



Twin-Safe: Advancing Road Safety Through Twinning

Deliverable 3.3

Guidelines for implementation of measures for increasing the safety on rural roads

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Project identification

Grant Agreement No	101159114
Acronym	TWIN-SAFE
Project Title	TWIN-SAFE: Advancing Road Safety Through Twinning
Start Date	1 May 2024
End-Date	30 April 2027
Project URL	https://twin-safe.com

Document summary

Deliverable	3.3
Deliverable Title	Guidelines for implementation of measures for increasing the safety on rural roads
Work Package	3 - Research of road infrastructure impacts on driver behaviour
Contractual due date	M30
Actual submission date	M30
Nature	Report
Dissemination level	Public
Lead Beneficiary	University of Zagreb, Faculty of Transport and Traffic Sciences
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Please refer to the document as:

Babić, D. et al. (2026). *Guidelines for implementation of measures for increasing the safety on rural roads*. Deliverable 3.4 of the EC Horizon Europe project TWIN-SAFE: Advancing Road Safety Through Twinning.

Revision history (including peer review & quality control)

Version	Issue date	% Complete	Changes	Contributor(s)
v1.0	July 18 2026	30%	First draft of the first three sections	Bernard Kosovec, Darko Babić, Mario Fiolić, Marija Ferko
v1.1	August 20 2026	70%	First drafts of sections 4 and 5	Bernard Kosovec, Dario Babić, Darko Babić, Mario Fiolić, Marija Ferko
v1.2	August 24 2026	90%	Adjusting section 5	Bernard Kosovec, Dario Babić, Darko Babić, Mario Fiolić
V1.3	October 1 2026	100%	Minor improvements after review	Tom Brijs, Carmelo D'agostino

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Glossary and abbreviations

Word / Abbreviation	Description
ANCOVA	Analysis of covariance
ANOVA	Analysis of variance
AWS	Auditory warning sound
CBP	Checkerboard patterns
CTB	Red-coloured transverse bands
DID	Digital information display
DMSs	Dynamic message signs
DSDS(s)	Dynamic speed display sign(s)
DSFS(s)	Dynamic speed feedback sign(s)
DSMD	Dynamic speed monitoring display
EEG	Electroencephalography
FSZ	Floating speed zones

GIS	Geographic Information System
GLM	General linear model
HMs	(Innovative) horizontal markings
iRAP	International Road Assessment Programme
ITS	Intelligent transportation system
LED	Light-emitting diode
LP	Lateral position
MANOVA	Multivariate analysis of variance
NO _x	Nitrogen oxides
OSB(s)	Optical speed bar(s)
PCMS	Portable changeable message sign(s)
PM	Particulate matter
PPRS	Portable plastic rumble strip
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses
PRMs	Photoluminescent road markings
PTB	Peripheral transverse bars
PVMS	Portable variable message sign(s)
RDT	Red dragon's teeth (markings)
RE	Solid red edge line
RSDB	Radar speed display board
RWE	Red-white pattern edge line
RWM	(Alternating) red-white checkered median stripe
SDLP	Standard deviation of lateral position
SFS	Speed feedback signs
SFT	Speed feedback trailer
SPE	Speed photo-radar enforcement
TCM	Traffic calming measures
TCP	Traffic control person
TRID	Transport Research International Documentation
TRS	Transverse rumble strips
VMS	Variable message sign
WHO	World Health Organisation
WP	Work package

1 Introduction

Work Package 3 of the TWIN-SAFE project, entitled “Research of road infrastructure impacts on driver behaviour” aims to evaluate how road infrastructure affects driving behaviour on rural roads by integrating behavioural data with road characteristics. Based on the aforementioned, the WP aims to recommend safety-focused infrastructure modifications, and assess the effectiveness of these interventions through simulation and user feedback. Main objectives of the WP are as follows:

- Understand the influence of driver characteristics on driving patterns and behaviour on rural roads;
- Identify high-risk road sections where infrastructure and human factors interact to increase hazards;
- Evaluate promising infrastructure enhancements using driving simulator tests;
- Develop tailored infrastructure improvement proposals for high-risk rural road sections.

In addition to its main objectives, the WP pursues a linked sequence of targets. It starts with continuous monitoring using the TOECAN driver app that tracks whether a driver's operation stays within safety tolerance zones, capturing key patterns such as speeding, abrupt acceleration and deceleration and the use of handheld mobile phones. The critical phases of behaviour identified in this way are then combined with road infrastructure data such as geometry, speed limits, road signs and the presence of guardrails, within a Geographic Information System (GIS), and the iRAP star rating methodology which is used to pinpoint the most critical sections of rural roads.

The WP also has a task of reviewing the scientific and grey literature on infrastructure measures that influence driver behaviour at high-risk rural road locations, and translating the findings into practical guidelines for implementing these measures, which is the specific focus of this deliverable. This deliverable presents the overview of international peer-reviewed literature together with agency reports and design manuals. It covers leading journals and high-quality conference proceedings in road safety and human factors, with emphasis on road layout, road markings and signage. Core sources include main scientific journals in the domain, supplemented by relevant conference publications; agency reports and design manuals are consulted where they provide evaluated outcomes. Section 4 reports the results of this review across four high-risk rural road locations, transition zones, horizontal curves, work zones and intersections, and Section 5 turns these results into the guidelines for implementing measures to increase safety on rural roads that form the core deliverable of this report.

The deliverable is intended for an academic audience and those who decide on, design and maintain rural road infrastructure. Researchers in traffic engineering and traffic psychology are provided with a consolidated overview of the literature, including methodological approaches and identified evidence gaps that may guide further simulator and field studies, while lecturers and students in transport engineering and road safety programmes can use it as a reference text. Furthermore, national and regional road authorities and municipal technical services will find in the deliverable a structured basis for prioritising interventions and for justifying such interventions in investment programmes and road safety strategies. For road designers and traffic engineers, the review offers evidence on which layout, marking and signage treatments have measurably influenced driver behaviour, together with the reported magnitude of their effects, so that design choices can be supported by documented outcomes rather than by convention alone. Within the TWIN-SAFE project, the deliverable forms the evidence base for the infrastructure improvement proposals and the driving simulator evaluations.

2 General overview of road safety, driver behaviour, speed and crash risk

Transport is a key segment of modern society, enabling the mobility of people and goods and connecting urban and rural areas. The development of road infrastructure and the increase in vehicles on the roads have brought many benefits but also resulted in an increased number of crashes, which represent one of the greatest challenges in the transport system. Road safety is generally measured in terms of the number of road crashes and their consequences. According to the World Health Organisation (WHO), road crashes cause about 1.19 million deaths and an estimated 50 million injuries each year (Global Status Report on Road Safety 2023, 2023).

Overall, road safety depends on three key factors: the driver, the vehicle, and the road infrastructure. Firstly, the driver is responsible for speed adaptation, following traffic rules and timely reaction to changing driving conditions. Experience, perception and drivers' psychophysical condition are crucial in road safety. Secondly, the vehicle must be in proper working condition, with a functional braking system, lighting and stability control to ensure safe speed adaptation. Finally, road infrastructure must be clearly marked, well-lit and designed to meet safety requirements, including adequately placed traffic control measures (Charlton & O'Brien, 2002).

The Safe System Approach is the leading framework for road safety in Europe and the pathway towards casualty-free road traffic ("Vision Zero"). It starts from two facts: people make mistakes, and the human body has limited tolerance to crash forces. The road traffic system should be forgiving across all its parts, safe roads and roadsides, safe speeds, safe vehicles, safe road users, and effective post-crash care (European Road Safety Observatory, 2023). A core element of this approach is speed management, and according to this, speeds must be set and managed to a level that allows people to survive if a crash occurs. The European Union has endorsed this approach in its road safety strategy, which calls for limiting speeds to survivable levels and designing every part of the system to reduce the chance and severity of crashes (European Road Safety Observatory, n.d.). It also calls for measures to help the world achieve the goal of reducing the number of deaths and serious injuries from road accidents by 50% by 2030. Furthermore, Goal 6 of the global plan is to halve the proportion of vehicles exceeding the posted speed limit and to achieve a reduction in speed-related injuries and fatalities, a goal that cannot be met by enforcement and education alone (*Global-Plan-for-Road-Safety*, n.d.).

Moreover, the relationship between speed and the risk of a crash is complex. Specifically, at high speeds, the time to react to changes in the environment is shorter, the stopping distance is larger, and the manoeuvrability is reduced (Aarts & Van Schagen, 2006). Furthermore, speed is a major factor in overall road safety performance (Aarts & Van Schagen, 2006). Excessive and inappropriate speed accounts for about one-third of fatal collisions and is an aggravating factor in most collisions. Often, however, speed is not the main cause but a contributing or aggravating factor. For example, in New Zealand, speeding is involved in around 60% (Soames Job & Brodie, 2022) of fatal crashes, and in India, almost 70% (Ministry of Road Transport and Highways [MoRTH], 2021). It is estimated that 10 to 15% of all crashes and 30% of all fatal crashes are the direct result of speeding and inappropriate speed (European Road Safety Observatory Road Safety Thematic Report-Speed, 2021).

Inappropriate speed increases the risk of crashes and the severity of their consequences. This relation between the severity and frequency of traffic events is often visualised in the form of a pyramid (Hyden, 1987) as shown in Figure 1. Many drivers fail to adjust their speed according to road conditions, which becomes particularly critical in high-risk locations such as transition zones, curves, intersections, etc., where drivers need to lower their speed and adjust their behaviour to different road characteristics. In these zones, road crashes often occur due to inadequate speed adjustment,

late driver reaction or inadequate infrastructure that does not facilitate gradual speed reduction and proper behaviour. Several factors, including unclear traffic signs, changes in speed limits, visual and mental driving demands, and individual driver characteristics, can cause drivers' lack of adaptation to different road conditions.

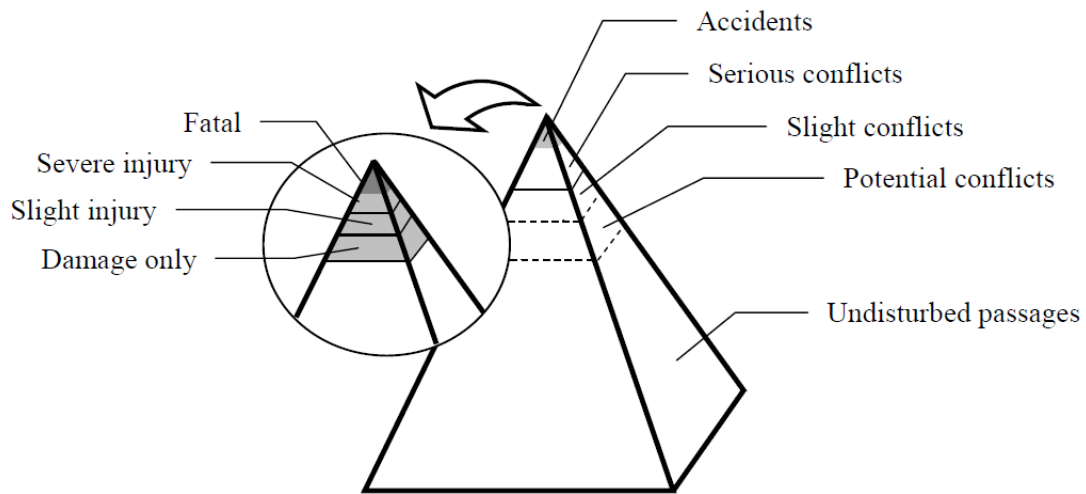


Figure 1. The "safety pyramid" (Hyden, 1987)

To reduce road crashes in high-risk areas and improve driver behaviour, it is important to examine current issues and create safer roads for all users. This can be accomplished through low-cost interventions and measures, such as enhanced and new road signs and road markings, which will assist drivers in better adapting to speed variations and road conditions.

As vehicle speed increases, the driver has less time to react, the useful field of view becomes narrower, and a longer distance is required to bring the vehicle to a complete stop. Higher speeds also substantially increase the risk of fatal or serious injury to pedestrians in the event of a collision. The following infographic illustrates these relationships at 50, 70 and 90 km/h. The presented values are approximate and may vary depending on road conditions, vehicle characteristics, braking performance and driver reaction time.

- When a vehicle is traveling at:



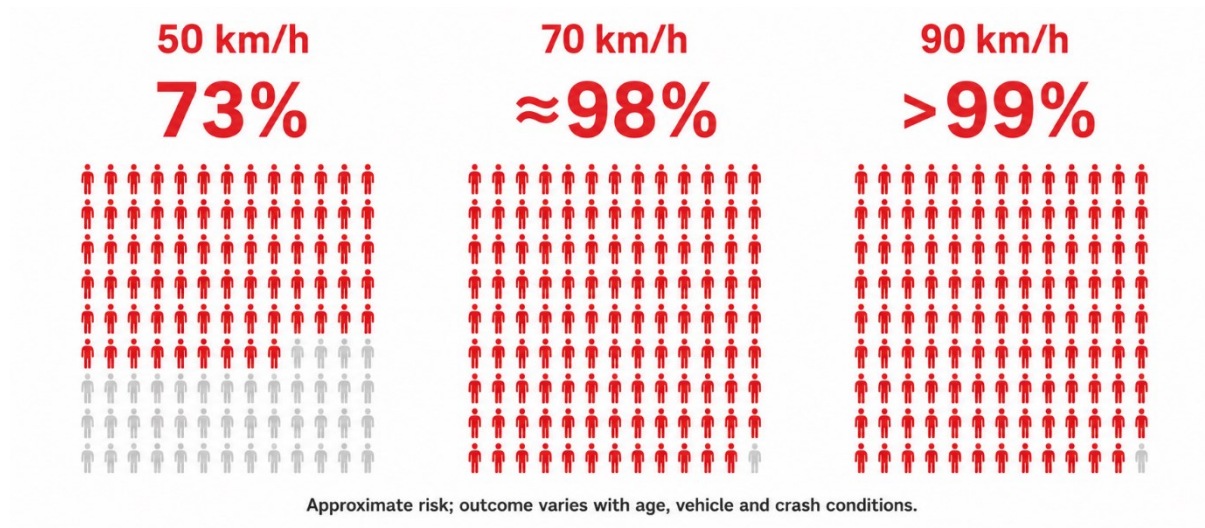
- Driver's field of vision is:



- It takes to stop:



- Likelihood of fatality or serious injury:



3 Research methodology

Articles were identified following PRISMA 2020 guidance (Page et al., 2021), searching Web of Science Core Collection, Scopus and IEEE Xplore, supplemented by Google Scholar and the websites of national and international road authorities and associations (e.g., TRID, PIARC, Austroads) for grey literature. After identifying core articles for each high-risk location, the search was extended using a snowball method, reviewing the reference lists of included articles for additional sources. The search was restricted to peer-reviewed journal articles published in English; TRID technical reports were included as grey literature where they offered evaluated outcomes relevant to engineering practice, even though they are not peer-reviewed.

