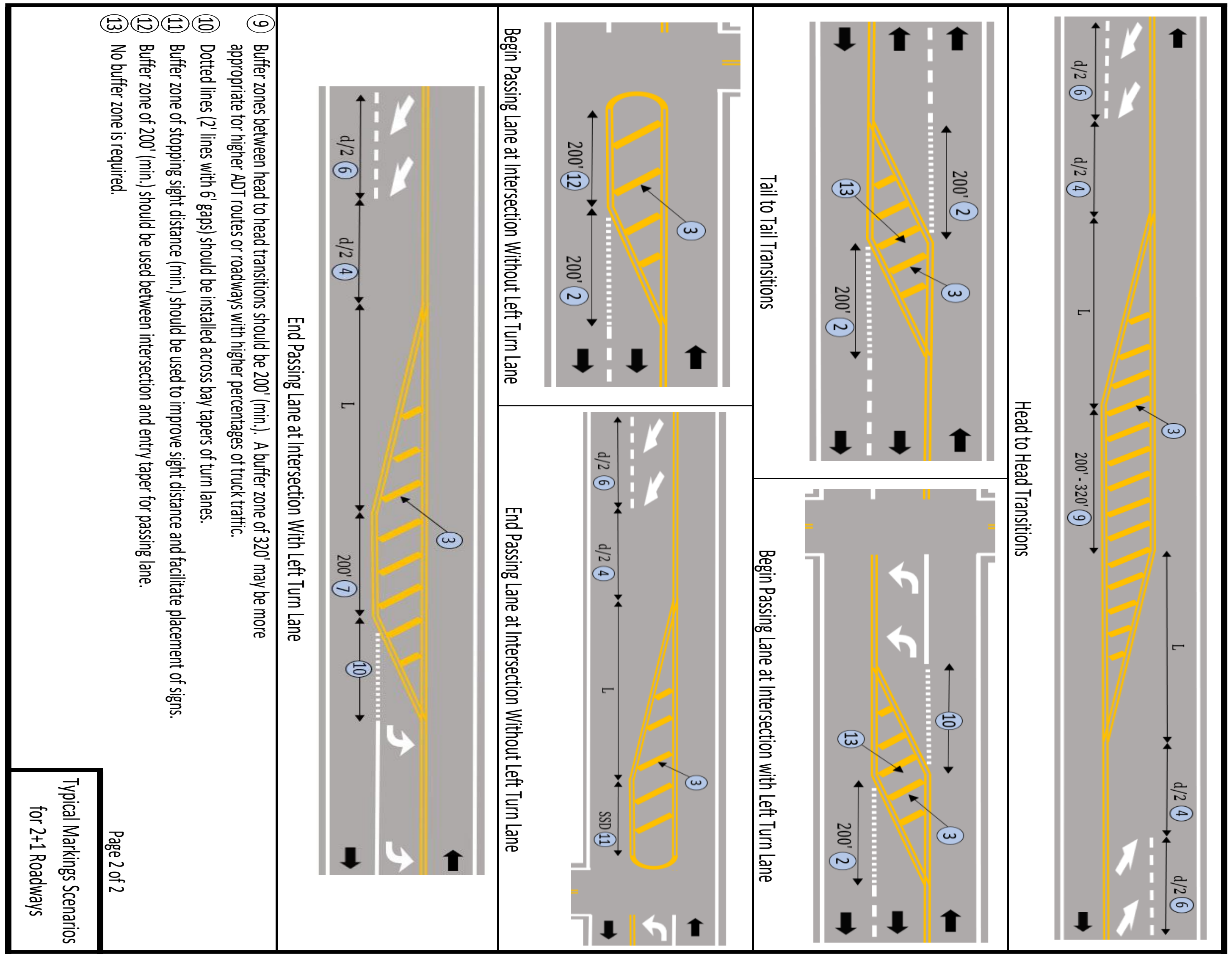
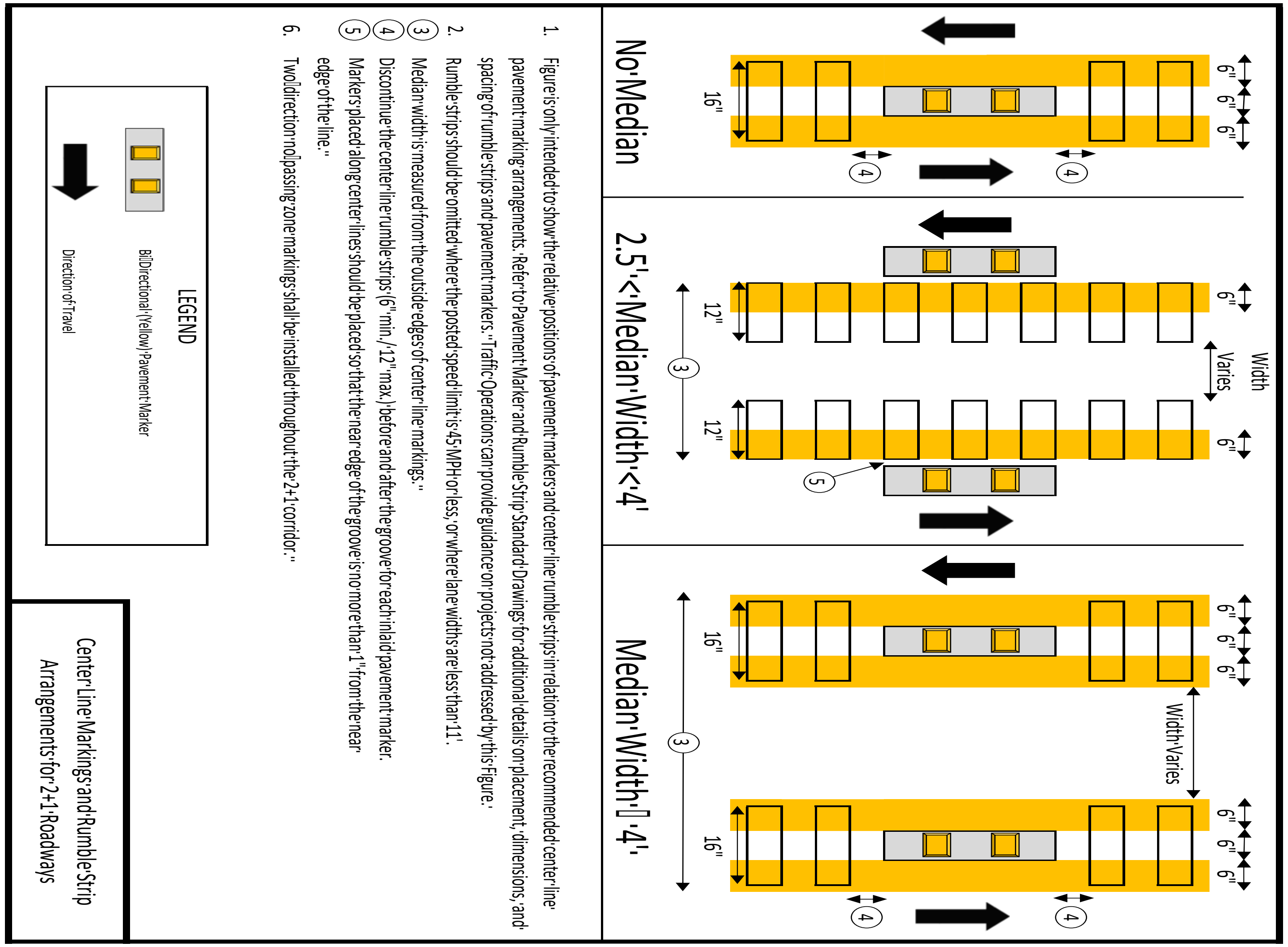
Typical Markings Scenario for 2+1 Roadways

Typical Markings Scenarios for 2+1 Roadways (1/2)



Typical Markings Scenarios for 2+1 Roadways (2/2)



Centerline Markings and Rumble Strip Arrangements for 2+1 Roadways