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A literature study

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Kort sammanfattning

Vägutrustning används för att hjälpa trafikanter att läsa av och förstå trafikmiljön. Det är särskilt relevant att korrekt information finns att tillgå vid korsningar och kurvor. På platser där oskyddade trafikanter korsar vägen är det mycket viktigt att förare av motorfordon uppmärksammar fotgängare och cyklister.

Syftet med denna studie är att fastställa kunskap om användning av vägutrustning i samband med kurvor, korsningar och korsningspunkter med oskyddade trafikanter. Fokus är på motorfordonsförares perspektiv, dvs. hur en förare av ett motorfordon reagerar i dessa situationer. Rapporten är i huvudsak tänkt att användas av nordiska vägmyndigheter och forskare, för att få en överblick av forsknings-resultat och identifiera forskningsbehov.

För att uppfylla syftet genomfördes en litteraturstudie om förarbeteende i samband med vägutrustning i kurvor, korsningar och korsningspunkter med oskyddade trafikanter. Litteraturstudien kompletterades med en översikt av regelverken i Danmark, Finland, Norge och Sverige.

Några slutsatser från litteraturstudien är att förare bör varnas inför situationer som kan komma att överraska dem och att vägutrustning bör användas på ett konsekvent sätt och utformas så att den förstås intuitivt av trafikanterna. Nya typer av utformning av vägutrustning bör studeras och följas upp för att undvika negativa bieffekter.

Identifierade forskningsbehov är forskning på andra fordon än personbilar, vägutrustningens funktion vid olika väderförhållanden och i mörker, samt studier om cykelöverfarter och -passager i samband med förarbeteende och vägutrustning.

Nyckelord

Vägutrustning, vägmarkering, vägbelysning, trafiksignal, vägmärke, kurva, korsning, övergångsställe, gångpassage, cykelöverfart, cykelpassage, förarbeteende, hastighet, sidoläge

Abstract

Road equipment is used to help the road users read and understand the traffic environment. It is particularly relevant that correct information is provided in connection with curves and intersections. At positions where vulnerable road users cross the road, it is very important that drivers of motorised vehicles attend to cyclists and pedestrians.

The aim of the prevailing study is to clarify knowledge concerning use of road equipment in connection with curves, intersections, and crossings with vulnerable road users. The focus is on the motor vehicle driver perspective, i.e., how a motorised driver reacts to these infrastructure situations. The report is mainly intended to be used by the road authorities and traffic researchers in the Nordic countries, to get an overview of research results and identify research gaps.

To fulfil the aim, a literature study was carried out on driver behaviour in response to road equipment at curves, intersections, and crossings with vulnerable road users. The literature study was supplemented by an overview of the current regulations in Denmark, Finland, Norway, and Sweden.

Some conclusions from the literature study are that drivers should in general be warned of situations that might surprise them, and that road equipment should be used in a consistent way and be designed to be intuitively understood by road users. New designs of road equipment should be studied and followed up to avoid unwanted side-effects.

Research gaps identified are research on other vehicles than private cars, performance of road equipment in adverse conditions and at night-time, and studies on cycle crossings and passages in relation to driver behaviour and road equipment.

Keywords

Road equipment, road marking, road lighting, traffic signal, road sign, curve, intersection, pedestrian crossing, pedestrian passage, cycle crossing, cycle passage, driver behaviour, speed, lateral position

Preface

This report presents the results from the project “Litteraturstudie om vägutrustning i korsningar och kurvor”, searched via BVFF, which is an industry programme for research, development and innovations in road and railway construction and maintenance. The project was funded by the Swedish Transport Administration with Peter Aalto as contact person and Klas Hermelin as project sponsor.

The database literature search was carried out by Hillevi Ternström, VTI, and the literature study by Sara Nygårdhs, VTI.

Linköping, May 2021

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Innehållsförteckning

List of abbreviations

- AADT annual average daily traffic
- AYM advance yield marking
- CDT count-down timer
- DGS diagrammatical guide sign
- DRS directional rumble strips
- FWSS four-way stop signs
- HAWK high-intensity activated crosswalk
- HP herringbone pattern
- ICWS intersection conflict warning system
- LED light emitting diode
- MSYM modified standard yield marking
- OFB overhead flashing beacon
- OSB optical speed bars
- PHB pedestrian hybrid beacon
- PTB peripheral transverse bars
- RIAWS rural intersection active warning system
- RRFB rectangular rapid flashing beacon
- TRS transverse rumble strips
- VMS variable message sign
- VR virtual reality
- VRU vulnerable road user

1. Background and aim

Road equipment is used to help the road users read and understand the traffic environment. It is particularly relevant that information about the road's future route is provided in connection with curves and intersections. For a road user it can be a problem with too much information in some environments, especially at intersections, where the cognitive load is large. At positions where vulnerable road users (VRUs) cross the road, it is of extra importance that drivers of motorised vehicles attend to cyclists and pedestrians. However, it is not clear how road equipment should be used in an optimal way in connection to those crossings. The same is true for road equipment in relation to curves of different radii.

The prevailing study aims to clarify knowledge concerning use of road equipment in connection with **curves, intersections, and crossings with vulnerable road users**. The focus is on the motor vehicle driver perspective, i.e., how a motorised driver reacts to these infrastructure situations.

To fulfil the aim, a literature study was carried out on the subject. The literature study was supplemented by an overview of the current regulations in the Nordic countries Denmark, Finland, Norway, and Sweden. The report is mainly intended to be used by the road authorities and traffic researchers in the Nordic countries, to get an overview of research results and identify research gaps.

2. Literature search

The literature search was carried out in the three databases:

- VTI National Transport Library catalogue, which is the largest collection of transport research literature in Sweden,
- TRID, which is a freely accessible database with over 1.25 million references to literature and research projects within transportation research, and
- Scopus, which is an abstract and citation database with over 75 million records.

Literature search was carried out using three different groups of words where at least one of the words should be present for the result to be a match. The literature found in the three groups was then combined so that at least one word from each group should be present. The three word groups were as follows:

1. marker post, bollard, guidepost, traffic cone, delineator, edge line, broken line, solid line, rumble strip, carriageway marking, road marking, hazard marking, guidance marker, road stud, chevron, traffic sign, traffic signal, traffic control device, safety fence, crash barrier, guardrail, lighting, illumination
2. driver, driving, behaviour, braking, mental load, cognition, perception, speed, stress, human factor, reaction, decision
3. curve, bend, curvature, junction, interchange, intersection, crossing, ramp, crosswalk.

In the VTI National Transport Library catalogue the search was primarily made with words from the thesaurus of the database to collect the literature irrespective of the words used by the authors. The same method was used in TRID, complemented by a search in the title field. In Scopus, the search was made in the title field and keywords field.

The literature search was limited in time by publication date 1990 and onwards in the VTI National Transport Library catalogue and in TRID, and by publication date 2010 and onwards in Scopus. The search was carried out in 2020.

For regulations in the Nordic countries, searches with a search engine on the internet have been combined with personal contacts. Only regulations that could be found this way were included.

3. Results from the literature study

When reading through the literature found in the literature search, only references that included some measure of driver behaviour in connection to use of road equipment in either curves, intersections or crossings with vulnerable road users were selected. Measures of driver behaviour included driver speed, lateral position, yield compliance, deceleration start and gaze behaviour.

The literature study is concerned with overall design of road equipment, not the exact design. Hence the exact placement or design of traffic signs etc. is not included here. Different designs or colours of the same type of road equipment are only compared if there are studies made on comparing these designs or colours.

3.1. Curves

Curves can be either horizontal (left and right) or vertical (up and down) or a combination. Research studies seem to be more focused on horizontal curves, which in addition to deceleration and acceleration manoeuvres demand more lateral control. Appropriate speed and steering for the present curvature make the driver remain in the lane and not run off the road or move to the lane for oncoming traffic.

On approach to and throughout a curve, a driver needs to be able to adapt the driving in order to navigate the curve in a safe way. This implies that the curve must give enough information to be detected and for the driver to choose an appropriate speed to stay within the lane and avoid conflict with other potential road users. In the literature review, most research has been on road markings and road signs, but there are also some studies on road user behaviour in relation to signals, barriers, road lighting, road studs and delineator posts.

3.1.1. Road markings

Road markings in the form of edge lines and lane or centre lines make the boundary of the road or lane visible for the road users, especially at night-time. Hence, they guide driver expectations about the future course of the road. Transverse road markings of different designs have also been studied in relation to curves.

Unless otherwise stated, the road marking studies in this section were carried out in daytime visibility conditions.

No markings vs markings

Havránek et al. (2020) found that on a secondary rural road with sharp curves (curve radii of 100-135 m) and without road markings, application of continuous edge road markings resulted in decreased speeds at daytime and dry weather in the inside lanes (right curves for right-hand traffic) but not in the outside lanes (left curves). In addition, the lateral position was about 0.3 m further to the centre of the road in the inside lane. Where instead only intermittent centre lines were applied on the road, vehicle speeds were lower, and the lateral position was about 0.3 m further to the edge of the road for both the inside and outside lanes. This implies that longitudinal road markings have an effect in warning the driver of sharp curves and making it possible to adjust the speed. Both kinds of markings made the drivers compensate away from them laterally.

Transverse rumble strips

Different tests and efforts have been made to inform drivers of upcoming curves. A speed-reducing measure meant to also evoke awareness of a curve is use of transversal lines, normally with reduced spacings along the driving lane, often termed transverse rumble strips (TRS). This measure has predominantly been investigated in daylight simulator studies, often in conjunction with other measures, where the speed reducing effect of transverse rumble strips has been found to vary between about 0 and 25 km/h, depending on curve sharpness and where in the curve the speed is measured (Ariën et al., 2017; Charlton, 2004; Comte & Jamson, 2000; Montella, Galante, Mauriello, & Pariota, 2015).

Comte and Jamson (2000) found that information provided by TRS could be effective to reduce driver speed in curves. A couple of years later, Charlton (2004) reported that at sharp curves (with recommended speed of 45 km/h) TRS were effective in reducing speed, especially when there was an additional auditory and verbal task at the same time.