Each high-risk location was searched separately in Web of Science and Scopus using Boolean combinations of location-specific keywords together with *driver behaviour*, *speed reduction* and *traffic calming measures: transition zone, rural-urban transition, gateway and entry treatment* for transition zones; *horizontal curve* and *lateral position* for horizontal curves; *work zone* and *construction work* for work zones; and *intersection* and *junction* for intersections. The table below summarises the search and screening results for each high-risk location.

High-risk location	WoS records	Scopus (new)	Full-text assessed	Included after full-text screening	Grey literature (TRID)	Snowball added	Total included in synthesis
Transition zones (4.1)	100	1 of 10	22	13	n/q*	6	18
Horizontal curves (4.2)	154	3 of 7	28	16	6	4	19**
Work zones (4.3)	657	0 of 4	30	17	3	8	25
Intersections (4.4)	206	0 (all dup.)	32	8	3	4	10***

* Not separately quantified in the original search log for this location. ** The narrative previously reported 20 studies for horizontal curves; this has been corrected to 19 to match the number of studies presented in Table 2. *** Comprises 10 journal articles corresponding to the entries in Table 4; 3 additional TRID technical reports were reviewed as grey literature and are cited in the narrative rather than tabulated. In three of the four rows above, the WoS, Scopus, TRID and snowball counts do not sum exactly to the total included, which most likely reflects duplicates identified only once sources from different databases were merged for full-text review. We recommend re-checking these figures against the original PRISMA extraction records before submission.

4 Literature review of high-risk locations

High-risk locations are parts of the road where drivers need to lower their speed and adjust their behaviour to different road characteristics. As stated, high-risk zones in this document are divided into four categories: transition zones, horizontal curves, work zones, and intersections. In these zones, road crashes often occur due to inadequate speed adjustment, late driver reaction or inadequate infrastructure that does not facilitate gradual speed reduction and proper behaviour.

The design of transition zones in high-risk locations is closely related to the traffic calming measures (TCM). Furthermore, TCMs are, according to Vis et al. (1992), classified based on the level of coercion on four different types of measures:

- **Informative measures** alert the road users to the fact that a particular kind of behaviour is expected from them. The most well-known informative measure is the maximum speed sign.
- **Suggestive measures** do not physically enforce particular behaviour but try to achieve this by visual suggestion or illusion to encourage a certain kind of behaviour. For example, by emphasising an area's residential function through special paving construction or road surfacing or by suggesting a road narrowing through line techniques.
- **Persuasive measures** more convincingly persuade road users to behave in a certain manner. Various types of bumps and other bumpy shapes are examples of this. With these measures, the desirable speed is in the strictest sense not physically enforced, but in practice, it makes most drivers reduce their speed.
- **Obstructive measures** are based on an obstructive effect that makes higher speeds impossible, for example, by forcing drivers to follow a specific course or creating a blocking mechanism caused by oncoming traffic. The most well-known examples of this are chicanes.

The scope of this report is limited to low-cost traffic calming engineering measures, including road signing, road markings, traffic islands, and variable message signing (VMS). Most of the reviewed studies in this report were conducted with a driving simulator.

Driving simulators are a popular instrument for researching driver-vehicle-environment interaction (Bella, 2009). In driving simulators, participants sit in a mock-up vehicle and drive through a virtual road environment projected on one or more screens. A virtual road environment is designed to include a specific scenario of interest, often with traffic signalisation. The driving simulator can record a large number of driving parameters, including speed, acceleration, lateral position, etc. Moreover, in the context of road design, driving simulators are used to test driving behaviour and new road infrastructure features, and they let us compare design options before building anything (Bella, 2009). Beyond the high level of the resulting data, simulators offer several further advantages, such as full control of the road environment and the interaction with other, virtual, road users, while ensuring complete safety for participants and the public (Godley et al., 2002).

Validity is central to interpreting simulator results. According to (Blaauw, 1982), absolute validity refers to the numerical correspondence between behaviour in the driving simulator and behaviour in a real traffic situation, and relative validity refers to the correspondence between effects of different variations in the driving situations. Building on this distinction, (Törnros, 1998) argues that relative validity is necessary, and absolute validity is not essential, because most research questions focus on the effect of independent variables, typically the differences between a control scenario and other experimental scenarios.

A continuing concern is how well behaviour in a simulated setting matches driving in real-life environments (Bella, 2008; Fisher et al., 2011). Furthermore, driving behaviour should be based on a

multi-dimensional approach, a combination of both longitudinal and lateral driving parameters (Rosey et al., 2008). The longitudinal dimension mostly focuses on how drivers manage their speed. Among the different speed-related parameters, mean speed is widely used as a base for safe driving, since higher mean speeds are associated with increased crash risk and severity (Shinar, 2017). Another common parameter is the standard deviation of longitudinal acceleration and deceleration, which reflects how well drivers control variations in speed. For example, abrupt speed changes can disrupt the homogeneity of traffic flow and reduce the time available for anticipation and reaction. The lateral dimension concerns lane-keeping, for instance, poor harmonised lane position is a key factor in single-vehicle run-off-road and head-on crashes (Rosey et al., 2008). Accordingly, the variation of the standard deviation of the lateral position is often used to indicate lateral trajectory control. Also, the standard deviation of lateral position is a sensitive measure of driver impairment, for example, due to increased mental workload and various drugs (De Waard, 1997).

Finally, a driving simulator can be combined with additional measurement systems, such as an eye tracking system or electroencephalography (EEG), to monitor another driver's behaviour as visual behaviour or electrical activity of the brain (Fiolić et al., 2023; Wu et al., 2013).

4.1 Transition zones in approaching settlements

Literature in the field of speed and speed management is extensive, but the applicability of this literature to transition zones is limited. In current literature, it is sometimes difficult to identify measures that are specific to transition zones, as researchers do not always correctly state and distinguish between measures located in the settlement and measures located in the transition zones.

A transition zone is located between the rural zone and urban zone and represents an area where drivers are expected to complete a reduction in speed to ensure safe driving in a more developed environment (Forbes, 2011). In fact, the transition zone is not to be intended as the specific point at which the lower speed limit is enforced, but as the whole section in which the perceptual change from rural to urban takes place (Torbic, 2012). The theoretical location and length of this zone are determined by a number of physical, operational and safety characteristics. It can include a part that has similar characteristics to the rural zone, but also the edge of an urban zone. However, the transition zone should contain elements that clearly distinguish it from these two zones and inform and assist drivers in achieving an appropriate speed reduction. The two main units that make up the transition zone are the perception-reaction area and the deceleration area (Torbic, 2012), as shown in Figure 2.

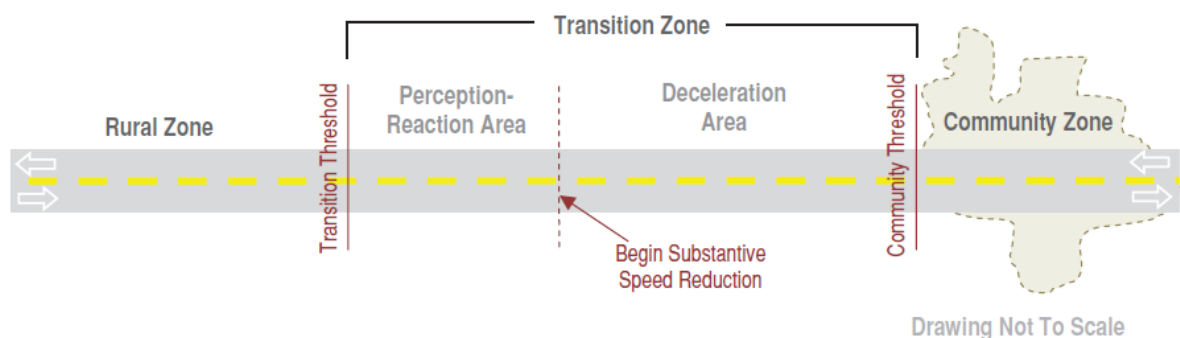


Figure 2. Definition of transition zone (Torbic, 2012)

Many studies show that, in terms of road safety, the transition zones between rural and urban areas are a serious problem (Charlton & O'Brien, 2002; Galante et al., 2010; Wheeler & Taylor, 1999). In many situations, speed limits on rural roads approaching urban areas are higher than 70 km/h, and drivers are accustomed to driving at higher speeds for a longer period before entering an urban area (50 km/h). Such a transition can have a detrimental effect that can lead to reduced cognitive arousal

and workload (mental overload) and the risk of underestimating the actual speed (i.e., a phenomenon called speed adaptation). Mental underload and speed adaptation can cause unsafe situations, mainly due to inadequate speed reduction (Dewar & Olson, 2007; Hallmark et al., 2007).

Although different treatments have been proposed and validated in the past by researchers and road agencies, their efficiency depends on a system composed of infrastructure, environment, and vehicle, in which the driver represents a key variable. Furthermore, Forbes (2011) provides in his research some fundamental and general information about transition zones: more extensive and aggressive measures generally produce larger speed reduction than passive measures. The study highlighted that the design of settlements should establish a clear relationship between lower limits and changes in roadway character; no single treatment is appropriate for all situations; each settlement requires treatments based on its specific characteristics; and that a speed reduction should be maintained downstream of the transition zone. He added that it is necessary to provide additional measures through the settlement, otherwise, speeds may rebound to previous levels as soon as 250 m from the start of the lower speed zone.

The most implemented treatments in transition zones include TCMs such as road markings, road signs, gateways, raised islands, and dynamic speed feedback signs. These interventions may operate individually, but many studies show that combinations, such as signage and markings, tend to produce stronger behavioural effects. A variety of perceptual treatments have been tested in driver simulators and field studies.

First, road markings are cost-effective TCMs that is easy to implement and maintain. The most common treatments include transverse lines, converging chevron markings, longitudinal lines and dragon teeth markings, all of which give the impression of narrower lanes. For example, Hurtado-Beltran et al. (2025) in their field study compared speed data for three scenarios: no markings (baseline), transverse bars (conventional treatment), and dragon teeth markings (experimental treatment). They found that dragon teeth achieved a maximum speed reduction of up to 12 km/h compared to the baseline scenario. These results indicate that dragon's teeth may work effectively than standard transverse bars, especially where vehicles approach at high speed.

Similar results were reported by Lantieri et al. (2015), who studied 12 gateways along Italian provincial routes. All gateways had dragon's teeth markings and a town sign. The only different element was central island design (no island, central ghost island or raised island). For capturing gaze behaviour about the attention of the driver, an eye-tracking system is used. After analysing the data from eye-tracking, results show that raised islands drew the longest gaze durations, followed by the extended town sign and the dragon's teeth markings. Mean speed reductions ranged from approximately 3,5 km/h without a curb to over 7 km/h with a curb, suggesting that combining perceptual markings like dragon's teeth with physical vertical elements (raised islands) creates a stronger impression of boundary and control. A raised traffic island, as noted, plays a significant role in reinforcing gateway effects. By creating both physical deflection and perceptual narrowing, they signal the transition from open to built-up areas. Other studies have documented reductions of over 17 km/h depending on design, width, and placement (Berger & Linauer, 1999; Vaitkus, 2017).

Gateway treatments have been widely researched as entry-defining features. Galante et al. (2010) conducted driver simulator test of two gateway alternatives: a low-cost option featuring rumble strips, optical bars, and coloured brick strips, and a higher-cost option incorporating chicanes (islands). Both designs significantly reduced entry speeds by 11-17 km/h, depending on direction, with drivers beginning to decelerate as far as 400 m before the gantry. Crucially, differences between the low and high-cost alternatives were not statistically significant, showing that perceptual and low-cost physical measures can achieve effects comparable to more expensive treatments. Makwasha & Turner (2013), in a before-and-after crash-analysis of 102 New Zealand sites, confirmed that gateways can

substantially improve road safety, reducing all crashes by 26% and fatal or serious crashes by 23%. Pinch-point gateways, which combine narrowing and vertical elements, were found to be the most effective.

Ariën, Jongen, et al. (2013) conducted research on a driving simulator and found that gate constructions, located at settlement entrances, have a significant effect on speed and increase driver workload. They noted that gate construction locally reduces driving speed from 97 m before to 97 m after the entrance and increases variability of acceleration/deceleration and lateral position near the entrance in settlement. The authors conclude that a higher workload can make drivers more alert. However, too much variation might indicate overcompensation. For this reason, gateways should be designed to maintain a balance, capturing attention without overwhelming the driver.

Akbari & Haghighi (2020) research was conducted on a driving simulator. They investigated the speed and lateral positioning of four TCMs: modified signs, peripheral markings, continuous rumble, and hatched design. They found that all tested measures reduced mean driving speeds in transition zones. However, only peripheral hatched markings significantly improved both speed and lateral positioning. Modified signs and transverse rumble strips reduced speed but did not improve lateral positioning. They also highlighted that while these treatments reduced speed at entry points, their effectiveness faded within the settlement, and speeds began to rise again. This shows the need for continuity, indicating that traffic calming measures in transition zones should be supported by additional calming within the settlement.

Additionally, perceptual road markings like optical speed bars (OSBs) and circles have also shown effectiveness in reducing driving speed. Balde & Dissanayake, (2013) conducted a field study to evaluate the effectiveness of optical speed bars. After a before-and-after analysis, they noted a significant speed reduction from 65 mph (104 km/h) to 45 mph (72 km/h). Hussain et al. (2021) built on this, tested perceptual measures on a driving simulator. They simulated speed limit pavement markings with a gradual increase of brightness and size. Study results show that differences in brightness and size of road markings led to a reduction of 4.6 to 5.3 km/h. They also measured lateral position and highlighted that proposed markings did not negatively influence drivers' lateral control. At the end, these interventions prove that minor adjustments to visual flow can change speed perception and encourage earlier slowing down.

In addition to perceptual and physical measures, dynamic speed feedback signs and variable message signs are very effective in reducing driving speed in transition zones. Sandberg et al. (2008) did field research where they installed a dynamic speed monitoring display (DSMD). They collected the speed data at all implemented sites at defined intervals over the time of one year. Results of the study show that DSMD signs have a significant long-term (one year) effect on driving speed. For example, the average reduction of driving speed was around 7 mph (11 km/h) for over a year. Furthermore, Cruzado & Donnell, (2009) did a before-and-after study at 12 transition zones in Pennsylvania to determine the effectiveness of dynamic speed display signs (DSDSs). They found reducing driving speed by an average of 6,3 mph (10,1 km/h). However, the effect decreased once the DSDSs were removed. It is important to note that 10 of 12 DSDSs were installed and activated for just one week. Hallmark et al., (2015) in their research installed three different types of dynamic speed feedback signs (DSFS), such as a simple speed feedback sign, alphanumeric sign, and a speed limit sign with LED array. After a before-and-after analysis, they found overall speed reductions of up to 9 mph (14 km/h). They also conclude that DSFS signs have a long-term effect on speed in transition zones. Vertlberg et al. (2023) investigated the effect of speed display radars at six locations on district roads in the Republic of Croatia. They did a before-and-after analysis in a way that displays were switched off for one week and then switched on for another week. They found statistical significance in speed reduction just in one location, with a difference of 5 km/h.

Furthermore, Ariën, Cornu, et al. (2013) investigated digital information displays (DID) and tested three messages like “laughing and sad smiley”, “Thank you”, “You are speeding”, and “Speed control”. Research was conducted on a driving simulator, and they collected driving speed, acceleration/deceleration and lateral control. Results show that the message “Speed control” was most effective in reducing driving speed, which implies the “financial” risk.

In conclusion, the literature shows that transition zones in approaching settlements, between rural and urban areas, are high-risk areas. At the same time, a variety of treatments have shown to be effective in helping drivers adjust their speed when approaching settlements. When perceptual, physical, and digital treatments are used in combination, they can create clear transition zones that promote earlier deceleration, reduce average speeds and speed variation, and encourage greater driver focus. Despite this, this area is still less studied than other aspects of road safety. Further research is needed to explore innovative and combined treatments and assess their long-term effectiveness across different traffic conditions and cultural environments.

For a systematic review, see Table 1. The full catalogue of transition-zone measures, including illustrative images and complete source references, is provided in Section 5.1.

Table 1. Systematic review of measures/treatments used in transition zones in approaching settlements

Title	Authors	Measures/treatments	Location of measures	Participants	Type of the study	Variables	Main statistical tests
Raised traffic islands at city limits - their effect on speed	Berger & Linauer (1999)	Raised islands	Transition zone	Free-flow	Field	Speed	Before-after analysis
Long-term effectiveness of dynamic speed monitoring displays (DSMD) for speed management at speed limit transition	Sandberg et al. (2008)	Dynamic speed monitoring display (DSMD)	Transition zone	Free-flow	Field	Speed	Before-after analysis
Traffic calming along rural highways crossing small urban communities	Galante et al. (2010)	Transverse rumble strips, transverse optical bars, peripheral transverse bars, roadside fence, coloured brick strip, gantry	Transition zone	30 (18 M, 12 W)	Driving simulator	Speed	Student's t-test, Mann-Whitney test
Evaluating effectiveness of dynamic speed display signs in transition zones of two-lane, rural highways in Pennsylvania	Cruzado & Donnell (2009)	Dynamic speed display signs (DSDS)	Transition zone	Free-flow	Field	Speed	Regression model
A simulator study on the impact of traffic calming measures in urban areas on driving behavior and workload	Ariën, Jongen, et al. (2013)	Gate constructions	Entrance of urban area, horizontal curve	46 (24 M, 22 W)	Driving simulator	Speed, acceleration, lateral position	MANOVA

Title	Authors	Measures/treatments	Location of measures	Participants	Type of the study	Variables	Main statistical tests
Evaluating the use of rural-urban gateway treatments in New Zealand	Makwasha & Turner (2013)	Gateway	Transition zone	Free-flow	Field	Crash	Before-after analysis
Measuring the impact of digital information displays on speed: A driving simulator study	Ariën, Cornu, et al. (2013)	Digital information display (DID)	Transition zone	66 (41 M, 25 W)	Driving simulator	Speed	MANOVA
Effectiveness of optical speed bars in reducing approach speeds to rural communities	Balde & Dissanayake (2013)	Optical speed bars	Transition zone	Free-flow	Field	Speed	F test, T test
Gateway design assessment in the transition from high to low speed areas	Lantieri et al. (2015)	Steel gate, dragon's teeth, 4° chicane, raised island	Transition zone	15 (10 M, 5 W)	Field	Speed, eye movement	ANOVA
Use of DSFS as a speed transition zone countermeasure in small, rural communities	Hallmark et al. (2015)	Dynamic speed feedback signs (DSFS)	Transition zone	Free-flow	Field	Speed	Before-after analysis

Title	Authors	Measures/treatments	Location of measures	Participants	Type of the study	Variables	Main statistical tests
Traffic calming measures: An evaluation of the effect on driving speed	Vaitkus (2017)	Safety islands	Transition zone	Free-flow	Field	Speed	Before-after analysis
The impact of perceptual countermeasures on driving behaviour in rural-urban transition: A driving simulator study	Hussain et al. (2018)	Optical circles, optical bars	Transition zone	44 (30 M, 14 W)	Driving simulator	Speed	ANOVA, MANOVA
Optical pavement treatments and their impact on speed and lateral position at transition zones: A driving simulator study	Hussain et al. (2021)	Speed limit pavement markings	Transition zone	78 (55 M, 23 W)	Driving simulator	Speed, lateral position	ANOVA
Speed display radars' impact on speed reduction on district roads at settlement entrances	Vertlberg et al. (2023)	Speed display radars	Transition zone	Free-flow	Field	Speed	Before-after analysis

Title	Authors	Measures/treatments	Location of measures	Participants	Type of the study	Variables	Main statistical tests
Are panels indicating vehicles' speed an efficient traffic calming measure in short urban areas, when they are placed alone	Ángel Salas et al. (2023)	Signals with a speed limit, panel indicating vehicles' speed, entrance of the village	Transition zone	Free-flow	Field	Speed	Before-after analysis
Evaluating of dragon teeth markings in high-speed to low-speed transition zones on rural highway: An empirical study in a developing city	Hurtado-Beltran et al. (2025)	Transverse bars, dragon teeth marking	Transition zone	Free-flow	Field	Speed	T-test
A driving simulator-based assessment of traffic calming measures at high-to-low speed transition zones	Pirdavani et al. (2025)	Chicane, road narrowing, transverse road marking, avenue planting	Transition zone	54 (41 M, 13 W)	Driving simulator	Speed, acceleration, lateral position	ANOVA
Comparing driver behaviour with measured speed - An innovative approach to designing transition zones for smart cities	Majer & Sołowczuk, (2026)	Chicane, central island, refuges island, dynamic speed feedback signs (DSFSS)	Transition zone	Questionnaire, free-flow	Field	Fixation point, speed	Before-after analysis

4.2 Horizontal curves

Horizontal curves are well known to pose challenges for road safety, particularly on rural roads where geometric complexity and limited visibility can significantly impact driver behaviour. In fact, more than 25% of fatal crashes on rural roads occur on horizontal curves, making them a priority as high-risk locations (Federal Highway Administration, 2023). These risks are more pronounced at nighttime conditions, when reduced visibility impairs drivers' ability to perceive colours, shapes, and the roadway path. Under such conditions, drivers face difficulties in maintaining longitudinal and lateral control (Fiolić et al., 2023; Goswamy et al., 2018; Plainis et al., 2006). Furthermore, conventional road marking relies on retroreflection and offers only limited visibility under nighttime conditions because the retroreflective effect does not extend beyond the distance illuminated by vehicle lamps (Babić et al., 2022).

The curve driving task is divided into four primary segments. Each segment is related to the individual set of tasks that the driver should perform to safely navigate the horizontal curve (Figure 3). Moreover, these tasks are subdivided into information-processing elements (perceptual, cognitive, and psychomotor requirements) necessary to adequately perform each task. First, perceptual elements usually refer to the visual information about the curve where the driver estimates curvature, determines lane position, etc. Second, the cognitive element refers to the evaluations and decisions about adopting according to the curve or the driving situation. Lastly, psychomotor requirements relate to the control action, such as steering adjustments and braking, that the driver must make to keep the vehicle stable and to support ongoing information gathering (Prendez & Lee, 2021).

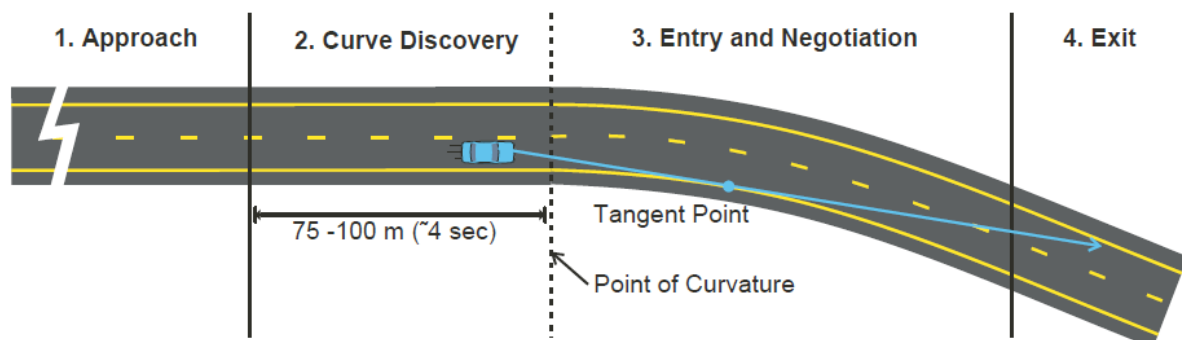


Figure 3. The four primary segments of the curve driving task (Prendez & Lee, 2021)

In this review, most evaluations of traffic calming measures at horizontal curves were conducted in daytime visibility, whether in driving simulators or field settings. Bella & Calvi (2013) highlighted that nighttime conditions alter speed choice and lane keeping, so measures should be investigated and evaluated also in nighttime conditions.

In their further study, Calvi (2015) investigated how geometric characteristics of horizontal curves influence driving behaviour using a controlled driving simulator experiment with 30 participants and 72 simulated curves of varying radius, visibility, and cross-section. It was reported in the study that driving speed increased with wider lanes and larger curve radii, while restricted visibility led to lower speeds, although not sufficiently to ensure safe stopping distances. The inclusion of the transition part of the curves (clothoids) improved driver comfort and lane-keeping performance, reducing pathological discomfort and trajectory dispersion, especially on sharper curves. Based on the study, geometric design elements such as curve radius, visibility, and transition curves have a noteworthy impact on driver performance and safety. The findings are significant since they emphasise the importance of incorporating behavioural considerations into rural road design.

One of the most promising strategies for influencing driver behaviour at horizontal curves involves the use of perceptual countermeasures. These include road markings designed to alter a driver's visual interpretation of the road, creating the illusion of increased speed or lane narrowing. For example, Garach et al. (2022) found that when longitudinal road markings were widened, drivers tended to perceive the road as narrower and themselves as going faster, which led to a natural reduction in speed. Their video-based study involved 185 participants. The authors found that a majority perceived higher speeds with wider markings, which prompted more cautious driving. This finding is in accordance with optic flow theories, which imply that the exaggeration of lateral peripheral visual cues can induce a speed reduction, even when the actual speed remains unchanged (Calvo-Poyo et al., 2020; Garach et al., 2022).

Similar approaches using optical illusions have been tested in driving simulators. Authors Ariën et al. (2021) researched the effects on traffic of transversal rumble strips and herringbone markings. These studies demonstrated that the mentioned treatments enabled drivers to reduce their speed earlier and maintain better lane positioning when entering and navigating curves. Interestingly, the herringbone pattern appeared especially effective at improving lateral positioning, helping drivers stay centred in their lane. These treatments work by enhancing visual complexity or contrast, which in turn captures the driver's attention and increases engagement with the driving task.

Building on these insights, Babić & Brijs (2021) explored the impact of two low-cost road marking measures alone and in combination with traditional vertical signage. Their simulator-based study demonstrated that both tested measures reduced the speed compared to the vertical warning sign alone. This supports the idea that layered interventions may be more effective than single treatments.

Visual design and simplicity also play a role in how drivers respond to these treatments. In a simulator study of curved exit ramps, Raimondo et al. (2022) compared red internal lane bands and zebra-style external markings. The bands, being more straightforward, proved more effective in terms of longitudinal and transversal driver behaviour. On the other hand, the more complex zebra markings had a lesser impact, possibly due to increased cognitive load or distraction. These findings suggest that clarity and contrast may be more important than novelty or artistic complexity when considering primary visual interventions.

In addition to the type of treatment used, the characteristics of the road and the driver also influence how effective an intervention will be. For instance, Martin-Castresana et al. (2025) investigated the impact of road geometry, driver characteristics, and traffic-calming markings on vehicle lateral position in horizontal curves by conducting a driving simulator study involving 48 participants. In the experiment, three road-marking configurations across curves with different radii and turning directions were tested: checkerboard patterns (CBP), red peripheral transverse bars (PTB), and red-coloured transverse bands (CTB). The authors analysed the mean lateral position (LP) and its standard deviation (SDLP) through a general linear model. In the mentioned study, the authors found that male, younger, and high-exposure drivers tended to drive further from the lane centreline and exhibited higher lateral variability. In comparison, the older and female drivers maintained more centred and stable trajectories. CTB markings improved lane centring before left-curve entry, CBP before right-curve entry, and PTB reduced lateral variability most effectively across both directions. Wider-radius curves resulted in more stable and centred paths, whereas smaller radii increased lateral deviation and oscillation. Based on their results, the authors concluded that driver demographics, curve geometry, and certain marking types have a significant influence on lateral stability. Furthermore, well-designed traffic-calming treatments can modestly improve lane-keeping in curve approaches.

Driver distraction is one factor that can reduce the effectiveness of traditional signage. Additionally, mental workload may be a factor influencing the driver's performance. This was investigated in a simulator study by Charlton (2004). In that study, drivers were asked to perform secondary tasks (using

a phone) while driving through curves. The author focused on the effectiveness of three types of curve warnings (diamond signs, chevron boards, and transverse road markings) under varying attentional demands. Using a driving simulator, 30 participants drove through curves of different severities (45, 65, and 85 km/h) while performing either no secondary task or a hands-free cell phone task. The study found that all warnings effectively reduced speeds on sharp (45 km/h) curves, but only perceptually based warnings (chevrons and road markings) remained effective when drivers were distracted by cell phone use. Diamond warning signs, which rely more on explicit attention, lost effectiveness under higher cognitive load. This highlights the value and the potential of research investigating solutions that work subconsciously or do not require active attention, especially when drivers are cognitively overloaded.