Provision of TRS with tactile and auditory feedback before the curve (150-66 m) was found to decrease speeds before the curve but not within the curve (Ariën et al., 2017). The same was found for application of a pattern of equally spaced strips at 150 m and 75 m before the curve, respectively (Montella et al., 2015).

Directional rumble strips

Special cases of curves are highway entrance and exit ramps. Directional rumble strips (DRS), that in addition to TRS are meant to alert wrong-way driving, were implemented successively on two existing exit ramps in Alabama and investigated by Xue, Zhou, and Xu (2020) both during daytime and night-time. They found that for a wedge-shaped pattern before the ramp curve, driver speed can be reduced by 4-10 km/h, depending on the current speed limit and the operational speed, while the standard deviation could either be reduced by 4 km/h or increased by 2.3 km/h. This pattern was noted as having a potential to reduce aggressive driving and comply with the recommended ramp speed limit. Next, three sets of stripes between the ramp curve and the end of the ramp were implemented, with each set having shorter distance between the stripes than the previous set (1.52 m, 0.60 m and 0.30 m), resulting in decreased mean speeds as well as standard deviation of the speed by 0.8-4.3 km/h. The standard deviation of the speed was also somewhat lower at night-time than at daytime for this pattern. Finally, a supplementary DRS was implemented at the end of the ramp, consisting of transverse lines with equal distance but gradually shorter length (3.60-0.30 m) and thickness (0.23-0.08 m), forming an arrow pointing towards the stop or yield line, respectively. A somewhat reduced standard deviation of the speed was found at the stop (0.8 km/h) and yield (1.6 km/h) lines for this pattern.

Optical speed bars

In two Italian simulator studies three sets of optical speed bars (OSB), where each set had an increasing bar width (0.20-1.20 m) and decreasing spacing between bars (1.10-0.30 m), were used on two-lane rural roads before vertical (Calvi, 2018) and horizontal (Calvi, D'Amico, Ciampoli, & Ferrante, 2019) curves, respectively. The OSB sets were at 200 m, 100 m and 0 m before the curves and had no effect before the vertical curve and only a small speed reduction (about 2 km/h at 60 km/h speed limit) at the beginning of the vertical curve (Calvi, 2018). Before the horizontal curve there seems to be a speed reducing effect of the OSB, especially at 100 m before (about 10 km/h with posted speed limit 50 km/h) compared to baseline (Calvi et al., 2019). A Japanese simulator study analysed different sequencing of transverse road markings in combination with roadside poles (2.5 m high) (Yotsutsuji, 2017). It was found that at large curve radii (up to 800 m) vehicle speed was more reduced with a sequence pattern that had smaller distances between transverse markings in the middle of the curve, whereas at small curve radii (up to 200 m), speed reduction was more influenced by smaller distances between the markings at the end of the curve (Yotsutsuji, 2017). The author concluded that for drivers that were close to the posted speed limit, reduced distance between markings was not effective, and that the sequential pattern of the markings would need to change depending on the curve radius.

Peripheral transverse bars

Another measure that uses the driver's visual perception to decrease speed, is use of peripheral transverse bars (PTB), see Figure 1. These bars consist of squares that are applied on the pavement at both centre and edge lines, pointing towards the inside of the lane, with the longitudinal distance between the bars continuously shorter in the driving direction (Calvi, 2018; Calvi et al., 2019). Both red and white PTB were tested in the Italian simulator studies, where PTB were implemented from the start to the crest of a vertical curve and before a horizontal curve, respectively. Both designs had a speed reducing effect in daylight conditions before and in the curve, which was higher for red than for white PTB (about 4.5-6 km/h for a vertical curve (Calvi, 2018), and around 5-8 km/h for a horizontal curve (Calvi et al., 2019)).

Figure 1. Illustration of peripheral transverse bars.

Herringbone pattern

An additional optical measure used in connection with curves are variations of the so-called herringbone pattern (HP), see Figure 2. The HP is applied at the edge and centre lines and has in connection with curves been designed as backward pointing parallelograms (Ariën et al., 2017) or forward pointing transverse bars placed on alternating sides of the lane throughout the curve to indicate a more narrow and flat path through it (Awan et al., 2019; Charlton, 2007; Kazemzadehazad, Monajjem, Larue, & King, 2019).

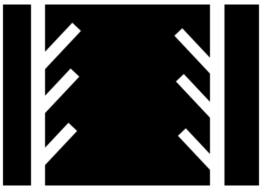

Figure 2. Illustration of herringbone pattern as forward pointing transverse bars.

The first reported use of HP in connection with curves was a simulator study from New Zealand by Charlton (2007), where HP was one of the different types of measures tested. The forward pointing transverse bars placed on alternating sides of the lane made the driver's path through the horizontal curve flatter but there was no speed reducing effect (Charlton, 2007). The author discusses that this is a probable effect of the indicated optimal path making it possible to keep a higher speed, in spite of lane narrowing. In any case, it seems that the drivers avoided traversing the bars and hence followed the path between them, whether consciously or not. A later simulator study, using the same herringbone pattern in combination with chevron arrows through combined horizontal and vertical curves was carried out in Australia, using an implemented Iranian road and Iranian drivers that were familiar with that road (Kazemzadehazad et al., 2019). The results here were different, with the mean lateral position being high (i.e. large deviation between centre of vehicle and centre of lane) in the curve entry, and with oncoming traffic present the mean lateral position being higher than in curves with chevrons only (Kazemzadehazad et al., 2019). The authors suggest that this is due to unfamiliarity with the treatment and that the impact of road markings is less than that of vertical signs. In addition, with HP and facing an oncoming vehicle, drivers were observed to change lane or stop, which is hazardous behaviour according to the authors (Kazemzadehazad et al., 2019). A Belgic simulator study with treatments in two real implemented horizontal curves, showed less variation in lateral position with the HP, as well as decreased mean speeds before and in the curves (Awan et al., 2019). The speed did however increase after the start of the curve, as opposed to baseline (no treatment). This is interpreted as the drivers being comfortable driving through the curve at higher speeds because the HP path created a larger radius for the driver trajectory than the normal lane.

Backward pointing parallelograms throughout horizontal curves, but not before or after them, were implemented in a simulator and reported by Ariën et al. (2017). They found that this type of HP did not alter lateral position but that it induced speed reductions along the curve and could potentially reduce accidents at the end of the curve. In comparison with TRS that were applied before the curve, HP implied a later onset of speed reduction with a longer duration within the curve (Ariën et al., 2017).

Optical circles

Awan et al. (2019) also reported on another road marking treatment in the curves of their simulator study, called optical circles. This treatment consisted of fully painted circles in the middle of the lane at about 190 to 100 m before the curve, with constant centre-to-centre distance but gradually increasing diameter (from 1.4 to 2.3 m). The optical circles had seemingly the same effect as the HP before the curves, although with a somewhat less speed reduction. The acceleration values for optical circles were decreasing in a uniform manner, in contrast to HP and baseline, where they decreased more sharply before the curve.

Centre, edge, and lane line treatments

In a field observational study in Finland, a worn barrier centre line was first re-painted and later provided with a rumble strip (Räsänen, 2005). Without oncoming traffic, re-painting of the centre line led to a reduced share of centre line crossings from 9.2% to 2.5%, but there was no additional effect of the rumble strip. With oncoming traffic and rumble strip, however, there were no observed centre line crossings, neither in the short nor long term (almost a year after application). It was also found that oncoming traffic made vehicles move 15-20 cm closer to the edge line, irrespective of treatment. In situations without oncoming traffic, the applied rumble strip led to less variation of the lateral position and less standard deviation of speed, but there was no effect on mean speed (Räsänen, 2005).

A simulator study in New Zealand where rumble strips were tested on the centre and edge lines simultaneously, showed that this treatment led to lower speeds (mean reduction 3.5 km/h) than a white intermittent centre line or a double yellow centre line only, or a herringbone pattern on alternating sides of the lane, especially from the middle of the curve and onwards (Charlton, 2007). The lateral position did not differ between the treatments.

In France rumble strips were tested around the centre line at vertical crests, first during daylight conditions in a simulator where the geometry of a real road was implemented, and thereafter in the field on the real road, for both daytime and night-time (Auberlet et al., 2012). With centre line rumble strips at vertical crests drivers kept the vehicle more in the middle of the lane, as shown both in simulated and real road driving (Auberlet et al., 2012).

A field experiment where regular white edge and lane markings were combined with yellow intermittent extra markings next to them was performed on a Chinese expressway at daytime with no precipitation (Ding, Zhu, Wang, & Jiao, 2017). It was demonstrated that time headways were larger with the extra markings, and that intermittence of 2 and 4 m led to larger time headways than 8 m. Horizontal curve radius (800-1800 m) was not found to influence time headway.

In Austria, a before-after study in sharp curves with obscured sight was performed, where the problem of motorcycle riders leaning into the curve and supposedly being hit by a heavy vehicle with a certain distance claim within the opposing lane, was addressed (Winkelbauer, Bagar, Hoeher, & Wollendorfer, 2014). The real-road curves were equipped with a guide line to the right of the centre line (right-hand traffic), and was designed as either a dotted line, a dotted line and dotted “clouds” at some parts between the dotted line and the centre line, or an ellipse-shaped marking. Field observations of 811 motorcycle riders in these sharp curves before treatment discovered that 5% of the motorcycle riders drove in a way such that their total tilted silhouette was at least 0.5 m from a potential oncoming bus, whereas 16% were totally in the possible path of a potential oncoming bus in the curve, and 79% closer than 0.5 m from a potential oncoming bus. All tested kinds of guide line treatments led to a lateral distance further to the right, i.e. away from the centre line and hence from potential oncoming traffic. However, the effect was most evident for ellipse shaped markings. An interpretation of this result is that this can be an effect of two things: first, that they were largest and hence gave the largest perceptual effect, and second, that riding on these large shapes would mean a large discomfort, or perhaps even danger, for two-wheelers.