The specific design elements of road markings also matter. For example, Iio et al. (2023) researched how different speed reduction marking patterns affect driving speed, lane position, mental workload, and visual attention using a driving simulator with 39 participants. The authors tested four marking types (Parallelogram Edge Line, Wide Chevron, Narrow Chevron, and Optical Dots) under constant and converging intervals on rural highway curves. The results showed that all marking types produced modest speed reductions ($\approx 1\text{--}2$ km/h) before curves. Additionally, the shape and interval of markings did not significantly affect speed choice or lateral stability, although some markings increased subjective feelings of speed and driving difficulty. Further, visual attention analyses revealed that markings influenced gaze patterns. More precisely, chevrons and optical-dot markings encouraged broader visual scanning of the road. The authors also concluded that the measures are most effective when driving in unfamiliar locations. However, their long-term impact may decline as drivers become accustomed to them. Similarly, a driving simulator study by Calvi et al. (2019) found that perceptual markings, specifically red peripheral transverse bars, effectively reduced speeds on the approach to and within a sharp rural curve, confirming their potential as low-cost countermeasures for speeding when approaching the curve. However, they reported limitations related to nighttime visibility and the sample (comprising young and middle-aged drivers), and based on that, recommended further studies to assess long-term effects and performance under different lighting conditions and driver populations.

Beyond static road signs, dynamic feedback systems present a more responsive way to influence behaviour. Hallmark et al. (2012) evaluated the efficacy of Dynamic Speed Feedback Signs (DSFS) in reducing speeds. They conducted their research on 22 high-crash rural horizontal curves across seven US states and compared two DSFS types: (1) displaying a driver's actual speed and (2) showing a curve warning symbol when a vehicle exceeded a speed threshold. Speed data were collected at the point of curvature (PC) and centre of curve (CC) before installation and up to 12 months after. Results showed that DSFS significantly reduced mean and 85th percentile speeds at most sites, with mean speed reductions up to 6.5 mph at the PC and 7.9 mph at the CC. The percentage of vehicles exceeding the posted or advisory speed also declined substantially, since reductions of up to 34–64% were observed for certain thresholds. The authors concluded that DSFS are a promising and cost-effective intelligent transportation system (ITS) countermeasure for reducing speeding-related crashes on rural curves, with sustained effects even after one year of operation. Since DSFS showed especially effective in lowering high-end speeds, targeting those drivers most at risk, it can be concluded that there is significant potential for more frequent application.

It is also valuable to acknowledge and consider the differences between simulator-based and field-based road safety studies. In field studies, such as those conducted by Garach et al. (2022) and Hallmark et al. (2012), On the other hand, driving simulator studies allow for precise control over variables and more detailed behavioural measurements. Besides that, they are conducted in safe environments. Although the environments differ, both types of studies have consistently shown that

infrastructure-based treatments, especially those that influence perception and provide tactile feedback, can effectively modify driver behaviour in horizontal curves. However, there is still a significant gap in investigating various solutions and creating the most effective solutions.

Cost-effectiveness is another key consideration when choosing which measures to implement. Proper allocation of available resources can significantly contribute to improving road safety. In other words, for the same amount of money, more low-cost measures can be installed (in more places), rather than using all the funding to carry out high-cost interventions, but with much less frequency. Numerous visual and tactile measures (e.g., various road marking solutions, painted illusions, and rumble strips) are relatively inexpensive and straightforward to apply. They do not require extensive maintenance and can be deployed widely, especially in rural areas with limited budgets. Meanwhile, more advanced systems, such as DSFS or smart signage, offer substantial long-term benefits but involve higher initial investments.

Taken together, the literature clearly supports the use of infrastructure-based treatments to promote safer driving through horizontal curves. Whether through perceptual illusion, tactile feedback, or real-time speed warnings, these measures help drivers better perceive, process, and respond to the demands of curved road segments. By guiding drivers through each phase of the curve-navigation task, from detection and decision-making to control, these treatments reduce the likelihood of errors and increase overall road safety. Most importantly, they make safe behaviour more intuitive, reducing reliance on active monitoring and enabling a more forgiving, self-explaining road environment.

For a systematic review, see Table 2. The full catalogue of horizontal-curve measures, including illustrative images and complete source references, is provided in Section 5.2.

Table 2. Systematic review of measures/treatments used in horizontal curves

Title	Authors	Measures/treatments	Location of measures	Participants	Type of the study	Variables	Main statistical tests
Perceptual and attentional effects on drivers' speed selection at curves	Charlton (2004)	Diamond warning sign, chevron warning, road marking warning	Horizontal curve	30 (13 M, 17 W)	Driving simulator	Speed	ANOVA
Increasing road safety by influencing drivers' speed choice with sound and vibration	Lank & Steinauer (2011)	Transversal rumble strips	Horizontal curve	Free-flow	Field	Speed	Before-after analysis
Speed reduction impact of dynamic speed feedback signs on high crash curves	Hallmark et al. (2012)	Dynamic speed feedback signs (DSFS)	Horizontal curve	Free-flow	Field	Speed	Before-after analysis
The effect of pavement marking on driving behavior in curves: A driving simulator study	Ariën et al. (2014)	Transversal rumble strips, backward pointing herringbone pattern	Horizontal curve	35 (23 M, 12 W)	Driving simulator	Speed, acceleration, lateral position	ANOVA, MANOVA
A study on driving performance along horizontal curves of rural roads	Calvi (2015)	Road configurations of 24 horizontal curves	Horizontal curve	34 (20 M, 14 W)	Driving simulator	Speed, pathologic discomfort (PD), dispersion of trajectory (DT)	ANOVA

Title	Authors	Measures/treatments	Location of measures	Participants	Type of the study	Variables	Main statistical tests
Effect of traffic control devices on rural curve driving behavior	Montella et al. (2015)	Transversal rumble strips, curve warning signs, chevrons	Horizontal curve	50 (33 M, 17 W)	Driving simulator	Speed, deceleration	ANOVA
Modeling the influence of chevron alignment signs on young male driver performance: A driving simulator study	Wu et al. (2016)	Chevrons	Horizontal curve	36 M	Driving simulator	Speed, lateral position	Linear regression
Evaluating the effectiveness of perceptual treatments on sharp curves: a driving simulator study	Calvi et al. (2019)	White and red peripheral transverse bars (PTB), optical speed bars (OSB), chevrons	Horizontal curve	38 (26 M, 12 W)	Driving simulator	Speed	ANOVA
Impact of perceptual countermeasures on driving behavior at curves using driving simulator	Awan et al. (2019)	Optical circles, herringbone patterns	Horizontal curve	43 (15 M, 28 W)	Driving simulator	Speed, acceleration, lateral position	MANOVA
Low-cost road marking measures for increasing safety in horizontal curves: A driving simulator study	Babić & Brijs (2021)	Red median, horizontal warning sign	Horizontal curve	47 (25 M, 18 W)	Driving simulator	Speed, acceleration, lateral position	ANOVA
A driving simulator study on the effect of transversal rumble strips located nearby dangerous curves under repeated exposure	Ariën et al. (2021)	Transversal rumble strips	Horizontal curve	18 (8 M, 10 W)	Driving simulator	Speed	ANOVA

Title	Authors	Measures/treatments	Location of measures	Participants	Type of the study	Variables	Main statistical tests
Alternative horizontal along curved exit ramp terminals to improve driver-safety-related performance	Raimondo et al. (2022)	Innovative horizontal markings (HMs)	Horizontal curve on exit ramp terminals	48 (21 M, 27 W)	Driving simulator	Speed (S), lateral position (LP), diverging abscissa (DA)	ANOVA
The effect of widening longitudinal road markings on driving speed perception	Garach et al. (2022)	Widening longitudinal road markings	Horizontal curve	185 (119 M, 54 W)	Video analysis, surveys	Speed	-
Effect of chevron design on driver behaviour when encountering and passing through a dangerous curve	Babić, et al. (2022)	Chevrons	Horizontal curve	60 (33 M, 27 W)	Driving simulator	Speed, acceleration, lateral position	ANOVA
Effects of speed reduction markings patterns on simulated driving speed and lane position	lio et al. (2023)	Parallelogram edge line, wide chevrons, narrow chevrons, optical dots	Horizontal curve	39 (32 M, 7 W)	Driving simulator	Speed, acceleration, lateral position	ANOVA
Improving road safety at horizontal curves using V2I speed warning messages	Doulabi et al. (2024)	Text message, audio message	Horizontal curve	37 (27 M, 10 W)	Driving simulator	Speed, deceleration	ANCOVA

Title	Authors	Measures/treatments	Location of measures	Participants	Type of the study	Variables	Main statistical tests
Effectiveness of smart horizontal marking on drivers' behavior along horizontal curves: A driving simulator study	Angioi et al. (2025)	Green photoluminescent road markings (PRMs), red PRMs, white retroreflective markings	Horizontal curve	30 (14 M, 16 W)	Driving simulator	Speed, acceleration, lateral position	ANOVA
The impact of perceptual road markings on driving behavior in horizontal curves: A driving simulator study	Pirdavani et al. (2025)	Red-white pattern edge line (RWE), solid red edge line (RE), alternating red-white checkered median stripe (RWM), red dragon's teeth (RDT)	Horizontal curve	47 (32 M, 15 W)	Driving simulator	Speed, acceleration, lateral position	ANOVA
Analysis of vehicle lateral position in curves using a driving simulator: Road markings, human factors and road features	Martin-Castresana et al. (2025)	Checkerboard patterns (CBP), red peripheral transverse bars (PTB), red-coloured transverse bands (CTB)	Horizontal curve	48 (26 M, 22 W)	Driving simulator	Lateral position	General linear model (GLM)

4.3 Work zones

Work zones present some of the most challenging and hazardous driving environments, as they require drivers to adjust quickly to new conditions, temporary alignments, lane closures, and the presence of workers and machinery. These changes often occur after long stretches of driving at high speeds, meaning that drivers must adapt their behaviour in contexts that demand heightened attention. In such conditions, inappropriate speeds are a main contributing factor to crashes, and an adequate base to identify treatments that improve safer behaviour. Across this literature, three major categories of measures stand out: physical and perceptual treatments such as rumble strips and auditory warnings, enforcement-based approaches including photo-radar and police presence, and digital feedback systems like portable variable message signs and speed-activated displays. Although each category has distinct strengths, the most consistent finding across studies is that a combination of multiple treatments is most effective at reducing speed throughout the work zones.

Among the earliest and most widely used treatments in temporary work zones are rumble strips, which generate tactile and auditory cues as vehicles pass over them. Their function is not simply to reduce speed but also to alert drivers that they are entering a high-risk location requiring higher attention. Meyer (2000) studied the effect of orange removable rumble strips on vehicle speeds in highway work zones. They found these measures stable and effective, reducing mean speeds by 4 km/h. Researchers highlighted the easy installation and removal of rumble strips. Fontaine and Carlson (2001) were among the first to evaluate portable rumble strips, showing that they produced clear auditory warnings but with minimal speed reduction for cars, but provided greater effects for trucks, with speed reductions of 4.8 to 6.4 km/h. They found the same insights as previous research that rumble strips have a greater impact on trucks than cars. Despite their advantages, rumble strips face some limitations, including durability under heavy traffic and the noise for nearby residents. Moreover, their speed-reduction effect tends to be modest and often short-lived.

When perceptual measures are combined with enforcement, results often have a stronger impact. Enforcement-based treatments are another approach to improving safety in work zones. Zech et al. 2005 in their field study evaluated two types of measures: rumble strips and police presence in combination with rumble strips. Researchers found that 3M rumble strips reduced the speed of all vehicles by 4.35 km/h. They observed an even stronger effect when rumble strips were combined with the presence of a police car, resulting in speed reductions by 6.44 to 9.66 km/h. While effective, however, the presence of police near work zones requires significant resources and exposes police to risk. Additionally, to reduce these challenges, automated photo-radar systems have been tested. Medina et al. (2009) investigated the effects of various measures to reduce driving speeds in work zones. For free-flow traffic, automated speed photo-radar enforcement (SPE) shows a reduction in speed by 3.2 to 6.1 km/h for cars and by 1.3 to 8.5 km/h for trucks. Other measures, like speed feedback trailer or police vehicles with emergency lights on or off, showed no significant effects on speed reduction. Researchers also highlighted that reduced speeds at monitored work zones also produce downstream benefits for several kilometres. This persistence is important, as drivers often accelerate once they see the end of the work zone.

Perhaps the most rapidly developing category of treatments involves digital and dynamic systems, especially in the USA. Speed-activated signs, which display a driver's current speed relative to the posted speed limit, have shown speed reduction up to 16 km/h, according to Fontaine & Carlson (2001). In addition to rumble strips, they investigated speed displays and found significant speed reduction for both cars and trucks. Furthermore, McAvoy (2011) confirmed in their research that radar-activated displays are effective in reducing speed and are among the most cost-effective temporary

measures, particularly because they require minimal maintenance and can be adapted to different situations.

Variable message signs (VMSs) have been widely tested in simulator and field settings, and this is confirmed by the following research. Yan & Wu (2014) found on their driving simulator research that the information format profoundly influences driving behaviours. They also highlighted that the graphic information VMS format is better than the format with text message only. Furthermore, researchers Ahmed et al. (2016) using a survey among workers perceived VMSs to have a positive effect on safety, and that VMS provides reliable information. However, after analysis of speeds before and after, they found no statistically significant change in speeds. In the other driving simulator study, Bham & Leu, (2018) found that all four used portable changeable message signs overall reduced mean speeds. They highlighted that strong and clearly worded messages have the greatest impact on driver behaviour. For example, the message sign “Prepare to Stop/Stopped Traffic Ahead” showed the largest overall reduction in mean speed. Despite all the research using message signs, Kang & Momtaz, (2018) highlighted that word messages are not often observed, and drivers do not even recognise the safety messages despite being displayed on roadside signs in good visibility conditions. So, they did a study focused on the auditory warning sound (AWS). Results showed that drivers are more compliant with roadside safety signs when combined with AWS. Almallah et al. (2021) evaluated VMSs in the state of Qatar using a driving simulator and found that driving speed was significantly reduced by 6.3 to 11.1 km/h. Additionally, Pahari et al. (2025) used speed feedback trailer (SFT) in a freeway work to evaluate the right position of SFT. They conclude that positioning SFT slightly beyond the end of the lane closure taper resulted in speed reduction.

When considered collectively, the literature indicates several key patterns. First, physical and perceptual treatments such as rumble strips and auditory pavement markings are highly effective at capturing attention and initiating speed reduction, particularly in short-term and mobile work zones. Their low cost makes them acceptable, and their easy implementation makes them attractive. Second, enforcement-based treatments, especially photo-radar or police car presence, have shown consistent speed reduction. However, these treatments may face limitations due to cost and public acceptance. Third, digital and dynamic systems, including variable message signs and speed-activated signs, are effective across different contexts, with the biggest advantage of being adaptable to real-time conditions. Fourth, the most effective approaches are those that combine multiple treatments into a coherent system that sustains safe driver behaviour in complex environments like work zones.

In conclusion, work zones remain high-risk segments of the road network where excessive speeds can affect both drivers and workers' safety. The research reviewed in this report shows that a wide range of treatments can mitigate these risks, with each treatment offering particular strengths. Nevertheless, challenges remain in terms of durability and long-term behavioural adaptation. Future research should prioritise evaluating innovative and combined treatments across different cultural, traffic and environmental contexts, with particular attention to long-term effectiveness and driver adaptation.

For a detailed systematic review, see Mahmud et al. (2024) and Table 3, which builds upon the earlier work of Debnah et al. (2012). The full catalogue of work-zone measures, including illustrative images and complete source references, is provided in Section 5.3.

Table 3. Systematic review of measures/treatments used in work zones

Title	Authors	Measures/treatments	Location of measures	Participants	Type of the study	Variables	Main statistical tests
Speed reduction effects of speed monitoring displays with radar in work zones on interstate highways	McCoy et al. (1995)	Digital display panel	Work zone	Free-flow	Field	Speed	Before-after analysis
Evaluation of orange removable rumble strips for highway work zones	(Meyer, 2000)	Rumble strips	Work zone	Free-flow	Field	Speed	Before-after analysis
Evaluation of supplementary traffic control measures for freeway work-zone approaches	Bernhardt et al. (2001)	White lane drop arrows, CB wizard alert system, orange rumble strips	Work zone	Free-flow	Field	Speed	Before-after analysis
Evaluation of speed display and rumble strips at rural-maintenance work zones	Fontaine & Carlson (2001)	Speed display, portable rumble strips	Work zone	Free-flow	Field	Speed	Before-after analysis
Effectiveness of condition-responsive advisory speed messages in rural freeway work zones	McCoy & Pesti (2002)	Portable changeable message signs (PCMS)	Work zone	Free-flow	Field	Speed	Statistical Analysis of Mean Speeds

Title	Authors	Measures/treatments	Location of measures	Participants	Type of the study	Variables	Main statistical tests
Evaluation of rumble strips and police presence as speed control measures in highway work zones	Zech et al. (2005)	Rumble strips, police presence	Work zone	Free-flow	Field	Speed	Before-after analysis
Improving compliance with work zone speed limits	Brewer et al. (2006)	Speed display trailer, changeable message sign with radar, orange-border speed limit sign	Work zone	Free-flow	Field	Speed	ANOVA
Development and evaluation of speed-activated sign to reduce speeds in work zones	Mattox et al. (2007)	Speed-activated sign	Work zone	Free-flow	Field	Speed	Statistical Analysis of Mean Speeds
Downstream effects of speed photo-radar enforcement and other speed reduction treatments on work zones	Medina et al. (2009)	Speed photo-radar enforcement (SPE)	Work zone	Free-flow	Field	Speed	Statistical Analysis of Mean Speeds
A closed-course feasibility analysis of temporary rumble strips for use in short-term work zones	Heaslip et al. (2010)	Steel rumble strips, plastic rumble strips	Work zone	Free-flow	Field	Driver speed, Lateral movement of strips	-

Title	Authors	Measures/treatments	Location of measures	Participants	Type of the study	Variables	Main statistical tests
Elevated-risk work zone evaluation of temporary rumble strips	Sun et al. (2011)	Rumble strips	Work zone	Free-flow	Field	Speed, Lateral movement of strips	Pearson's chi-squared (χ^2) test
Work zone speed reduction utilizing dynamic speed signs	McAvoy (2011)	Dynamic speed signs	Work zone	39 (36 M, 3 W)	Driving simulator, eye-tracking system	Speed, acceleration, lateral position	ANOVA
Performance of temporary rumble strips at the edge of highway construction zones	Elghamrawy et al. (2012)	Rumble strips	Work zone	Three study vehicles: sedan, cargo van, and 26-ft truck	Field	Speed, sound level	Pearson's chi-squared (χ^2) test
The effect of design and placement of work-zone warning signs on driver speed compliance: A simulator-based study	Strawderman et al. (2013)	Dynamic message signs (DMSs)	Work zone	39 (31 M, 9 W)	Driving simulator	Speed	Before-after analysis
Effectiveness of variable message signs on driving behavior based on a driving simulator experiment	Yan & Wu (2014)	Variable message signs (VMSs)	Work zone	52 (30 M, 22 W)	Driving simulator	Speed, lane changing	MANOVA
Effectiveness of countermeasures to reduce vehicle speeds in freeway work zones	Hildebrand & Mason (2014)	Floating speed zones (FSZ), traffic control person (TCP), narrow lanes, radar speed display board	Work zone	Free-flow	Field	Speed	Statistical Analysis of Mean Speeds

Title	Authors	Measures/treatments	Location of measures	Participants	Type of the study	Variables	Main statistical tests
		(RSDB), variable message sign (VMS), fake police vehicle					
Effectiveness of temporary rumble strips in alerting motorists in short-term surveying work zones	Yang et al. (2015)	Portable plastic rumble strip (PPRS)	Work zone	Free-flow	Field	Speed	F-test
Evaluation of the effectiveness of portable variable message signs in work zones in United Arab Emirates	Ahmed et al. (2016)	Variable message signs (VMSs)	Work zone	Free-flow	Field, Survey	Speed	Before-after analysis
Speed behaviour in work zone crossovers. A driving simulator study	Domenichini et al. (2017)	Eight alternative configurations of speed limits, median opening width, lane width, variable message signs, channelizing devices, perceptual treatments	Work zone	42 (33 M, 9 W)	Driving simulator	Speed	Student t-test
Assessment of driver compliance on roadside safety signs with auditory warning sounds generated from pavement surface-a driving simulator study	Kang & Momtaz (2018)	Auditory warning sound (AWS), variable message sign (VMS)	Work zone	31	Driving simulator	Speed	ANOVA

Title	Authors	Measures/treatments	Location of measures	Participants	Type of the study	Variables	Main statistical tests
A driving simulator study to analyze the effects of portable changeable message signs on mean speeds of drivers	Bham & Leu (2018)	Portable changeable message signs (PCMS)	Work zone	52	Driving simulator	Speed	ANOVA
Speeding in highways work zone: An evaluation of methods of speed control	Ravani & Wang (2018)	Radar trailer, police presence	Work zone	Free-flow	Field	Speed	Before-after analysis
Influence of work zone signage on driver speeding behavior	Banerjee et al. (2019)	Speed photo enforced sign, dynamic speed display sign (DSDS), reduced speed limit signs	Work zone	66 (36 M, 30 W)	Driving simulator	Speed	ANOVA
Improved traffic safety at work zones through animation-based variable message signs	Almallah et al. (2021)	Animation-based variable message signs (VMSs)	Work zone	66	Driving simulator	Speed, acceleration, lateral position	ANOVA
Evaluating driver response to a speed feedback trailer at median crossovers within freeway construction work zones	Pahari et al. (2025)	Speed feedback trailer (SFT)	Work zone	Free-flow	Field	Speed	Linear regression

4.4 Intersections

Intersections represent one of the most critical points of the roadway network, as they are locations where traffic ways merge, diverge or cross. These conflict points are complex and require drivers to process a high volume of visual and cognitive information within a short period. A large number of crashes with severity, on both urban and rural roads, occur at intersections, where drivers often approach at inappropriate speeds, misjudge the intentions of other users, or fail to detect regulatory control devices in time. Numerous studies have therefore focused on identifying infrastructure-based measures that influence driver behaviour to reduce crash risk and improve safety. This literature consistently demonstrates that perceptual, physical and dynamic countermeasures, such as optical markings, rumble strips, speed feedback signs, and geometric design modifications, can significantly impact driver behaviour and reduce speeds at approaching zones to intersections. Figure 4 shows how the speed decreases as the vehicle transitions to the target speed at the intersection.

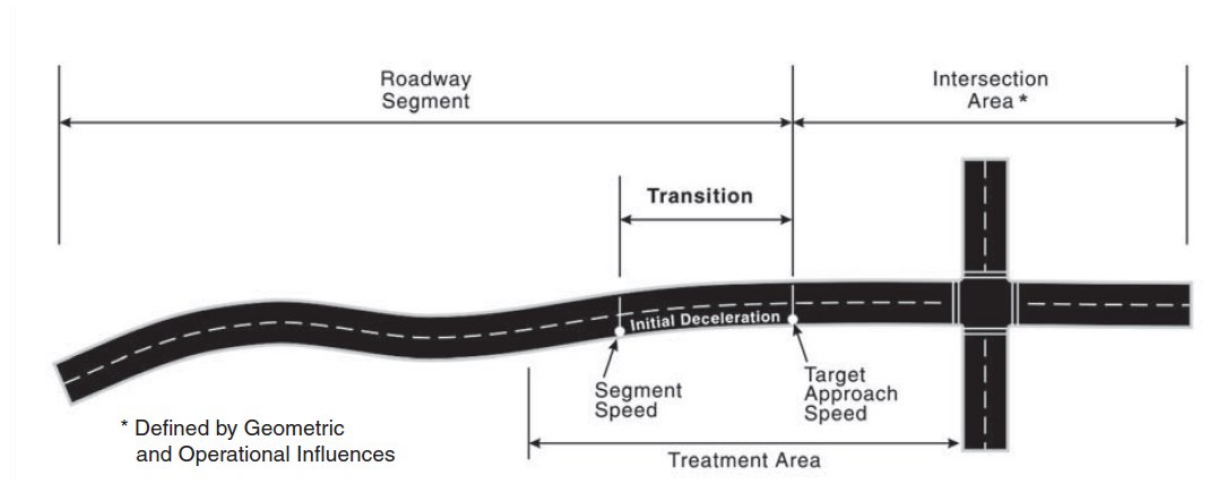


Figure 4. Roadways segment and intersection speed relationships (Ray, 2008)

Rural high-speed intersections are particularly challenging due to their geometric designs and operating speed environment. Drivers on rural roads often maintain high approach speeds and may not adequately perceive the need to slow for intersections.

To address this, researchers have explored the use of transverse rumble strips in approaching zones to intersections. For example, Thompson et al. (2006) investigated the effectiveness of transverse rumble strips in approaching rural stop-controlled intersections. Overall, they found that transverse rumble strips produced small but statistically significant reductions in approaching speed. However, the changes in the before-and-after study were of a magnitude of 3 to 5 km/h. Moreover, Liu et al. (2011) investigated the use of transversal rumble strips at pedestrian crossings in intersections on rural roads in China. They implemented these lines on rural roads with posted speed limits of 60 km/h and 80 km/h. Results showed that the mean speed decreases by 9.2 km/h on roads with speed limits of 60 km/h, and 11.9 km/h on roads with a speed limit of 80 km/h. However, they found no statistically significant speed reduction for a speed limit of 40 km/h. They highlighted that transverse rumble strips may reduce crash frequency by 25%.

Furthermore, several studies found that drivers exposed to perceptual and tactile markings showed smoother steering control, better lane positioning, and improved gaze concentration at conflict points. For example, Montella et al. (2011) in a driving simulator study, investigated driving behaviour in terms of speed, deceleration and lateral position. Seven measures along the approach to the intersection were tested. They noted that optical speed bars and transverse rumble strips both reduced speed. However, rumble strips are usually preferred because they alert inattentive drivers who may miss

visual cues. Additionally, rumble strips last longer than optical speed bars, which wear out faster. The most effective measure included dragon teeth marking, which visually narrows the road, the colored intersection area, which highlights the intersection's presence, and the raised median island, which physically narrows the road. Researchers Yang et al. (2016) studied the effects of transverse rumble strips on approaches to high-speed intersections. In their field study, five intersection approaches with implemented transverse rumble strips were investigated. The study was evaluated by driver speed choice and braking behaviour. They found that tested transverse rumble strips showed a positive effect on speed reduction, with overall braking behaviour accounting for 40% to 80% of all recorded vehicles.

While rumble strips and other tactile measures primarily operate through auditory and vibratory feedback, it is important to understand how noise and vibrations affect driving behaviour. In addition, Hossen et al. (2019) developed demand-responsive rumble strips, which activate only when a vehicle approaches at excessive speed. These adaptive systems deliver a warning only when necessary, reducing both noise and driver desensitisation over time. They highlighted that these measures can also be useful in school zones and residential areas where roadside noise is objectionable.

Horne et al. (2020) investigated low-noise transverse rumble strips (TRS) in the approach to an intersection. They used three types of conditions: a) before conditions (TRS geometric characteristics), b) after conditions (epoxy filled TRS), and c) after conditions (paved TRS). They collected a total of 24 sound measures (10 before, 14 after) and found that epoxy filled TRS sound level dropped from 94 dB to 87 dB in comparison to before conditions. Additionally, the sound from the epoxy TRS is higher than the paved condition, a 4 dB. Comparing the original TRS to the after paved TRS, the sound difference is 11 dB. Such intelligent measures demonstrate how traditional engineering measures can be enhanced through technology, providing a communication between road and driver

Martínez et al. (2013) studied the effect of low-cost measures on driving speed and traffic accidents. The treatments they used were transversal white lines in combination with reflecting “cat eyes” road studs, and “linear delineation system” in the crash barrier with reflecting barrier studs in the other barriers, and placing high-visibility panels along both traffic directions to sign the crossing. Average traffic speed was 73.4 km/h before measures, and after the implementation of new measures and after six months of monitoring, average speed dropped to 50,5 km/h. These findings reinforce the idea that modifying a driver's visual environment can encourage safer behaviour without relying on enforcement or aggressive physical interventions.

Dynamic and feedback-based treatments also play an important role in improving intersection approach behaviour. Karimpour et al. (2021) used traffic sensor data to evaluate the effectiveness of speed feedback signs (SFS) on intersection approaches. These devices, which display real-time vehicle speeds, produced meaningful reductions in both average and 85th percentile speeds. In a before-and-after study on four arterial roads, they noted that speed reductions were sustained for several weeks after installation. They highlighted that drivers adapted their behaviour after they were informed of their speed by SFS.