Transitions between a motorway and a two-lane road were studied in a simulator in New Zealand, to identify which design of centre line road markings best prepared drivers to slow down for horizontal curves after traveling at the high-speed road (Charlton & Starkey, 2018). There were video clips shown in the simulator and the speed of these was affected by drivers braking and accelerating, while steering led to adjusting the central part of the scene. The different designs of centre lines at the transition were either 1) an intermittent white road marking (standard), 2) two intermittent white markings with 1 m between, or 3) a complex line that shifted from two continuous yellow lines to one continuous yellow line and one white intermittent, and finally to two continuous white lines with transverse white lines in between them. The results showed that the reaction time for braking at a curve located on the two-lane road (always with intermittent white markings) was shortest for the standard marking, i.e. the white intermittent centre line. The standard marking also had lower mean speeds through the curve (66 km/h with advisory speed 55 km/h) by 2-4 km/h compared to the other designs. It is not certain whether these results are achieved because drivers were familiar with the marking or not, or whether the change of road type is considered consciously by the drivers or not. The authors showed that the road must give unambiguous expectations to the drivers and that a transition to a two-lane road should best be made by making the road look like that road as soon as possible.

Dragon's teeth

Use of dragon's teeth (see Figure 3) is another road marking measure that has been tested in connection with curves. Dragon's teeth are triangle-shaped road markings along the inner sides of the lane. A simulator study with a combination of transverse rumble strips before a curve and dragon's teeth starting closer to the curve and ending after the curve, showed that dragon's teeth led to reduced speeds inside the curve compared to use of transverse rumble strips alone (Montella et al., 2015). Dragon's teeth on a section of road before a curve that led up to an intersection was tested in another simulator study, showing no speed reducing effect of dragon's teeth (Rossi, Gastaldi, Gecchele, Biondi, & Mulatti, 2014). Hence, the position where dragon's teeth are used in connection to curves is important for the outcome. However, we do not know whether the attention of the curve was raised with dragon's teeth, possibly leading to better readiness to handle the curve.

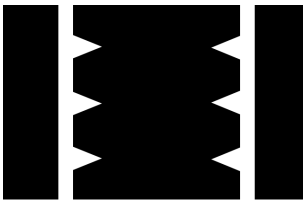

Figure 3. Illustration of dragon's teeth.

3.1.2. Road signs and signals

Road signs are vertical signs that can be used to inform the driver of the upcoming or present curve and its characteristics. They can be physical signs placed outside of the vehicle or in-vehicle signs of different designs. Sometimes physical signs are combined with a signal. A small simulator study showed increased subjectively experienced workload with increased amount of information on road signs (Xie, Wu, Lyu, & Duan, 2019).

All road sign and signal studies in the simulator are conducted in daylight conditions.

Curve warning signs

A curve warning sign together with a speed limit sign, that was related to the sharpness of the curve, were tested in a simulator study, where the curve radii and the position of the road sign were varied (Guan, Zhao, Qin, & Rong, 2014). When the road sign was placed far enough in advance of the curve (100-400 m), the drivers let go of the accelerator pedal with road sign distance. When the road sign was placed close to the curve (0 and 50 m in advance), a smaller curve radius gave smaller advance release of the accelerator pedal (Guan et al., 2014). Although this is opposite to logic it may be a result of the very sharp curves used in this study, ranging from 20 to 60 m radius, where the first release of the accelerator pedal was always made at least 300 m before the curve entrance, i.e. well in advance of the curve.

In the afore-mentioned simulator study by Montella et al. (2015), a curve warning sign was present 150 m before the curve, either alone or equipped with flashing beacons. In addition, a driver feedback sign showing the driver's current speed together with the posted speed limit was tested at 75 m before the curve. The results showed that a curve warning sign alone reduced speeds (by 8 km/h) 100 m before the curve but not inside it. Combining the sign with flashing beacons led to reduced speeds from 200 m before the curve until the curve entry. Using the curve warning sign combined with the driver speed feedback sign led to a significant speed reduction from 350 to 200 m before the curve and also reduced mean speeds throughout and after the curve compared to the warning sign alone.

A real-road study where three curves were selected on basis of accident history due to either an established or potential problem with excessive speed in the curve, was conducted by means of applying vehicle-activated curve warning signs that contained a depicted curve and the text "SLOW DOWN" (Winnett & Wheeler, 2003). The signs were activated for drivers violating the speed limit and mean speeds were reduced in the selected curves by about 3.5-11 km/h, with the largest mean speed reduction for the curve with the lowest speed limit, around 50 km/h (30 mph). Although the number of accidents at the curves was reduced after installation of the curve warning signs, one should be careful with interpreting the results. As with all studies where site-selection is biased, there is a risk of a regression effect: There might have been a natural decrease in accidents on the sites even without the treatment.

A curve warning sign together with a speed advisory sign (at about 60 m before the curve) was shown to be effective for curves with a small radius (advisory speed limit 45 km/h), but not for larger radii (65 and 85 km/h speed limit) when there was an additional task at hand (Charlton, 2004).

Guide signs

Diagrammatical guide signs (DGSs), which are signs showing graphically the delineation of the road ahead with destinations, were tested at exit ramps in a fixed-base driving simulator with different types and numbers of signs (Huang et al., 2020). The DGSs reduced the number of late lane changes (at less than 500 m before the exit ramp) and led to less missed exits in right- and left-turn direct connectors.

Chevrons

Chevrons are placed along the outside of a curve and is a widely used measure to make drivers aware of the curve and of the sharpness of the curve. Simulator studies in daylight have shown speed reducing effects inside the curve of up to around 3-5 km/h for repeater arrows (one arrow present at each sign) (Calvi et al., 2019; Montella et al., 2015), and also that the speed reducing effect may be present some distance (200 m) after the curve (Montella et al., 2015). Using a fluorescent border or sequential flashing beacons on the repeater arrows did not affect the speed further (Montella et al., 2015). A chevron board (multiple arrows on same sign) with advisory speed limit placed inside the curve reduced speed effectively in curves of various radii (45, 65, 85 km/h), and more effectively in curves with larger radii (advisory speed limit 85 km/h) compared to curve warning signs with speed advisory sign or TRS in simulator daylight driving (Charlton, 2004). The chevron board led to an earlier speed reduction than symbols in the roadway did, possibly because of earlier detection (Charlton, 2004). Chevrons have also been shown to be somewhat more stable in reducing speed under additional tasks compared to other treatments (curve warning signs with speed advisory sign or TRS) (Charlton, 2004).

Following up on the previous study, another daylight simulator study showed that use of chevrons, either as repeater arrows or chevron boards or a combination of the two, reduced speeds in horizontal curves of different radii (45, 65, 85 km/h) (Charlton, 2007). Repeater arrows on exit ramps were also noted to reduce speeds but also driver stress, as measured by heart rate and a subjective questionnaire, in a simulator study in daylight (Wu, Zhao, Rong, & Ma, 2013). Another daylight simulator study with young male drivers found that chevrons reduced speeds before and in curves regardless of curve radius (125, 400 and 1000 m), but that the speed at the beginning of the curve was independent of chevrons, because it had to be reduced there anyway (Zhao, Wu, Rong, & Ma, 2015). Chevrons were also found to decrease the lateral position for moderate curves (r=400 m) but not for sharp or flat curves (Zhao et al., 2015).

Bearing in mind that in China chevrons are not solely used in curves, repeater arrows reduced mean speeds in curves to the left but not to the right in a Chinese fixed-base simulator study (Wu et al., 2016), and the chevrons were noted to possibly reduce the variation of the lateral position.

Chevrons equipped with a yellow flashing signal to warn of an oncoming vehicle reduced vehicle speed as well as speed variation and lane position in a simulator study on a two-lane road with small radii (<220 m) and 60 km/h speed limit (Kazemzadehazad et al., 2019).

A study conducted with an instrumented vehicle on two-lane highways at night showed that with chevron repeater arrows drivers stopped accelerating earlier before the curve, the speed in the curve was lower, and the lateral acceleration was lower than without (Brimley et al., 2016). In addition, about half of the total speed reduction was made before the curve with the minimum speed reached near the midpoint of the curve. A field study with eye tracking on drivers on two-lane roads in China was conducted with and without chevrons of different colours in a curve under dry versus snowy road surface conditions, respectively (Zhao, Xu, Xi, Wang, & Runge, 2017). It was noted that chevrons made identification of road alignment easier and that the red chevron arrows were paid more attention than the blue and green, because they were more associated with prohibition or warning. Red and green chevron arrows led to speed reductions in the curve both at snowy and dry road surface conditions, while blue chevron arrows did not reduce speed in the snowy condition. In addition, red chevron arrows reduced speed up to 80 m before the curve, and were recommended in harsh winter conditions, on virtue of contrast.

An observational field study in large curves (radius 1000-1200 m) with baseline, regular chevron repeater arrows and repeater arrows that also had retroreflective material on the pole, showed that the two chevron treatments gave similar results and that the lateral position was closer to the edge line both at the point of curvature and at the middle point of the curves, compared to without chevrons (Chrysler, Re, Knapp, Funkhouser, & Kuhn, 2009). Chevrons also led to reduced mean speed and less variation in lateral position at the beginning and middle of the curves. There were also indications of that repeater arrows led to less centre line encroachments. The results were independent of time of day.(Chrysler et al., 2009)

A smaller field study with eleven participants driving a 350 m curve radius on real road at night showed that the lowest speeds on approach as well as at the entrance of the curve were obtained without chevrons, but that a condition with progressively larger repeater arrows that were positioned closer together at the end of the curve than regular chevrons resulted in the largest speed reduction (Bullough, Skinner, Brons, & Rea, 2012). In addition, drivers rated the curve radius sharper for the modified repeater arrows configuration compared to the other configurations. The study was followed up by speed observations at the entrance of two curves both at night-time and in daylight where existing regular repeater arrows were exchanged for progressively sized repeater arrows. The results showed slightly lower mean speeds for the progressively sized repeater arrows than for the regular ones, indicating a larger speed reducing effect at night (Bullough et al., 2012).

There are implications that at night, eye fixations are more focused for curves with chevrons than without (Brimley, Carlson, & Hawkins, 2014), but this is based on a very small field study with only four participants. If focussed eye fixations are good or bad for safety is not clear, although the authors seem to find them beneficial. It may however be that drivers would benefit more from confirming the infrastructure setting with a wider field of view.

In-vehicle holograms

Comparisons between traditional physical signs and holographic in-vehicle guidance through curves were made in an American simulator study (Noyce et al., 2016). The traditional post-mounted signs at the curve were curve warning signs with and without advisory speed and chevron repeater arrows. The holographic signs were projected about one decimetre above the bonnet of the car, they were slightly transparent and flashed during 4 seconds with a rate of 0.25 seconds. Speed profiles were evaluated for eight curves and the results showed that traditional signs and their holographic counterparts basically gave the same effect, which was lower speeds compared to a roadway without any signs. The average speed was somewhat higher for in-vehicle holograms, which is speculated to be a result of the extra comfort of having symbols on the roadway showing the curvature in relation to driver position instead of the post-mounted signs on the outside of the roadway. It should be acknowledged that in this study, the posted speed limit was always the same as the advisory speed limit of the curve.

3.1.3. Guardrails

The impact of guardrails on curve speed has not been investigated to a large degree. In an Israeli simulator study, it was noted that right-hand side guardrails increased the mean speed in curves to the right (right-hand traffic), whether flat or sharp, but not in curves to the left (Ben-Bassat & Shinar, 2011). Another simulator study on a tree-lined rural two-lane road in Italy where guardrails on both sides of the road were studied, there was no effect of guardrail existence in curves, neither on speed nor side position (Bella, 2013).

3.1.4. Road lighting

Road lighting in curves have not been investigated to any larger degree. One simulator study in night-time driving was found, where road lighting (evenly spaced by 50 m) almost 300 m before and in curves with 200 or 300 m radius were tested against other measures (Shahar, Brémond, & Villa, 2016). The results showed no significant speed difference between road lighting or not in neither inner (right) nor outer (left) curves, although speed before outer curves was higher with road lighting than without. The lateral position was significantly closer to the centre line in both inner (around 5 cm) and outer (around 8 cm) curves compared to unlit road, and the lateral position varied less in inner curves with road lighting. (Shahar et al., 2016)

3.1.5. Retroreflectors

Retroreflectors can be used on road equipment either beside the road, as retroreflectors on delineator posts, or in the road, as road studs.

Delineator posts

Delineator posts in real night-time traffic on a two-lane highway was shown to reduce curve entrance speed (by 3.7 km/h) and maximum deceleration rate in the curve (by 0.28 m/s^2), in a study with an instrumented vehicle and 103 drivers (Brimley et al., 2016), which is a large study. The drivers began to react to the curves earlier (about 23 m) with the delineator posts than without them.

A moving-base driving simulator was used in a Nordic study comparing different road delineator configurations at night in curves with 250 and 1000 m radius, respectively, where the only visual cues were road markings and reflectors from the road delineators (Nygårdhs, Lundkvist, Andersson, & Dahlbäck, 2014). The results showed that using more densely spaced road delineators in curves with smaller radius than with larger had a potential to reduce approach speeds before the sharper curves. Additionally, lowest speed in curves was found for the configuration with road markings only, while adding road delineators before and in curves led to significantly higher speed in curves with 1000 m radius, but not in curves with a 250 m radius (Nygårdhs et al., 2014). A follow-up observation study on real road with a subset of the configurations showed no significant speed differences related to the configurations in curves with neither small (300 m) or large (1100 m) radius, measured as spot speeds (Rajamäki, Luoma, & Rämä, 2013).

Because of delineator posts visual impression, it might also be of interest to study them in daylight, although the problem with visual aspects of curves is not as relevant at daytime as at night-time. Different heights and distances between post-mounted road delineators were tested in a simulator daytime study, resulting in that high (1.8 m) delineator posts or delineator posts that were both closer to each other than regular (5 m instead of 10 m distance) and were closing in on the roadway (from 2.05 m to 0.30 m from the edge lines) led to decreased approach speeds of around 2 km/h compared to baseline (Rossi et al., 2014). The narrowing delineator posts in addition led to an increased variation of the lateral position.

Six curves were treated with increasingly higher post-mounted delineators at the curve in a before-after field study in daylight conditions (Fildes et al., 2005). In this study, the results were somewhat ambiguous, where mean speed on approach increased after installation in several curves although the long-term effect was generally reduced mean speed.

Both daytime and night-time observations at curves with 600-650 m radius were made with baseline, regular post-mounted delineators with a reflector, and post-mounted delineators were the whole pole was covered in retroreflective material in a field study by Chrysler et al. (2009). Both treatments resulted in driving closer to the edge line and reduced centre line encroachments compared to baseline. However, the treatments in these curves did not affect speed at the point of curvature or at the middle point of the curve. The results did not depend on time of day. (Chrysler et al., 2009)

Road studs

No speed reducing effect of road studs in curves was noted in a study conducted on real road night-time driving, concerning where deceleration before the curve started or on the maximum speed before the curve (Carlson et al., 2015).

A desktop simulator study with VR glasses showed effects of retroreflectors in the continuous edge and centre road markings throughout an S-shaped curve, by speed reduction before (from 47 to 44 km/h) and after the first curve (from 49 to 44 km/h) (Pasetto & Barbati, 2012).

3.1.6. Comparison studies

Some studies evaluating different road equipment in connection to curves are reported here.

A daylight simulator study (Charlton, 2004) showed that road signs (chevron boards and warning sign+advisory speed limit) reduced speed earlier than road markings (TRS+advisory speed limit). This could lead to the conclusion that there are perceptual advantages with vertical markings. Another daylight simulator study (Calvi et al., 2019) showed that repeater arrows were not better than PTB or OSB. However, another daylight simulator study (Charlton, 2007) showed that a combination of HP and a chevron board followed by repeater arrows led to reduced speeds and better (more in the middle of the lane) lane keeping.

With chevron repeater arrows, road delineators or large arrow signs, 50-65% of the total speed reduction was carried out before the curve and the minimum speed was reached near the midpoint of the curve, in a field study at night-time conditions (Brimley et al., 2016). Drivers responded 23 m earlier with delineators and 42 m earlier with chevrons, while the curve entrance speed was reduced by about the same (ca 4 km/h) compared to without. In their study, the authors recommend that at high-speed curves road markings only are used, whereas they should be complemented by warning signs when the approach speed is somewhat higher than the curve speed, and additionally by delineators when the difference is even higher. When the approach speed is much higher than the curve speed, then chevrons should be used together with warning signs and road markings.

Matírnez, Mántaras, and Luque (2013) studied a hazardous road stretch with a curve followed by an intersection. They investigated two sets of interventions, where the first set consisted of transversal road markings in a chess pattern, repeated five times with decreasing distance between markings + road studs on both sides of the road + reflectors in the road barrier. The second set included the first one and was complemented by an intersection warning and speed limit 60 km/h on the same sign with fluorescent reflective yellow background. The speed after the curve was reduced from around 73 km/h to 68 km/h for the first set of interventions, and to around 50 km/h as a long-term effect after the second set. Since the second set included the introduction of a speed limit, the reduced speed is logic, although the speed limit is higher than the average speed for the road stretch measured.

A British simulator study with variable message signs (VMSs) showing an advisory speed for the curve, versus in-car advice about the advisory speed, or TRS, showed that information or support of any form seemed to be effective for reducing speed in curves (Comte & Jamson, 2000). The VMS led to an earlier reduction in speed than the other systems. This could be interpreted as a result of early detection or that a speed reduction was necessary to read the sign.

Comparing road studs with road lighting and an unlit condition in a desktop night-time simulated driving scenario, the results differed depending on whether it was an inner or outer curve (Shahar et al., 2016). In summary, in outer curves road lighting led to higher speeds and road studs led to less variation of the lateral position compared to the other conditions. For inner curves there was no speed effect but the lateral position was significantly closer to the centre line for road lighting and closer to the edge line for road studs.(Shahar et al., 2016)

3.1.7. Summary

- TRS positioned before curves have a potential to reduce speed there, but the effect does not seem to remain inside the curve.
- PTB, HP and dragon’s teeth have all been used at edge and centre lines for making the driver attend to a curve by visual perception.
- Dragon’s teeth might be effective, but there is not much research on them in connection to curves. From studies found it seems to be important where in relation to the curve the dragon’s teeth are placed.
- Overall, it is important to consider where road markings should be positioned in order for them to affect driver behaviour in an appropriate way.
- At curves with small radius, warnings of various kinds seem to affect speed.

- Night-time studies of performance of road equipment in connection to curves are often lacking.
- Research studies about other vehicles than private cars are few.
- Retroreflective materials such as road studs and road delineators provide long visibility distances and *may* be suitable for curves at night and during adverse weather conditions.
- Large size of signs, such as chevrons *may* lead to a visibility contribution both at daytime and night-time.
- HP may lead to a better path through a curve but not decreased speed.
- There have been many attempts to make road users take a better path through the curve and to decrease speed in connection to curves. Some attempts may even have dangerous side-effects, e.g. large, slippery road markings that create a danger to drivers or two-wheelers.
- Few studies have been carried out on vertical curves.
- Studies on road lighting in curves are rare. This might be due to problems with light conditions in a simulator and that it is hard to do these kinds of studies in real world conditions.
- Field studies suggest that road delineators can have a speed reducing effect in curves and potentially also bring traffic away from the centre line. There are implications that varying the distance between road delineators can influence driver speed.
- There are not many studies on road studs in curves.
- Speed advisory signs should only be used in sharp curves.
- Chevrons reduced speeds in curves both in daylight and night-time conditions.

3.2. Intersections

Intersections are interesting from a road user perspective, because they require attention from more than one direction. On approach, the road user needs to be aware that there is an intersection ahead to be able to adapt speed and look for other road users. Intersections can be signalized or unsignalized, and the number of legs differ.

3.2.1. Road markings

Road markings can be used for attentional purposes and/or reducing speed in connection to intersections.