Several researchers have examined combinations of treatments to determine whether integrated approaches offer additional benefits. One of those were Qin et al. (2024) who conducted research on unsignalized intersections in a driving simulator using an eye tracking system. Analysed parameters were speed and acceleration recorded by simulator and driver's visual data recorded by eye tracker. The scenario was assessed with four low-cost speed-calming measures: anti-collision barrels, traffic-channelising lane markings, their combination and the integration of speed bumps with cross-hatched intersection markings. All measures were found to significantly reduce speed and improve visual attention, but the greatest benefits were observed when measures were combined. Drivers who received both tactile and visual signals had the smoothest braking and the best vehicle control. This

supports the conclusion that a combination of sensory, tactile, and dynamic measures is often more effective than single measures.

Intersection safety research has also emphasised the value of geometric and operational design in speed management. Ray (2008) and Torbic et al. (2015), recommend in their guidelines and reports integrating perceptual and physical elements to create “self-explaining” intersections. According to these guidelines, effective treatments should clearly communicate the upcoming change in driving environment. Their recommended measures include advanced pavement markings, rumble strips, speed feedback signs and improved lighting. They also emphasise that interventions must be specific in context, for example, too aggressive treatments may disrupt traffic flow, while some other measures may fail to generate the right behavioural impact. In addition to these highlights, further studies have supported these recommendations. For example, Godavarthy et al. (2017) tested four traffic calming measures at a two-way stop-controlled intersection in some locations in Kansas. Four measures were implemented: solar speed display units, mobile speed trailers, optical speed bars, and coloured pavement. They found that both solar speed display units and mobile speed trailers were more effective in speed reduction by 2.7 km/h to 11.4 km/h. On the other hand, optical speed bars and coloured pavements did not show a significant speed reduction.

Despite the proven impact of used measures on driving behaviour, challenges remain in ensuring long-term effectiveness. Moreover, maintenance, noise, and public acceptance can limit the long-term sustainability of some measures, such as rumble strips. Furthermore, some researchers highlight that combining measures worked much better than individual methods (Montella et al., 2011; Matínez et al., 2013; Yang et al., 2016; Qin et al., 2024).

The growing integration of smart and responsive technologies represents a promising evolution of these approaches. However, further research is still needed to understand how different measures perform over time and across diverse traffic and environmental conditions. Future studies should focus on evaluating combined and adaptive systems to ensure that intersection safety continues to evolve in line with changes in driver behaviour and vehicle technology.

For a systematic review, see Table 4. The full catalogue of intersection measures, including illustrative images and complete source references, is provided in Section 5.4.

Table 4. Systematic review of measures/treatments used in intersections

Title	Authors	Measures/Treatments	Location of measures	Participants	Type of the study	Variables	Main statistical tests
Speed changes due to transverse rumble strips on approaches to high-speed stop-controlled intersections	Thompson et al. (2006)	Transverse rumble strips	Intersection	Free-flow	Field	Speed	ANOVA
Simulator evaluation of drivers' speed, deceleration and lateral position at rural intersections in relation to different perceptual cues	Montella et al. (2011)	Base intersection, optical speed bars, transverse rumble strips, peripheral transverse bars, dragon teeth markings, colored intersection area, painted median island, raised median island	Intersection	23	Driving simulator	Speed, deceleration, lateral position	ANOVA
Effects of transverse rumble strips on safety of pedestrian crosswalks on rural roads in China	Liu et al. (2011)	Transverse rumble strips	Intersection	Free-flow	Field	Speed	Before-after analysis
Reducing posted speed and perceptual countermeasures to improve safety in road stretches with a high concentration of accidents	Matérnez et al. (2013)	Transversal white lines, reflecting "cat's eye" road studs, linear delineation system for the crash barrier, reflecting barrier studs, high visibility panels	Intersection	Free-flow	Field	Speed	Before-after analysis

Title	Authors	Measures/Treatments	Location of measures	Participants	Type of the study	Variables	Main statistical tests
Operational effects of transverse rumble strips on approaches to high-speed intersections	Yang et al. (2016)	Transverse rumble strips	Intersection	Free-flow	Field	Speed, braking, sound, vibration	ANOVA
Speed reduction mitigation strategies on rural highways at two-way stop control intersections and curves	Godavarthy et al. (2017)	Solar speed display, mobile speed trailers, optical speed bars, colored pavement	Intersection	Free-flow	Field	Speed	T-test
Design and preliminary testing of demand-responsive transverse rumble strips	Hossen et al. (2019)	Transverse rumble strips	Intersection	3 vehicles	Field	Noise, vibration	Before-after analysis
Evaluation of low noise transverse rumble strips in proximity to a stop controlled intersection	Horne et al. (2020)	Transverse rumble strips (TRS)	Intersection	24 vehicles (10 before, 14 after)	Field	Sound level	ANOVA
Traffic sensor data-based assessment of speed feedback signs	Karimpour et al. (2021)	Speed feedback signs	Intersection	Free-flow	Field	Speed	Linear mixed models

Title	Authors	Measures/Treatments	Location of measures	Participants	Type of the study	Variables	Main statistical tests
A simulator study on the driving impacts of four speed-calming measures at unsignalized intersection	Qin et al. (2024)	Anti-collision barrels, traffic-channelizing lane markings, anti collision barrels & traffic-channelizing lane markings, speed bumps & cross-hatched intersection markings	Intersection	20 (15 M,5 W)	Driving simulator, eye tracker	Eye movement, speed, longitudinal acceleration, acceleration noise	Analysis of significance

5 Guidelines for implementation of measures for increasing the safety on rural roads

Building on the evidence reviewed in Section 5, this section translates the identified infrastructure and road-design measures into practical guidance for selecting and combining low-cost interventions at each type of high-risk location. For each location type, Tables 5 to 8 summarise the applicable measures, their expected effect and the supporting evidence, to help engineers and road authorities choose measures that suit the local context, target speed and available budget.

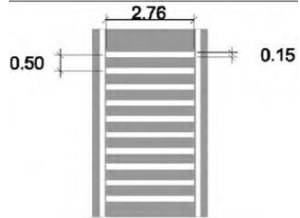
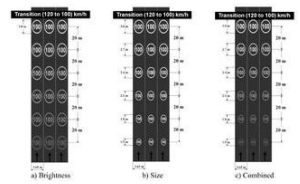
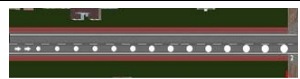
5.1 Measures for transition zones in approaching settlements

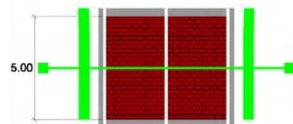
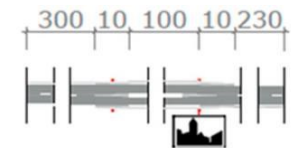
Combining perceptual and physical treatments consistently produces stronger and more durable speed reductions than any single measure applied on its own. Where a settlement lacks an obvious location for physical narrowing, dynamic speed feedback signs or optical road markings offer an effective lower-cost alternative, although their effect can fade once the novelty wears off or the device is removed. Because the benefit of a gateway treatment is often concentrated at the entrance itself, it should be reinforced with additional calming within the settlement to prevent speeds rebounding further along the road.

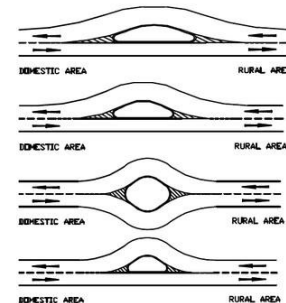
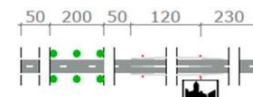
Table 5 lists the low-cost infrastructure and road-design measures identified in the transition-zone literature reviewed in Section 5.1, grouped by treatment type, with an illustrative image and the supporting sources for each measure.

Table 5. Catalogue of infrastructure and road design measures for transition zones in approaching settlements

Group	Measure	Description	Illustration	Source
Traffic signs and information	Regulatory and enhanced speed-limit signs	Clearly indicate the lower speed limit at the start of the transition zone. Enhanced or paired signs increase conspicuity; simulator evidence showed that modified signs can reduce speed, but signage alone may not ensure compliance and is stronger when combined with other gateway cues.		Galante et al. (2010); Akbari & Haghighi (2020); Salas et al. (2023); Pirdavani et al. (2025)
	Dynamic speed display and feedback signs	Measure approaching speed and provide vehicle-specific feedback through the detected speed, a warning message or an activated display. Field studies report meaningful short- and long-term reductions, although effects vary by site and may fade after temporary devices are removed; panels used alone may reduce speed without achieving full compliance.		Cruzado & Donnell (2009); Sandberg et al. (2006); Hallmark et al. (2015); Vertlberg et al. (2023); Salas et al. (2023); Majer & Sołowczuk (2026)
	Digital information displays	Electronic displays provide a salient message, warning or instruction at the approach to the settlement and can be adapted to traffic conditions. Simulator results indicate that the content and placement of the message influence how early and strongly drivers respond.		Ariën et al. (2013)

Group	Measure	Description	Illustration	Source
Pavement markings and perceptual treatments	Transverse rumble strips	Repeated full-width strips provide visual, audible and tactile warning on the approach to the lower-speed area. Decreasing spacing can create an impression of increasing speed. Simulator evidence found significant speed reductions, although lateral-position responses should be checked during design.		Galante et al. (2010); Akbari & Haghighi (2020); Pirdavani et al. (2025)
	Optical speed bars and transverse bars	Transverse bars are arranged across or beside the lane, typically with decreasing spacing toward the settlement, to increase perceived speed. Field evaluation of optical speed bars found significant reductions in mean speed and speed variance at four of five sites, showing that effectiveness is context-dependent.		Galante et al. (2010); Balde & Dissanayake (2013); Hurtado-Beltran et al. (2025); Hussain et al. (2018)
	Dragon's teeth markings	Triangular edge markings progressively project toward the traffic lane, visually narrowing the roadway and highlighting the gateway. A field study reported statistically significant reductions of up to 12 km/h compared with transverse bars and untreated conditions, while also noting the need for clear driver understanding.		Lantieri et al. (2015); Hurtado-Beltran et al. (2025)
	Speed-limit pavement markings	The speed-limit value is marked directly in the driver's primary field of view. Gradually increasing the size and brightness of repeated markings strengthens the perception of approaching speed change; the combined treatment reduced mean speed by up to 5.3 km/h without a meaningful adverse effect on lateral control.		Hussain et al. (2021)
	Optical circles	Circular markings with increasing diameter use forced-perspective cues to increase perceived speed and promote gradual deceleration. Simulator findings support optical circles as a low-cost treatment, but field before-after studies are needed to confirm long-term effects.		Hussain et al. (2018)

Group	Measure	Description	Illustration	Source
	Hatched road markings	Peripheral hatched areas continuously reduce the apparent lane width and concentrate the driver's path. In simulator testing, the treatment significantly reduced mean speed and produced the most consistent improvement in lateral positioning among four low-cost alternatives.		Akbari & Haghighi (2020)
Surface treatments	Coloured or textured surface treatment	A contrasting coloured or textured pavement section highlights the gateway and strengthens the change in road character. Evidence suggests that surface change is most effective as part of a combined treatment, for example with a chicane, rather than as an isolated visual cue.		Galante et al. (2010)
	Gateway treatments	Paired roadside elements, gantries or gate constructions create a recognisable threshold between the rural approach and the settlement. Evidence shows a local speed-reduction effect near the entrance; integrated gateway packages can also improve crash outcomes, but the effect depends strongly on their physical components and context.		Galante et al. (2010); Ariën et al. (2013); Lantieri et al. (2015); Makwasha & Turner (2013); Vaitkus et al. (2017)
Gateway and geometric treatments	Chicanes	A chicane introduces horizontal deflection and requires drivers to alter their path. Chicanes produced the largest speed reductions in simulator testing, although abrupt deceleration may occur. Field evidence indicates that width, surface treatment, surrounding development and downstream visibility strongly influence effectiveness.		Galante et al. (2010); Lantieri et al. (2015); Pirdavani et al. (2025); Majer & Sołowczuk (2026)
	Road narrowing	Physical narrowing reduces the available cross-section and increases enclosure. Simulator results show that it is most effective when combined with transverse markings, producing smoother and more gradual deceleration than a strong chicane while limiting driver discomfort and lateral instability.		Pirdavani et al. (2025)

Group	Measure	Description	Illustration	Source
Roadside and environmental treatments	Raised central traffic islands	A central island separates opposing flows and can create an artificial chicane by shifting one or both lanes. Greater lateral deflection generally produces stronger speed reduction. One gateway study found the raised island to be the most effective component, reducing speed by about 7.2 km/h; symmetrical islands without sufficient deflection may be ineffective.		Berger & Linauer (1998); Lantieri et al. (2015); Vaitkus et al. (2017); Majer & Sołowczuk (2026)
	Roadside fencing	Short sections of roadside fencing increase enclosure and help communicate the transition from an open rural road to a constrained settlement environment. The treatment is primarily supportive and should form part of a coordinated gateway package rather than function as the sole speed-management measure.		Galante et al. (2010)
	Avenue planting	Regularly spaced trees or other vertical roadside elements create an avenue effect and increase perceived enclosure. Simulator evidence found limited speed effects when avenue planting was used alone, but it can support smoother transitions when combined with physical measures. Safe setbacks and sight distance remain essential.		Pirdavani et al. (2025)

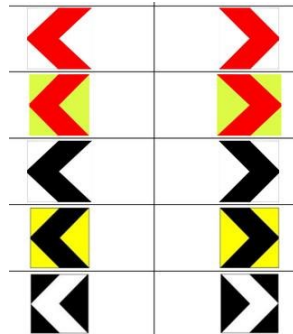
Note: Descriptions synthesise the evidence reported in the cited articles. Reported effects are study-specific and should not be interpreted as universal design values. Selection and detailed design must be adapted to the road context, target speed, traffic composition, available cross-section and applicable national standards.

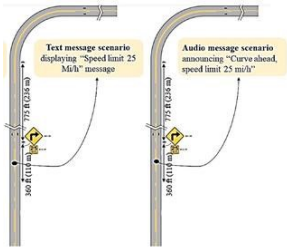
5.2 Measures for horizontal curves

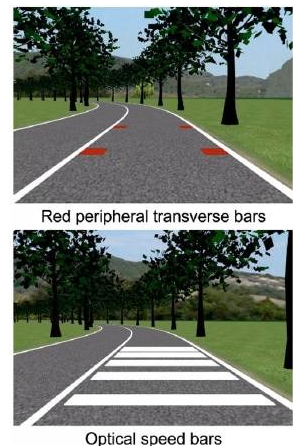
Measures on the approach to a curve should focus on early and gradual speed adjustment, while measures within the curve itself should prioritise lane-keeping and guidance rather than further speed reduction, since markings placed inside the curve can reduce skid resistance. Perceptually based treatments, such as chevrons and peripheral markings, remain effective even when drivers are distracted, making them a more reliable choice than conventional warning signs alone. Cost-effectiveness should also be weighed against crash history: modest measures deployed widely across many curves can outperform a small number of expensive treatments concentrated at only the highest-risk sites.