Transverse rumble strips

In a before-after field study in the United States, five sets of transverse rumble strips (thickness 2.8-5.3 mm) were applied over a road stretch of approximately 100 m and 200-400 m before intersections that had previously been described as risky (Yang, Zhou, Zhu, & Qu, 2016). Speed data provided by video cameras were analysed for observations on workdays with dry road surface, both in daylight and in darkness. The speed limit of these signalized and unsignalized intersections was high, 90-105 km/h (55-65 mph). The results showed that the TRSs led to a mean speed reduction of 1.5-14 km/h and that the 85th percentile speed decreased by about the same (1.35-15.6 km/h). Speed reductions were larger during the night than during the day. The sites which had the highest initial speeds achieved the largest speed reductions. In an unsignalized intersection, 20% of the drivers applied the brake while driving over the TRSs, whereas the overall braking behaviour for the signalized intersections in the study was

40-80%. At red traffic light speed reductions were generally increased with the TRSs, especially at night. (Yang et al., 2016)

Peripheral transverse bars

Peripheral transverse bars were applied on approach to six intersections (either a cross or a T-intersection) in a before-after field study with control sites in Australia, where daytime traffic was studied (Fildes et al., 2005). In general, the PTBs resulted in reduced speed in both the short- and long-term perspective.

Dragon's teeth

Implementation of dragon's teeth (for explanation, see Dragon's teeth above) on approach to an intersection effectively reduced approach speed in a daylight simulator study (Montella et al., 2011). The drivers started to brake farther in advance of the intersection and there were significantly more drivers reduced their speed, compared to without use of dragon's teeth.

3.2.2. Road signs and signals

As intersections are governed by rules about who goes first, road signs and signals are important to inform about the current regulations.

Vehicle-activated signs

In Great Britain, five intersection sites that either had a history of accidents due to excessive speed or where inappropriate speed for the intersection could pose a potential problem, were selected for application of junction warning signs at 100-150 m from the centre of the intersection, predominantly on the major legs (Winnett & Wheeler, 2003). With junction warning signs depicting the intersection and the text "SLOW DOWN", activated by vehicles violating the speed limit, mean speeds were reduced from 1 up to 15 km/h. The junction warning signs in these accident-prone intersections reduced accidents, but whether this is because of a bias in site selection or real effects is not clear. The drivers did not seem to become less responsive to the signs, even after three years. (Winnett & Wheeler, 2003)

Intersection conflict warning systems (ICWS) of different designs were tested in lab studies, where either dynamic or static signs, both with flashing beacons on the side, were used (Inman & Jackson, 2016). Participants were shown animations and images of the designs and were asked to tell how they interpreted them and to rate them. The activated signs were intended to inform drivers of cross traffic that they might otherwise have difficulties to detect. In this study it was noted that most (73%) of the participants expected no conflicting traffic if the dynamic sign was blank, and that 28% of the participants did not feel the need to check for cross traffic if the beacons were not flashing. Because of the misunderstandings, advice was given not to use blank-out signs for ICWS applications (Inman & Jackson, 2016).

Rural intersection active warning systems (RIAWS), i.e. electronic signs, were tested compared to traditional painted signs or no signage in a driving simulator in Australia (Meuleners, Fraser, & Roberts, 2020). The information on the signs were either "SLOW DOWN" or "80 km/h" 300 m in advance of the rural intersection, followed by a side road junction warning at 150 m in advance of the intersection. The results implied that the RIAWS "80 km/h" was the most effective for reducing speeds on approach to rural intersections; the reached mean speed of 78 km/h was more than 20 km/h slower than for the unsigned control sites and 10 km/h slower than for the traditional painted sign. The "SLOW DOWN" signs were less effective and RIAWS with this message did not affect speed significantly compared to no signage, whereas the traditional sign did (Meuleners et al., 2020).

In a before-after study in Florida, intersections were chosen partly due to their high pedestrian accident rate, and different road signs were installed to make drivers aware of pedestrians (Lin et al., 2019). Driver compliance was significantly higher with “Right Turn on Red After Stop” signs in the exclusive right-turn lanes compared to without, and the compliance with “No Turn on Red” blank-out sign was lower (75%) than with a static sign (91%) (Lin et al., 2019). This study however suffers from site selection bias.

Use of signs

Excessive use of road signs leads to too high demands on the driver, according to (Schmotzer, 1999). Use of information in a homogeneous manner means that the driver knows how the information is ordered and hence can assimilate it faster (Schmotzer, 1999).

By means of focus groups and letting drivers watch power point slides of real highway situations with destination information signs and asking them about their understanding and their lane change behaviour, driver preferences for use of destination signs in the United States were assimilated (Richard & Lichty, 2013). The focus groups revealed that most drivers have problems at complex multiple lane changes that are unfamiliar to them, and that surprises, having to change lanes several times on a short road stretch, or lack of expected information, make them stressed. They would expect that there is a long enough road stretch between a navigation sign and the last opportunity to change lanes safely and in appropriate time. In addition, they would expect that arrows, road signs, road markings etc. would give them the necessary information to build a mental model that is enough to support correct lane change decisions in the right time. It was concluded that signs and lane markings were effective in affecting driver expectations at interchanges. Recommendations regarding information on highway road signs were, among other things, to warn drivers of situations that might surprise them (such as exiting to the left), to let drivers be able to correct their mistakes, and to design for consistency and predictability (Richard & Lichty, 2013).

3.2.3. Comparison studies

Montella et al. (2011) tried several designs to reduce speeds at a four-legged intersection on a rural simulator road. Among optical speed bars, transverse rumble strips, peripheral transverse bars, dragon’s teeth, coloured intersection area, painted median island and raised median island, the most effective speed reducing measures were dragon’s teeth, coloured intersection area and raised median island. These three designs led to significant speed reductions on approach to the intersection of 13-23 km/h, and drivers started to reduce their speed further in advance of the intersection, compared to baseline (Montella et al., 2011).

An overall evaluation of different traffic safety measures on driver behaviour was reported by Sagberg et al. (1999). They concluded that transverse bars with decreasing distance between them for an optical illusion of increased speed were effective at intersections, and that the effect was larger if the bars were raised to permit sound and vibration. They also recommended a maximum of six destinations on road guidance signs, as a compromise between need of information and cognitive workload. (Risks were increased perception time which could lead to that important information would be missed.) (Sagberg et al., 1999)

A Japanese field study on a large and complicated intersection indicated that after implementing better road markings, warning signs and red road surface in specific lanes, problems with turning and straight-going vehicles were reduced, and a safer gap acceptance behaviour was achieved (Matsuo, Hirobata, & Komatsu, 2013).

3.2.4. Summary

- Both transverse rumble strips and peripheral transverse bars have been tested in the field with speed reducing results on approach to an intersection. However, the number of studies is small and only one study included night-time traffic. Dragon's teeth have not been investigated in the field, but a simulator study implicates that there might be a speed reducing effect.

- Non-activated intersection warning signs can lead to less attention of hazards of intersections and should therefore not be used. Compliance with vehicle-activated signs before an intersection seems to be higher if the driver is instructed to keep a certain speed limit rather than to "slow down".
- Drivers should in general be warned of situations that might surprise them.
- The need of information has to be traded against the cognitive workload in each situation.
- It is important that road design is used in a consistent manner to make the road user understand what to expect (i.e., the road should be self-explaining).

3.3. Crossings with vulnerable road users

Naturally, vulnerable road users need to cross the road from time to time to reach their destination. Similar to intersections with motorised traffic only, conflicts between VRUs and motorised traffic should be minimised. Rules governing these crossings are illustrated by e.g. road equipment.

Pedestrian crossings should be used by pedestrians for crossing a road or a cycle path and are often marked with a road sign accompanied with road markings. Pedestrian crossings can be mid-block or at intersections, and they can be signalized (regulated by signals or the Police) or unsignalized. In addition, pedestrian passages are other sites where pedestrians cross the road. Pedestrian passages can be raised for vehicles to drive slowly, have refuge islands for pedestrians to cross one lane at a time, or be a place where nothing in particular has been done.

Cycle crossings are often marked with road markings and road signs for cycle crossing. Cycle passages are often marked with road markings for cycle passage and should be used by cyclists or moped drivers to cross a road or a cycle path. Cycle passages can be either signalized or unsignalized.

The effectiveness of pedestrian crossings is often counted in driver compliance, i.e. how many drivers yield to pedestrians at or about to enter the crossing. Unless otherwise stated, the studies in section 3.3.1 and 3.3.2 concern daylight conditions.

3.3.1. Road markings

There are several road marking designs that can be used for pedestrian crossings, both with transverse and horizontal markings. Some examples from the United States are found in Figure 4.

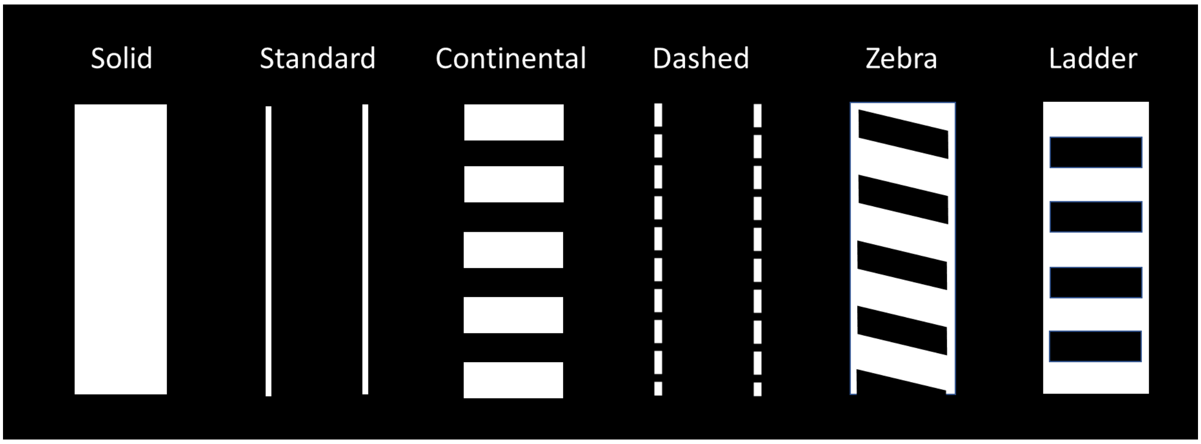

Figure 4. Examples of road marking designs at pedestrian crossings. Adapted from San Francisco Municipal Transportation Agency. https://www.sfbetterstreets.org

No markings vs markings

Removing the transverse road markings from unsignalized pedestrian crossings resulted in higher vehicle speeds and estimated risk of severe injury of crossing pedestrians, lower percentage of yielding drivers and hence longer waiting times for pedestrians, but also fewer conflicts between pedestrians and motor vehicles, when compared to similar pedestrian crossings without removed markings in Israel (Gitelman, Carmel, Pesahov, & Hakkert, 2017). Lower percentage of yielding drivers (from 27 to 14%) on the total, and an increasing share of drivers yielding at less than 3 m from the pedestrian crossing was seen in a similar study where road markings were removed from a pedestrian crossing in Minnesota (Craig, Morris, & Hong, 2019).

Results from a field observational study using staged pedestrians at 31 mid-block pedestrian crossings (Stapleton, Kirsch, Gates, & Savolainen, 2017) showed that with continental road marking design, i.e. markings parallel to the driving direction, compliance was 3.5 times higher than at unmarked pedestrian crossings. In the same study it was noted that US standard markings, i.e. stripes delineating the sides of the pedestrian walking area, increased compliance by 2.8 times compared to unmarked crossings at mid-block.

Coloured road surface

In an attempt to get better compliance of a pedestrian crossing for school children, it was painted green in a field observational before-after study (Wall, 2000). The observations showed that there was only a small increase in usage of the coloured pedestrian crossing, from 29% to 35%. (Speed data could not be separated from other changes made to the crossing in this study and are hence not reported.) Driving simulator studies of a pedestrian crossing showed that a red-coloured road surface (that also had a different texture) lead to earlier and larger speed reduction compared to driving towards a regular pedestrian crossing (Branzi, Meocci, Domenichini, & La Torre, 2018). The largest speed reduction was achieved when the coloured road surface was supplemented with vertical deflection.

Advance road markings

Advance yield markings (AYMs) were investigated in a simulator study as well as a field observational study reported by Fisher et al. (2016). The AYMs were designed as a line of white triangles 6-15 m before the pedestrian crossing and were compared with modified standard yield markings (MSYMs), which consisted of stop lines 1.2 m before the pedestrian crossing. AYMs had an additional road sign showing “yield here to pedestrian” and MSYMs were accompanied by a pedestrian crossing sign. The simulator study was a between-groups design, where the 32 drivers were either exposed to AYMs or MSYMs. The simulator study showed that AYMs increased the chance that drivers looked for pedestrians at the pedestrian crossing as well as at the side of the road before they entered the crossing. In the final scenario, a hidden pedestrian was simulated and less drivers crashed with it from the AYM group than from the MSYM group. In the field observational study with staged pedestrians, it was also noted that drivers were more likely to look towards an area where a pedestrian is hidden with AYMs than without. In total, AYMs were concluded to be effective for making drivers look for possible pedestrians at pedestrian crossings (Fisher et al., 2016).

Advance stop lines, tried in a field observational before-after study in Great Britain, were similarly found to increase the distance between waiting vehicles and pedestrians (Wall, 2000). It was implied that this leads to better visibility of pedestrians, especially for drivers of large vehicles.

Moving pedestrian crossing from intersection

A before-after study with pedestrian crossings directly at small roundabouts demonstrated positive effects of moving the pedestrian crossings further from the roundabouts and introducing a median refuge island (Vignali et al., 2020). Eye tracking showed that more drivers looked at the pedestrian crossing in the after condition and that their fixations of the crossing were longer. The stopping distance became shorter due to lower speeds.

Zigzag markings

A continuous zigzag road marking was applied over a distance of about 150 m in advance of two unsignalized crossings for pedestrians and cyclists in a field study in Virginia (Dougald, Dittberner, & Sripathi, 2012). The zigzag pattern was applied in the middle of the lane (claiming one third of the total lane) for one of the crossings and as edge and lane line (each 1/6 of the lane) for the other. The study showed that the zigzag road marking zones led to reduced speed, also in the long-term, but that the markings were not intuitively understood by drivers.

3.3.2. Road signs and signals

There are several ways to attract attention to a pedestrian crossing by means of signalling. Rectangular rapid flashing beacons, RRFBs, are yellow indicators at the same pole as the pedestrian crossing sign and are usually activated by a pedestrian push button. The RRFBs should catch the driver's attention and thereby increase yield compliance to pedestrians. The pedestrian hybrid beacon (PHB) is also activated by the pedestrian whereby it shows flashing yellow followed by steady yellow, steady red (where the pedestrians can cross) and finally flashing red to let drivers continue after stopping if the pedestrian has passed the lane (Fitzpatrick & Pratt, 2016). The PHB is also known as a high-intensity activated crosswalk (HAWK). In addition, overhead flashing beacons (OFBs) can be installed over the intersection to draw a driver's attention towards the current traffic control.

Placement and design

In the aforementioned field study with mid-block pedestrian crossings where compliance improved when road markings were used, it was also found that with RRFBs, PHBs or in-street "yield here to pedestrians" signs, yielding compliance rates improved even more, to 95-100% (Stapleton et al., 2017). These measures seemed to be effective irrespective of lane position. Introduction of RRFBs under the pedestrian crossing signs was also found to increase compliance rate in two Canadian before-after studies, where almost all drivers complied to pedestrians using RRFBs (Domarad, Grisak, & Bolger, 2013; Mishra & Iwaskow, 2015). In addition, yielding drivers at crossings with multiple lanes were found to stop at a distance of more than 10 m from the pedestrian crossing with RRFBs (Mishra & Iwaskow, 2015). Field observations both in daylight and at night-time by (Schultz, Galvez de Leon, Shahandashti, & Chamberlin, 2020) showed that a HAWK was more effective to increase driver compliance at pedestrian crossings with posted speed limit 56-72 km/h (35-45 mph) than using an OFB, which in turn was more effective than an RRFB.

A study by Vignali et al. (2019) showed that a median refuge island combined with flashing lights at the "yield here to pedestrians" sign led to reduced speed, also for the 85th percentile, and that drivers fixated the pedestrian crossing more. The exact contribution of the road sign is however not clear since it was used together with the median refuge island.

Field observations at 20 pedestrian crossings with PHBs installed in Arizona showed that 91-100% of drivers yielded (Fitzpatrick & Pratt, 2016). Non-compliance was mostly noted when the PHB had changed from steady yellow to steady red and the pedestrian was at the roadside, and sometimes when the pedestrian had just managed to cross the lane. It was observed that the probability of pedestrians activating the PHB was higher at larger traffic volumes (of those crossing without the PHB activated, 20% crossed at a traffic volume larger than 6 vehicles per minut and lane), and at higher posted speed limits (72 km/h; 45 mph compared to 64 km/h; 40 mph or less). The percentage of conflicts between pedestrians and motor vehicles was larger for pedestrians not crossing on the "go" phase.

Combining different arrangements to increase pedestrian and cyclist safety and driver compliance at a large intersection with posted speed limit 72 km/h (45 mph), driver yielding rates were found to increase dramatically when RRFBs were installed (Ross, Serpico, & Lewis, 2011). It was concluded that RRFBs should be used in combination with other measures to enhance the visibility of the crossing.

Comparisons between existing sites with either traffic signals, PHBs or RRFBs and staged pedestrians in Texas showed that in cities where a certain device was common, compliance was higher than where it was only sparsely used (Fitzpatrick, Brewer, & Avelar, 2014). In addition, compliance rate was higher where the device had been used for a longer time. Overall, compliance was highest for traffic signals (98%), followed by PHB (89%) and RRFB (86%).

Fluorescent signs

Different types of fluorescent signs were tried in a field study in Michigan using pedestrian crossings with standard (see Figure 4) road marking design at multiple lanes (Bennett & Van Houten, 2016). The types tested were all three short gate-way signs between and at the edge of the lanes, where one configuration showed yield to pedestrians, another was blank, a third was a fluorescent delineator between lanes while the ones at the edges showed yield to pedestrians, and in the fourth configuration the sign closest to the pavement was placed on the kerb. All the configurations led to increased yield compliance with the most effective configuration having the yield-to-pedestrians sign between lanes.

In-vehicle hologram

In-vehicle holograms displaying a flashing pedestrian warning sign at about one decimetre above the bonnet of the vehicle in a simulator study led to a heavy braking manoeuvre for two out of twenty drivers (Noyce et al., 2016). This could be interpreted as that there is a potential for improved pedestrian safety by using in-vehicle holograms, as commented by Noyce et al. (2016). However, another interpretation is that the heavy braking manoeuvres are reactions of surprise, which could have other consequences, such as rear-end accidents, and should be avoided in traffic.

Pedestrian count-down timers

Pedestrian count-down timers (CDTs) are used for guiding pedestrians to know when they will be able to cross the road by counting down the time until the traffic light changes. Only a few studies have investigated the effect on drivers of these pedestrian CDTs. There are studies indicating that pedestrian CDTs affect driver safety so that both rear-end crashes and angle crashes are reduced (Kitali, Sando, Castro, Kobelo, & Mwakalonge, 2017), but also the opposite; in a larger, long-term study it was concluded that introduction of pedestrian CDTs increase pedestrian-motor vehicle collisions (Richmond et al., 2014).

Weather conditions

Pedestrian crossings, either marked with side-mounted passive signs or with overhead flashing devices, were studied in Canadian winter conditions (LaCoste, Campbell, Klassen, & Montufar, 2014). The share of yielding drivers was higher for the overhead flashing devices (83-96%) than for the passive signs (42-65%). It was also concluded that more drivers yield when road conditions worsen, from no snow to light and heavy snow, which was probably due to reduced speeds. The authors found presence and height of snowbanks as well as weather conditions to have a potential impact on driver yielding behaviour. It should be kept in mind that none of the pedestrian crossings investigated were marked by road markings. Therefore, the signs and presence of pedestrians were the only features to detect the pedestrian crossing.