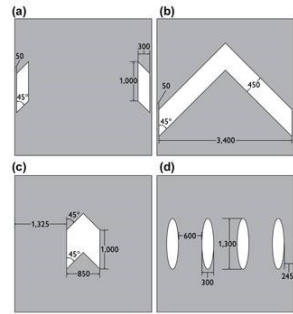
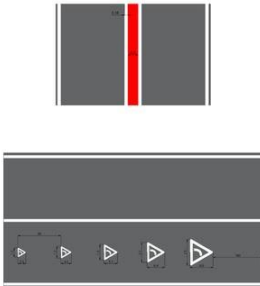
Table 6 lists the low-cost infrastructure and road-design measures identified in the horizontal-curve literature reviewed in Section 5.2, grouped by treatment type, with an illustrative image and the supporting sources for each measure.

Table 6. Catalogue of infrastructure and road-design measures for horizontal curves

Group	Measure	Description	Illustration	Source
Traffic signs and delineation	Curve warning and advisory-speed signs	Warn drivers about the direction and severity of the upcoming curve and may include an advisory speed. Conventional signs can reduce approach speed, but their effect may be limited when attention is divided; warnings with a strong perceptual component generally produce more reliable responses.		Charlton (2004); Montella et al. (2015); Doulabi et al. (2024)
	Chevron alignment signs	Repeated chevrons delineate the change in horizontal alignment and help drivers assess curve direction and sharpness. Evidence indicates improvements in speed selection and lane stability, with stronger effects than standard warning signs under distraction; design, colour contrast and spacing affect performance.		Wu et al. (2016); Calvi et al. (2019); Babić et al. (2022); Kučina et al. (2025)
	Dynamic speed feedback signs	Radar-based signs display a driver's speed or activate a curve warning only when a threshold is exceeded. A multi-site field evaluation found reductions in mean and 85th-percentile speeds at most high-crash curves and substantial decreases in the share of vehicles exceeding advisory or posted speeds, although site-level effects varied.		Hallmark et al. (2012)

Group	Measure	Description	Illustration	Source
Connected and in-vehicle systems	V2I speed-warning messages	Vehicle-to-infrastructure communication delivers a curve-specific speed warning inside the vehicle. Simulator results showed better speed compliance than standard roadside signs; audio messages were more promising than text messages, particularly because they require less visual attention.		<i>Doulabi et al. (2024)</i>
	Transverse rumble strips	Repeated strips on the tangent before a hazardous curve provide visual, acoustic and haptic warning. Simulator and field studies report earlier and more stable deceleration, with reductions of approximately 2.3-5.9 km/h that persisted under repeated exposure. Noise, wear, drainage and skid resistance require consideration.		<i>Lank & Steinauer (2011); Ariën et al. (2017); Ariën et al. (2021)</i>

Group	Measure	Description	Illustration	Source
	Optical speed bars and peripheral transverse bars	Bars with constant or progressively reduced spacing increase visual stimulation and perceived speed on the curve approach. Both white and red treatments can reduce speed; red peripheral transverse bars produced reductions of up to 12 km/h in one sharp-curve simulator study, although drivers did not always consciously understand the markings.	 Red peripheral transverse bars Optical speed bars	<i>Montella et al. (2015); Calvi et al. (2019); Martin-Castresana et al. (2025)</i>
	Herringbone patterns	Backward-pointing herringbone markings visually guide drivers through the curve and can influence vehicle trajectory. They generally reduce speed less effectively than transverse rumble strips but can improve lateral position by encouraging a safer distance from opposing traffic, making them relevant where head-on conflicts are a concern.		<i>Ariën et al. (2017); Awan et al. (2019)</i>
	Optical circles	Circular markings placed along the curve approach create a gradual perceptual cue and increase driver attention. Simulator evidence found a smoother speed reduction than with herringbone patterns, while their influence on lateral position was comparatively limited.		<i>Awan et al. (2019)</i>

Group	Measure	Description	Illustration	Source
Coloured and high-visibility treatments	Speed-reduction marking patterns	Parallelogram edge lines, pavement chevrons, optical dots and related patterns provide a cognitive alert before a curve. Experimental results show reduced throttle and mean speed, but marking shape and converging spacing did not consistently improve the effect; dense constant spacing may be equally or more effective.		<i>lio et al. (2023)</i>
	Internal lane bands at curved exit ramps	Internal bands visually reduce the usable lane width along a curved exit-ramp terminal. Simulator testing showed better longitudinal and lateral control than standard markings, although drivers sometimes initiated the exit later. External zebra stripes produced more limited benefits.		<i>Raimondo et al. (2022)</i>
	Red median and horizontal warning markings	A red median treatment or a warning symbol marked on the pavement increases curve conspicuity and reinforces the need to slow down. Both treatments significantly reduced speed compared with a vertical warning sign alone; the red median also shifted vehicles toward the edge line and is therefore relevant to head-on-crash prevention.		<i>Montella et al. (2015); Babić & Brijs (2021)</i>
	Red and red-white edge-line treatments	Continuous red or alternating red-white edge-line patterns visually emphasise the outside boundary of a curve. The treatments reduced speed and influenced lateral position, generally moving vehicles away from the edge; the direction and radius of the curve can modify the response.		<i>Pirdavani et al. (2025)</i>

Group	Measure	Description	Illustration	Source
	Red-white checkered median stripe and red dragon’s teeth	A checkered median stripe provides continuous central guidance, while red dragon’s teeth create a strong approach cue. The median treatment produced the clearest lateral-position effect; dragon’s teeth achieved the strongest initial speed reduction, but the effect weakened toward the middle of the curve.		Pirdavani et al. (2025)
Night-time and smart markings	Photoluminescent road markings	Green or red photoluminescent markings enhance delineation of the curve under night-time conditions without relying on vehicle headlamps. Simulator findings showed improved lateral positioning and greater distance from the edge line; the evidence for speed reduction was less consistent than for lateral guidance.		Angioi et al. (2025)

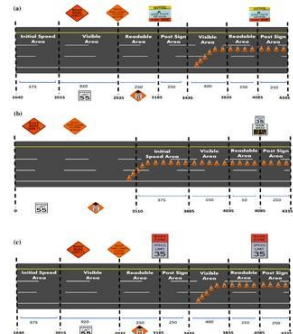
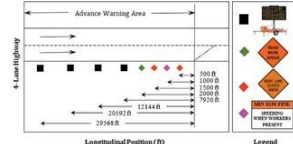
Note: Descriptions synthesise the evidence reported in the cited articles. Reported effects are study-specific and should not be interpreted as universal design values. Selection and detailed design must be adapted to curve geometry, direction, visibility, operating speed, lighting, traffic composition and applicable national standards.

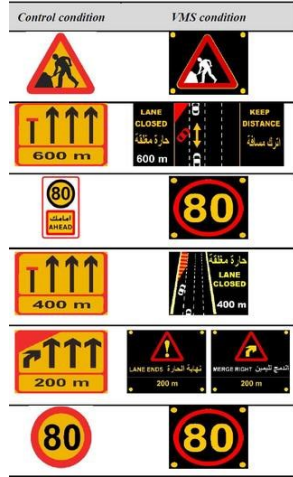
5.3 Measures for work zones

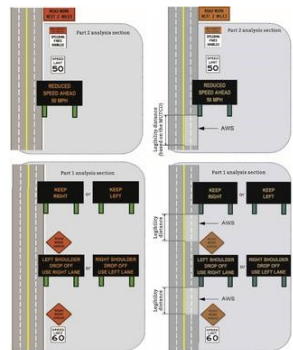
Because work-zone layouts are temporary and change as work progresses, measures should be easy to install, relocate and remove without compromising their effectiveness. A combination of a perceptual or tactile cue with a form of enforcement, such as rumble strips paired with police presence or photo enforcement, produced more consistent and larger speed reductions than either type of measure applied alone. Dynamic systems such as variable message signs are especially valuable where conditions or lane configurations change over the duration of the works, since they can be reprogrammed without physically altering the site.

Table 7 lists the low-cost infrastructure and traffic-control measures identified in the work-zone literature reviewed in Section 5.3, grouped by treatment type, with an illustrative image and the supporting sources for each measure.

Table 7. Catalogue of infrastructure and traffic-control measures for work zones

Group	Measure	Description	Illustration	Source
Warning and regulatory signs	Conventional work-zone warning signs and staged placement	Warning, regulatory and lane-closure signs should be staged so drivers first detect, then understand and act on the message. Simulator evidence indicates that sign design, position and repetition affect compliance; isolated first signs are less effective than a coordinated sequence that produces gradual speed reduction.		Strawderman, Huang & Garrison (2013); Banerjee, Jeihani & Khadem (2019)
Enforcement communication	Speed photo-enforced signs	Signs announcing photo enforcement increase perceived enforcement and voluntary compliance. In a simulator study they achieved the greatest reduction among three sign types, averaging 9.4 mph, and were more effective than dynamic speed display signs and reduced-limit signs.		Banerjee, Jeihani & Khadem (2019)
Dynamic information systems	Portable changeable or variable message signs (PCMS/PVMS)	Portable electronic boards provide site-specific queue, closure, lane-use, travel-time or target-speed information. Clear, strong messages and explicit speed targets produced significant reductions in simulation, whereas field effects can be mixed. Messages should be concise and speed variance or compensatory acceleration should be monitored.		Ahmed et al. (2015); Bham & Leu (2018); Bernhardt, Virkler & Shaik (2001)

Group	Measure	Description	Illustration	Source
	Animation-based variable message signs	Animated sequences illustrate lane-closure and merging progression and can prompt an earlier, smoother response. A simulator study reduced speed by 6.3-11.1 km/h, advanced lane changing by approximately 150 m and increased space headway from 37.6 to 56.3 m.		Almallah et al. (2021)
	Radar speed display boards	Radar-based boards display each approaching driver's measured speed. A field study reported mean-speed reductions of 6-8 km/h and a reduction of up to 40 percentage points in the share travelling more than 16 km/h above the advisory limit. Effects may decay over time, so relocation or reinforcement may be needed.		McCoy et al. (202); Brewer, Pesti & Schneider (2006); Hildebrand & Mason (2014)
	Speed-activated flashing warning signs	A flashing message activates only when an approaching vehicle exceeds a threshold. Field evaluations reduced mean speed, 85th-percentile speed and the proportion of violators; a dynamic 'SLOW DOWN 45' message improved compliance without creating unsafe distraction. Long-term novelty effects should be checked.		Mattox et al. (2007)
Temporary rumble strips	Orange removable transverse rumble strips	High-visibility removable strips across the lane provide an auditory and haptic warning before a stop, taper or temporary traffic control point. They are suitable for short-term deployment, but effectiveness depends on adhesion,		Meyer (2000); Bernhardt, Virkler & Shaik (2001); Fontaine & Carlson (2001)

Group	Measure	Description	Illustration	Source
Auditory and tactile warning	Reusable portable transverse rumble strips	weather, spacing and maintenance; motorcycle stability and roadside noise must be considered. Freestanding plastic strips can be reused in short-term work zones. Field and closed-course studies found more braking and modest speed/compliance benefits, but movement under heavy vehicles or high speeds and evasive motorcyclist behaviour require assessment. Perpendicular deployment is generally preferred.		<i>Heaslip et al. (2010); Sun et al. (2011); Yang et al. (2015)</i>
	Pavement-generated auditory warning treatment	A surface treatment generates an audible and tactile cue immediately before the roadside sign becomes legible, reinforcing its message without adding another sign. Simulator evidence showed improved sign compliance; noise, skid resistance, durability and maintenance must be evaluated before field implementation.		<i>Kang & Momtaz (2018)</i>
Human control and enforcement	Traffic control person or flagger	A visible traffic control person provides an immediate human cue and active control near exposed workers. In a freeway field study, a traffic control person combined with a 70 km/h floating speed zone produced the greatest mean-speed reduction, up to 23.9 km/h. Sight distance, protection and an escape path are essential.		<i>Hildebrand & Mason (2014)</i>
	Police presence and enforcement support	Passive or active police presence increases perceived enforcement and can reinforce rumble strips or message signs. Police deployments reduced mean and 85th-percentile speeds, although more intensive enforcement was not always more beneficial. Speed variance, novelty, staffing and safe vehicle positioning require attention.		<i>Zech et al. (2005); Ravani & Wang (2018); Hildebrand & Mason (2014)</i>

Group	Measure	Description	Illustration	Source
Operational speed management	Static or dynamic floating speed zones	A floating speed zone confines a lower temporary limit to the short active work section and shifts as the work progresses. Combined with a traffic control person, radar display or police presence, a 70 km/h zone achieved large reductions. It should remain tied to visible activity and not extend across inactive sections.		Hildebrand & Mason (2014)
Perceptual and channelising treatments	Perceptual barrier patterns and dense delineators	A high-contrast barrier pattern combined with taller or more closely spaced delineators increases optical density on a crossover approach. Simulator testing produced reductions of about 5-7 km/h and more homogeneous speeds, while the effect of a VMS alone was concentrated in the advance-warning area.		Domenichini et al. (2017)

Note: Descriptions synthesise the evidence reported in the cited articles. Reported effects are study-specific and should not be interpreted as universal design values. Selection and detailed design must be adapted to work-zone duration, road class, approach speed, lane-closure layout, traffic volume and composition, worker exposure, visibility, weather, noise constraints and applicable national standards.

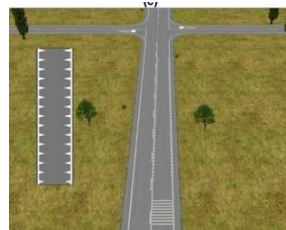
5.4 Measures for intersections

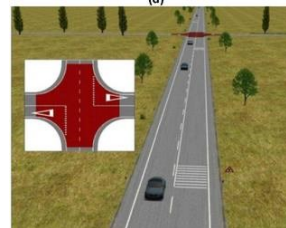
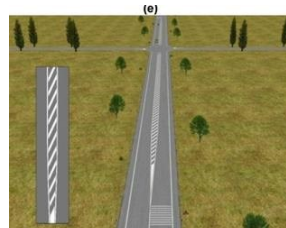
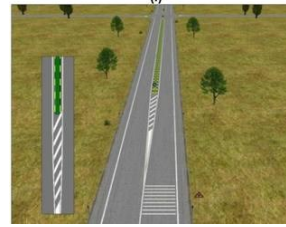
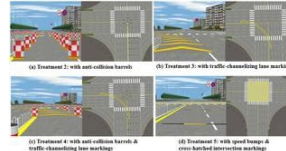
Treatment selection at an intersection should reflect its specific approach speed, geometry and traffic control, since a treatment that is too aggressive can disrupt traffic flow while one that is too subtle may fail to generate a meaningful behavioural response. Rumble strips remain the most consistently effective single measure for alerting drivers on approach, but combining them with a perceptual treatment, such as a coloured surface or raised median, produced the largest and most reliable speed reductions in the reviewed studies. Demand-responsive or low-noise variants of these measures should be considered near schools, residential areas or other noise-sensitive locations.