3.3.3. Road lighting

Better road lighting and enhanced visibility of pedestrians from a driver perspective are some of the safety measures available to reduce accidents at pedestrian crossings at night (Greisl, 2002). It should however be kept in mind that not all pedestrians cross at the dedicated crossing, and that more intense illumination may in fact decrease visibility under certain circumstances, as seen for pedestrians with dark clothing crossing behind the pedestrian crossing in a study where photographs of real pedestrian crossings were compared (Lundkvist & Nygårdhs, 2007).

Light emitting diodes

The impact of a light emitting diode (LED) system on driver speed at a pedestrian crossing with posted speed limit of 50 km/h was investigated in an Italian study (Patella, Sportiello, Carrese, Bella, & Asdrubali, 2020). The system normally functioned such that when a pedestrian passed an optical sensor, LED stripes at the end of each road marking of a continental road marking pattern (cf Figure 4) were illuminated. Testing was carried out with a staged pedestrian present and absent, both with and without the LED system activated. It was concluded that with a pedestrian present, the illuminated LED stripes led to a speed reduction by 19% compared to without. Without a pedestrian, but with the LED system activated, drivers' mean speed was the same as when there was a pedestrian and the system was turned off (Patella et al., 2020). However, this could lead to false alarm effects if the system is an unreliable predictor of pedestrians, i.e., does not work.

Combinations

Variations of the following measures were investigated in another Italian study: standard/increased lighting level when a pedestrian is detected, with/without flashing beacons above the pedestrian crossing sign, with/without LED strips along the pavement at both sides of the pedestrian crossing when a pedestrian was detected, and steady/flashing LED lights on these strips (Costa, Lantieri, Vignali, Ghasemi, & Simone, 2020). With increased lighting level at pedestrian detection, the rate of drivers yielding increased from 19% to 38%. Apart from that, the only significant difference was that if everything was activated (i.e. increased lighting, flashing beacon above the pedestrian crossing sign and flashing LED strips), then compliance rate was 64% which was higher than the other conditions. However, it is not clear whether it was the shock of flashing lights that made drivers slow down and if they attend to the pedestrian at all.

3.3.4. Cycle crossings

Only a few studies have been reported on driver behaviour at cycle crossings. In a field test on night-time visibility at cycle crossings (Nygårdhs & Fors, 2010) it was found that bicyclists standing still are detected at significantly longer distances, about 60 m, than cycle crossings, about 18 m. The cycle crossings studied were all combined with pedestrian crossings and consisted of 0.5 m-sided white road marking squares. Additionally, it was noted that cycle crossings were detected at significantly longer distances when the road surface was dry than when it was wet, while there was no such effect for bicyclists.

A study on pedestrian and bicyclist safety at 66 crosswalk sites at low-speed roads in Michigan, observed that in general driver yielding compliance increased when crosswalk markings were at hand, and even more so if RRFBs, PHBs and gateway yield-to-pedestrians signs were provided (Gates, Savolainen, Stapleton, Kirsch, & Miraskar, 2016). It was also stated that drivers were more likely to yield to pedestrians in any other lane than at the nearside kerb lane, due to conspicuity and vulnerability factors.

3.3.5. Comparison studies

A simulator study at mid-block pedestrian crossings was conducted with driving scenarios including limited view and obstacles, where one group of drivers had a stop bar 1 m from the pedestrian crossing (baseline), whereas another encountered advance yield markings and a "yield here to pedestrians" road sign at 9 m before the crossing (treatment) (Fisher & Garay-Vega, 2012). The results of this eye tracking study showed that people in the treatment group looked for pedestrians earlier and more often, and that the advance yield markings and road sign together increased the probability of drivers yielding, compared to the stop bar (Fisher & Garay-Vega, 2012). Which of the treatments was most prominent, i.e. the sign or the AYMs, is not certain from this study.

3.3.6. Summary

- At pedestrian crossings where drivers should yield to pedestrians, the crossing should be marked by road markings.
- Drivers stopping close to the pedestrian crossing can cause reduced view for drivers behind.
- Use of advance yield or stop markings has a potential to enhance drivers' attention to pedestrians. Pedestrians are also more visible for drivers when advance markings are used.
- Pedestrian crossings should not be in direct connection to a roundabout where attention is needed in the roundabout.
- Overall, design of road equipment should be intuitively understood by the road users.
- VRU activated signals are well understood and increase driver yield compliance.
- Familiarity with a traffic signal device increases compliance.
- Surprises contradicts predictability and should be avoided in traffic.
- Introduction of new road equipment should be made carefully and be studied to avoid unwanted side-effects.
- Studies on driver behaviour at cycle crossings and passages are lacking.

3.4. Discussion of results and conclusions from the literature study

In general, the amount of field studies is less than that of simulator studies. In a simulator, different types of road equipment are easily tested against each other, while field studies are needed to know how the road equipment performs in reality. Often, night-time or adverse weather conditions have not been considered in the simulator studies, but in real life these conditions are a fact and the help from road equipment to understand what to expect is needed even more. Some examples are road studs and fluorescent gate-way signs that might not work very well in countries with snow and hard ploughing. Another real-life issue is that the road equipment should not be a danger to any road user. For instance, transverse rumble strips should be used with care since these can be a problem for motorcyclists. Efforts such as leaving centre gaps might mitigate this adverse effect (Xue et al., 2020). In the same way, optical circles may in reality lead to friction issues, and optical speed bars in a simulator will in reality give tactile and auditory feedback on the road.

It seems that if a driver is insecure or uncomfortable with horizontal curve delineation, the speed is lower at the start of the curve, but increases when the driver knows what to expect. Feedback on own driving (own speed vs posted speed, "SLOW DOWN") seems to have a speed reducing effect in curves. At intersections, vehicle-activated speed limit signs seem to be more effective in reducing speed than the more general message "SLOW DOWN".

The measures used are not solely one-sided and it can for instance be debated whether less variability in lateral position is good or bad. Is it good, because it is safe, or bad, because it means that the driver is focussing hard on keeping the vehicle in the lane and may lead to less attention to other relevant information? In addition, there are road maintenance issues when there are ruts due to most drivers using the same track.

It is implicated that familiarity with a device increases compliance. When new measures are implemented, and also otherwise, it is important that all road equipment point in the same direction, so that the road user knows what to expect. In general, road equipment should be used in a consistent manner and be used for predictability.

The need for information must be traded against the cognitive workload for the road user in each situation. Hence, the number of attention objects should be minimised. This should especially be considered at intersections where attention is needed in terms of destination, rules and regulations at the intersection, and other road users to attend to.

Overall, the literature study led to the following conclusions:

- Drivers should in general be warned of situations that might surprise them.
- Design of road equipment should be intuitively understood by road users. Road equipment that is ambiguous should be avoided.
- Road equipment should be used in a consistent way.
- New designs of road equipment should be studied and followed up to avoid unwanted side-effects.
- Curves with small radius should be warned for.
- Advance yield and stop markings have a potential safety effect at VRU crossings.
- Research on other vehicles than private cars is often lacking.
- More research on performance of road equipment in adverse conditions should be carried out, such as winter, rain and snowfall aspects.
- More night-time studies of performance of road equipment in connection to curves should be carried out, for instance use of road lighting.
- Cycle crossings and passages in relation to driver behaviour and road equipment need to be studied.

4. Current regulations in the Nordic countries

Within the scope of the project, current regulations in the Nordic countries of Denmark, Finland, Norway, and Sweden should be compared. Not all regulations regarding curves, intersections, and crossings with vulnerable road users with respect to road equipment are regarded, though. Analogous to the literature study in Chapter 3, only those regulations that are likely to affect drivers with respect to speed, attention and situational awareness are presented. Hence, the exact design, such as the width of a specific road marking in a certain type of intersection, is not included, whereas more general aspects are. No geometrical data is given unless it is specific for curves, intersections, or crossings with VRUs. The number and position of signs or signals are not included. The overview here is not concerned with where curves, intersections, and crossings with VRUs should be positioned. Hence, given that they are already a fact, what road equipment can and should be used in connection to them, is the topic for this chapter. Please note that the overview of the regulations is not exhaustive and that regulations are constantly subject to change. The overview was carried out in spring 2021.

The regulations used are given below. An abbreviation used for referring to a regulation in the text is given in *italics* after the corresponding reference.

Denmark:

- Vejdirektoratet (2017). Håndbog Trafiksikkerhedsprincipper. *Trafiksikkerheds…*
- Vejdirektoratet (2020). Håndbog Vejbelysning. *Vejbelysning*
- Vejdirektoratet (2018). Håndbog Brug af trafiksignaler. *Trafiksign*
- Vejdirektoratet (2020). Håndbog Afmærkning på kørebanen, tværafmærkning. *Afmærkning*
- Vejdirektoratet (2018). Håndbog Vejkryds i byer. *Vejkryds, byer*

Finland:

Finlex (2020). Statsrådets förordning om användningen av trafikanordningar. *Finlex*
https://www.finlex.fi/sv/laki/alkup/2020/20200379

Norway:

- Statens vegvesen Vegdirektoratet (2019). Håndbok N100 Veg- og gateutforming. *N100*
- Statens vegvesen Vegdirektoratet (2014). Håndbok N300 Trafikkskilt Del 2. *N300-2*
- Statens vegvesen Vegdirektoratet (2014). Håndbok N300 Trafikkskilt Del 3. *N300-3*
- Statens vegvesen Vegdirektoratet (2015). Håndbok N302 Vegoppmerking. *N302*
- Statens vegvesen Vegdirektoratet (2014). Håndbok N303 Trafikksignalanlegg. *N303*
- Statens vegvesen Vegdirektoratet (2014). Håndbok V120 Premisser for geometrisk utforming av veger. *V120*
- Statens vegvesen Vegdirektoratet (2014). Håndbok V121 Geometrisk utforming av veg- og gatekryss. *V121*
- Statens vegvesen Vegdirektoratet (2017). Håndbok V127 Kryssingssteder for gående. *V127*
- Statens vegvesen Vegdirektoratet (2019). Håndbok V128 Fartsdempende tiltak. *V128*
- Statens vegvesen Vegdirektoratet (2014). Håndbok V320 Planlegging og oppsetting av trafikkskilt. *V320*