Table 8 lists the low-cost infrastructure and road-design measures identified in the intersection literature reviewed in Section 5.4, grouped by treatment type, with an illustrative image and the supporting sources for each measure.

Table 8. Catalogue of infrastructure and road-design measures for intersections

Group	Measure	Description	Illustration	Source
Traffic signs and speed management	Speed feedback signs	Radar-based signs show each approaching driver their measured speed and may display a warning such as SLOW DOWN above a threshold. A sensor-based before-after study found statistically significant link-speed reductions at three of four sites while the signs were active; the response depended on the vehicle's approach speed.		Karimpour, Kluger & Wu (2021)
	Reduced posted speed and reinforced warning	A lower posted speed combined with conspicuous roadside or pavement cues can begin deceleration before the conflict area. Simulator evidence indicates that reducing the posted speed and adding perceptual countermeasures can produce a more substantial response than a sign-only change, although the package and its placement must match the approach geometry.		Martinez, Mantaras & Luque (2013)
Rumble-strip technologies	Conventional transverse rumble strips	Sets of raised or grooved strips across the lane provide visual, acoustic and haptic warning on the approach to a stop-, signal- or crossing-controlled conflict. Field studies generally found small but often statistically significant approach-speed reductions and increased braking; at rural pedestrian crossings, expected crash frequency was estimated to decrease by about 25%. Noise, maintenance and avoidance manoeuvres require attention.		Thompson, Burris & Carlson (2006); Liu et al. (2011); Yang et al. (2016)
	Low-noise transverse rumble strips	Shallower epoxy-filled strips retain an audible and tactile warning while limiting roadside noise near stop-controlled intersections. Experimental testing reduced average exterior sound from approximately 93 to 88 dB(A), a noticeable difference, while still producing a detectable in-vehicle		Horne, Jashami & Hurwitz (2020)

Group	Measure	Description	Illustration	Source
Perceptual pavement treatments		warning. Site-specific acoustic and durability verification is needed.		
	Demand-responsive transverse rumble strips	Actuated strips remain level with the pavement during normal operation and rise only when a pedestrian, scheduled condition or abrupt traffic event is detected. Prototype testing showed sufficient haptic and auditory change to regain driver attention while avoiding continuous noise and habituation, making the concept relevant near schools, residential areas and pedestrian crossings.		<i>Hossen et al. (2019)</i>
	Optical speed bars	A sequence of transverse bars with changing spacing creates an impression of increasing speed and encourages earlier deceleration. At rural intersections, simulator results showed significant speed reduction without adversely affecting lateral position; effectiveness depends on conspicuity, spacing pattern and the distance over which the bars are applied.		<i>Montella et al. (2011); Godavarthy, Russell & Mirzazadeh (2017)</i>
	Peripheral transverse bars	Short transverse bars placed near the lane edges increase peripheral visual stimulation while leaving the wheel paths unobstructed. Simulator evidence found lower speeds on the intersection approach, particularly when the treatment was combined with transverse rumble strips, while maintaining acceptable vehicle positioning.		<i>Montella et al. (2011)</i>
	Dragon's-teeth markings	Triangular edge markings increase in size toward the intersection, creating a visual funnel that makes the lane appear narrower. The treatment produced significant and early speed reductions in simulator testing, including reductions of about 5-6 km/h compared with a rumble-strip baseline from roughly 150 m before the intersection.		<i>Montella et al. (2011)</i>

Group	Measure	Description	Illustration	Source
Channelisation and geometric guidance	Coloured intersection surfacing	A contrasting coloured surface across the conflict area increases intersection conspicuity and supports sustained deceleration. In simulator testing it generated one of the largest speed reductions near the intersection, but field evidence from other coloured-pavement applications was mixed; skid resistance, drainage and long-term colour durability must be checked.		Montella et al. (2011); Godavarthy, Russell & Mirzazadeh (2017)
	Painted median island	A long painted median island visually narrows and organises the approach, separates opposing movements and directs drivers toward the intended path. Combined with advance rumble strips, it reduced speed and improved deceleration behaviour in simulator testing; it offers a low-cost option where a raised island is not immediately feasible.		Montella et al. (2011)
	Raised median island	A physical median island creates stronger deflection and channelisation than markings alone. Among the intersection treatments tested in simulation, the raised island produced the greatest approach-speed reduction and a high share of controlled deceleration. Detailed design must address visibility, drainage, turning paths, roadside safety and winter maintenance.		Montella et al. (2011)
	Temporary barrels and channelising markings	Crash barrels, left-turn channelising markings, cross-hatched intersection markings and their combinations can provide a rapid, low-cost treatment at unsignalised intersections. All four simulated configurations reduced average intersection speed; channelising lane markings performed best overall, while abrupt or excessive treatments may reduce driving comfort and stability.		Qin, Wu & Guo (2024)

Note: Descriptions synthesise the evidence reported in the cited articles. Reported effects are study-specific and should not be interpreted as universal design values. Selection and detailed design must be adapted to intersection control, approach speed, traffic volume, pedestrian activity, visibility, road geometry, noise constraints and applicable national standards.

6 Conclusion

After a comprehensive review of literature and global road safety statistics, it has been proven that certain locations, such as horizontal curves, transition zones to approaching settlements, work zones, and intersections, have characteristics of high-risk locations within the road network. These locations are particularly common on rural roads, where higher driving speeds and different behavioural patterns compared to urban environments contribute to an increased crash risk. This review focuses on investigating the impact of low-cost infrastructure measures, such as road signs, road markings or variable message signs, aimed at improving safety in these areas. The main objective of this review is to summarise the key findings of previous studies, such as the methodology, used measures and their effect on driver perception, judgement, and behaviour.

This review, as mentioned earlier, is divided into several groups, as all of them represent types of high-risk locations within the road network. In transition zones between rural and urban areas, literature shows that drivers often fail to adjust their speed when approaching settlements (Dewar R. & Olson P., 2007; Galante et al., 2010; S. Hallmark et al., 2007; Torbic, 2012; Wheeler & Taylor, 1999). The most commonly applied low-cost measures in these zones include perceptual and optical road markings, as well as gateway treatments which aim to visually signal the need for speed reduction. Studies have shown that these treatments encourage earlier deceleration and smoother speed adaptation. Furthermore, when combined with geometric elements such as chicanes or raised medians, their impact on driving behaviour becomes even stronger (Pirdavani, Sadeqi Bajestani, et al., 2025; Sołowczuk & Kacprzak, 2021). However, the literature also points out that these measures are effective mainly at approaching settlements, and their benefits may diminish if there are no additional treatments within the settlements themselves to remind drivers to adapt their behaviour to the new road characteristics and the surrounding environment (Ariën, Jongen, et al., 2013).

For horizontal curves, there are two main reasons why they are classified as high-risk locations: excessive speed and loss of lateral control. Horizontal curves, especially in rural areas, are among the most critical locations in the road network, because in the United States, more than 25% of fatal crashes occur on horizontal curves, and the average crash rate on curves is approximately three times higher than on tangent sections (Federal Highway Administration, 2023). To improve safety on horizontal curves, it is useful to divide them into two segments: the approach to the curve and the guidance through the curve. Treatments applied in approaching horizontal curves, such as optical and tactile treatments, focus more on adjusting the speed and lateral position of the vehicle (Angioi et al., 2025; Ariën et al., 2014; Awan et al., 2019; Calvi, 2015; Calvi et al., 2019). Within the curve, treatments are more focused on road signs than on road markings, as markings can sometimes reduce skid resistance. The goal of these measures is to improve guidance and awareness through the use of chevrons. There are various chevron designs adapted to different curve types, such as standard or hazardous curves (Babić et al., 2022; Wu et al., 2013). In addition, emerging variable message signs and dynamic warning systems have proven to be highly effective in approaching zones to curves. Their high visibility under all weather conditions and ability to display changeable messages make them particularly valuable.

Work zones represent specific environments on roads where drivers face temporary changes in layout, reduced lane widths and less predictable driving conditions. Such conditions often increase the risk not only for drivers but also for road workers. To enhance safety in these environments, researchers commonly applied measures such as portable rumble strips, variable message signs, and speed-activated displays to warn drivers to reduce speed and adjust their lateral position in approaching work zones (Banerjee et al., 2019; Hildebrand & Mason, 2014; McAvoy, 2011; Meyer, 2000; Strawderman

et al., 2013; Sun et al., 2011). Some studies have also tested enforcement-based treatments such as police car presence, either alone or in combination with rumble strips, resulting in a reduction in speed up to 9 km/h. However, this approach is generally not sustainable for long-term period (Zech et al., 2005). Variable message signs (VMS) have emerged as the most investigated treatment in work zones, due to their adaptability to the real-world situations (Ahmed et al., 2016; Almallah et al., 2021; McCoy & Pesti, 2002). Research on these systems has shown that the content and tone of displayed messages significantly influence driver response, with enforcement-oriented messages producing the strongest behavioural effects (Medina et al., 2009). As digital and adaptive systems continue to develop, real-time management of work zones is one of the future important components in temporary work zones safety.

Intersections are another key focus area because they involve the interaction of traffic flows from two or more roads and the presence of other road users. In this review, the focus is on rural, non-signalised intersections. Researchers investigated various treatments, including road markings, signs, and variable message signs, to encourage drivers to reduce speed and increase attention when approaching an intersection (Godavarthy et al., 2017; Goswamy et al., 2018; Horne et al., 2020; Ray, 2008; Thompson et al., 2006; Yang et al., 2016). It is essential that treatments are carefully selected for the specific context of each intersection, because too aggressive treatments may disrupt traffic flow, while salient treatments may fail to generate meaningful behavioural reactions. This balance is particularly important at intersections, where clear communication and understanding between drivers, cyclists, and pedestrians is crucial for safety. Researchers have also highlighted that the lateral position of a vehicle when approaching an intersection plays an important role, as it provides cues to other drivers about intended actions and can help prevent misunderstanding or conflicts (Montella et al., 2015).

Three patterns cut across all four location types and shape how the guidelines group and rank measures. First, combining visual and tactile cues outperforms any single-measure intervention; drivers respond most consistently to a message repeated across sight, sound and vibration (Kang & Momtaz, 2018; Lank & Steinauer, 2011). Second, dynamic and adaptive systems hold growing potential for sustaining compliance over time by adjusting to traffic and environmental conditions. Third, a measure that performs well on a rural road may not transfer to an urban or suburban setting, so the guidelines are scoped to rural conditions throughout. Selecting a measure on effectiveness alone is not enough: public acceptance also determines whether a treatment survives in practice, since driver cooperation is what makes any measure work over the long term. Beyond speed reduction itself, these measures carry secondary environmental benefits: smoother acceleration and deceleration patterns measurably lower traffic noise and exhaust emissions, including nitrogen oxides (NOx) and particulate matter (PM) (Boulter et al., 2001; Brink et al., 2022; Musial et al., 2025), a benefit worth weighing alongside safety when authorities prioritise sites for implementation.

The evidence behind these guidelines rests on two complementary sources: simulator studies, which allow safe, controlled testing of perceptual and cognitive effects, and field studies, which validate those effects under real traffic conditions. Simulator studies offer full control over road design, environmental conditions and interaction with other road users while keeping participants safe (Godley et al., 2002), and where simulator and field results agree, that agreement strengthens confidence in the corresponding guideline recommendation.

Although the reviewed studies provide valuable insights, there are several limitations to take in consideration. Many studies included in this document were conducted in a driving simulator, which provides a controlled and safe environment for research on driving behaviour, but can also influence the validity of results. Simulator sickness remains a common issue, as visual–motion mismatch can cause nausea, dizziness, and discomfort, often leading to participant withdrawal and biased samples.

Drivers also know that the simulator poses no physical risk, which can change their behaviour during high-risk situations, particularly in braking and overtaking tasks. Repeated exposure can also create learning effects, as participants begin to anticipate events rather than respond naturally. Overall, driving simulators allow for experimental control but reduce ecological validity, producing behaviour that may not fully reflect real-world driving conditions. On the other hand, several real-world studies were also conducted, but most were short-term field trials, which may not capture how drivers adapt over the long term. To better understand how different TCMs influence driver behaviour, future research should include long-term field evaluations. Additionally, differences in geography, driving culture and enforcement practices mean that findings from one country cannot always be directly applicable to another country. While most reviewed research focuses on speed reduction, fewer studies evaluate other outcomes such as driver workload, environmental impacts and how these measures affect other road users. There is still significant potential for future research to go deeper into understanding how driver culture and behavioural patterns influence the success of TCMs. Some measures examined in this review were tested only in one specific high-risk location; those showing promising results should be further tested in other similar environments to confirm their effectiveness. Additionally, the performance of many treatments, particularly perceptual ones such as markings and signage, may vary across countries. Therefore, it is recommended that future studies test these interventions in regions with diverse traffic cultures to ensure the reliability and generalisability of the findings.

Another valuable approach for deeper future research would be to conduct multi-stage investigations, beginning with the collection of naturalistic driving data to monitor real driver behaviour and identify high-risk locations on the road network. Based on these findings, proposed TCMs could then be evaluated in a driving simulator to identify the most effective treatments before being implemented in real-world environments for long-term assessments. This combined approach enables controlled testing of human factors under simulated conditions, followed by validation of results under real driving conditions.

Infrastructure design has a demonstrable influence on driver behaviour and crash risk at every high-risk location examined in this review, and that is the premise on which the guidelines in Section 5 rest. Perceptual, physical and adaptive measures, supported by enforcement and education, can reduce speeds, improve awareness and create safer, more predictable driving conditions at transition zones, horizontal curves, work zones and intersections alike. The measures selected for the guidelines share one property in common: they use simple, visible and consistent feedback to make the road self-explaining, so that safe behaviour requires less active monitoring from the driver. Applied with attention to local context, target speed and available budget, the guidelines set out in Sections 5 give road authorities a practical, evidence-based route to increasing safety on rural roads.

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