Sweden:

- Trafikverket (2021). Krav – VGU, Vägars och gators utformning. TRV publikation 2021:001. *VGU001*
- Trafikverket (2021). Råd – VGU, Vägars och gators utformning. TRV publikation 2021:003. *VGU003*
- Transportstyrelsen (2020). Cykelpassage och cykelöverfart. *Transportstyrelsen* https://www.transportstyrelsen.se/sv/vagtrafik/Trafikregler/Generella-trafikregler/Cykeloverfart/

4.1. Curves

4.1.1. Denmark

Road lighting in curves on larger roads (Danish: motorveje and motortrafikveje) is only considered if the road is situated in an urban area and the curve has a small horizontal radius. (*Vejbelysning* 5.3)

Road studs can be used for separating different traffic directions in curves. (*Trafiksikkerheds…* 6.1)

If delineator posts are not enough for visualising a curve, then chevron boards or repeater arrows should be used. The signs can be combined with warning signs and signs showing recommended speed or a local speed limit. (*Trafiksikkerheds…* 7.3)

4.1.2. Finland

Warning signs are used before curves that are dangerous due to small curve radius, limited line of sight or similar. (*Finlex* 3 kap. 32§) Chevron boards and repeater arrows are used outside of the road. (*Finlex* 3 kap. 41§)

4.1.3. Norway

For straight road stretches and curve radii exceeding 300 m the distance between road delineators is 50 m, whereas the distance is 25 m in curves with a radius between 50 and 300 m. However, road delineator posts should only be used on main roads with road lighting, where the speed limit is at least 80 km/h, the AADT exceeds 5000 vehicles, and the lane width is 6.5 m at minimum. Road delineator posts should not be installed on the inside of curves with a curve radius less than 50 m, and the distance between posts should be 10 m on the outside. (*N300-2* 920)

Before certain curves, rumble strips can be used to reduce speed. (*V128* 3.5) The strips should be 5–10 cm long, have a thickness of maximum 4 mm and stretch over the lane. The distance between the strips is dependent on the average speed at the start of the rumble strips. As a consequence, the recommended distance between strips is 3.4 m at 90 km/h, 2.6 m at 70 km/h, 1.8 m at 50 km/h and 1.0 m at 30 km/h. (*N302* 10.3) To reduce driver speed, the distance between the strips is descending towards the area in which the speed should be reduced. Therefore, a rumble strip field with a certain distance can be followed by another field with a smaller distance and so on. (*V128* 3.5)

Centre lines as barrier lines can be marked in curves where it is especially important that vehicles keep to their right and should only be used in combination with lane line or warning line, or as a double barrier line. No barrier line should be used if the speed limit is 50 km/h or less. (*N302* 5.3)

The sign "dangerous curve" (see Figure 5) is used to warn of a curve where the road users need to make sudden speed reductions or changes in direction. (*N300-2* 100) In advance of very special curves where a safe speed is much lower than the normal driving speed, the sign can be combined with a sign for recommended speed.

100.1

Figure 5. Dangerous curve. From 300-2.

At very sharp curves where a large speed reduction is required, and in curves with very bad visibility, chevron boards are used in the curve. For warning of sharp curves that are not typical for the road stretch and hence can be surprising to the road users, repeater arrow signs are used. The first sign should be at the start of the curve and the next one in the extension of the sight for vehicles approaching the curve. The distance between repeater arrows depends on the curve radius (8–12 m for curve radius 50 m and 40 m for curve radius 400 m). (*V320* 3.5.1)

4.1.4. Sweden

On roads without road lighting where the speed limit is at least 80 km/h, white barrier reflectors should be used, which should be placed 25 m between in horizontal curves with a radius of 700 m or less. (*VGU001* 13.2.2.2)

Posts used for road lighting and road signs should be avoided in outside curves. (*VGU003* 7.1.1.3.2)

In concave vertical curves where the speed limit is at least 80 km/h, the annual average daily traffic (AADT) is at least 2000 vehicles/day and there is no road lighting (*VGU001* 13.2.2.1.1), at least three delineator posts on the same side should be visible at the same time. The distance between road delineators should be 25 m if the horizontal radius is less than 700 m or the convex vertical radius is less than 2500 m, otherwise the distance should be 100 m. (*VGU001* 13.2.2.1.2)

The curve warning sign is used when the road conditions before or in the curve do not clearly state that vehicles should drive slower than the posted speed limit. Sometimes repeater arrows can be installed to enhance visual guidance. Other measures that can be used for this purpose are road markings, road delineator posts, road lighting and guard rails. (*VGU003* 13.1.5.5) Guidelines state that signs with one arrow should be used at larger radii, two-arrow-signs at smaller radii and four-arrow-signs at sharp curves. In Sweden, the signs are blue with yellow arrows. (*VGU003* 13.1.14)

For curve radii of 700 m or less, road studs or LED markings can be used to increase visual guidance. They should be installed with a distance of 12 m if speeds are 90 km/h or less and 18 m for higher speeds (≥100 km/h) (which is half the distance compared to normal road). (*VGU003* 13.2.1.9.1-2)

Lower lighting poles compared to the whole interchange can be used on exit ramps, to clarify the change in traffic situation. If there is a decision to light access and exit ramps on an otherwise unlit road, then the whole ramp should be lit. (*VGU003* 14.1.1.2.2)

To avoid driving in the wrong direction, exit ramps should be equipped with road marking arrows in the lane, advising on proper direction. (*VGU003* 13.2.1.5.2)

4.2. Intersections

4.2.1. Denmark

Normally, rural intersections are not equipped with road lighting. (*Trafiksikkerheds…* 7.1) At signalized intersections between roads (Danish: trafikveje) the average illuminance on the roadway should be at least 7.5 lx. Unsignalized intersections on motorways (Danish: motortrafikveje) can also be lit under certain circumstances (such as ascertained night-time traffic accidents). In urban intersections the road lighting is normally chosen in accordance with the highest level of the intersecting roads. (*Vejbelysning* 5.5)

Traffic signals should be used in intersections where the amount of traffic at certain times is so large that yielding road users experience unfair waiting times and queuing. (*Trafiksign* 2.4.1) Traffic signals should not be used on roads with posted speed limit exceeding 70 km/h. (*Trafiksign* 2.4.2)

In intersections where motor traffic and VRUs meet, the speed should be lowered to maximum 30 km/h or the intersection be signalized. (*Trafiksikkerheds…* 2.5)

Duty to give way should be shown by a yield traffic sign and yield lines on the road. For roads with sparse traffic, the yield line alone can be used. (*Trafiksikkerheds…* 8.3.1) If the road surface makes it impossible to use a yield line, for example at roadworks, the duty to give way can instead be marked by a yield sign only. A yield line should normally be placed 0–1.5 m from the edge of the main road. (*Afmærkning* 1.1)

Stop signs and stop lines should be used for stop intersections. (*Trafiksikkerheds…* 8.3.2)

In signalized intersections the stop line should be around 5 m in advance of the pedestrian crossing or stop line for cyclists. In addition, this could be combined with traffic lights for cyclists showing green before the traffic light for motor vehicles. (*Trafiksikkerheds…* 8.5.3)

A stop line should only be used together with a stop sign, a traffic signal or at red blink signal. A cycle box can be marked in front of lanes with right-turning traffic at signalized intersections. No cycle box can be established in combination with green signal for right-turning traffic only. (*Afmærkning* 1.2)

Acoustic rumble strips or painted stripes across the road can be positioned on the approach to an intersection to alert drivers and lower their speed. (*Vejkryds, byer* 4.18)

Reflectors in the roadway can be used for separating different traffic directions from each other in intersections. (*Trafiksikkerheds…* 6.1)

4.2.2. Finland

Traffic signals can be used if the maximum speed limit is 70 km/h or less. (*Finlex* 2 kap.3§) The traffic signal is placed at the stop line or at a maximum of 10 m after the stop line, but always before a pedestrian crossing. (*Finlex* 2 kap. 10§)

An intersection warning sign is used if there could be uncertainties about the duty to give way or if the intersection is not visible from a far enough distance. (*Finlex* 3 kap. 32§)

Duty to give way at an intersection is shown by a yield traffic sign at a maximum of 30 m from the intersection. (*Finlex* 3 kap. 33§) Obligation to stop at the intersection is shown by stop signs, which are used together with stop lines, if technically possible. The stop sign cannot be placed farther than 30 m before the intersection. (*Finlex* 3 kap. 33§)

4.2.3. Norway

If a signalized intersection is too narrow for a dimensioning vehicle, the stop line on the secondary road (the road that the vehicle could turn in to) can be pushed farther back. (*V121* 2)

For smaller side roads the edge lines on the main road are continuous but passing larger side roads the edge line should be intermittent (2 m marking + 2 m opening). At intersections where drivers from the side road should yield to traffic on the main road, the yield sign is accompanied by yield line and the edge line of the main road passing the side road is intermittent (2+2). (*N302* 7.1)

Centre lines on main roads in intersections where traffic from side roads should yield should be designed as warning lines over a distance towards the intersection at least equal to the stopping distance. It can also be designed as a barrier line that is broken within the intersection area. (*N302* 7.3)

On side roads where the traffic should yield, yield lines should be marked approximately 1 m in advance of the intermittent edge line of the main road. They should be accompanied by a yield sign. If there are special circumstances calling for prewarning of the duty to give way, a yield symbol can be used 50–100 m before the yield line. (*N302* 7.3)

Stop lines should be established on access roads that are regulated with the stop sign. The stop line should be positioned approximately 1 m before the intermittent edge line of the main road. The road marking text “STOPP” (meaning STOP) can be used and if so it should be marked around 10 m in advance of the stop line. (*N302* 7.3)

At signalized intersections, the centre lines end at stop lines. (*N302* 7.1)

In signalized intersections, the distance between a stop line and a pedestrian crossing should be at least 2.0 m. Where there are two lanes or more on an access road, at least two arrow markings should be used in each lane. (*N302* 7.5)

Rumble strips can be installed as a warning of an upcoming intersection that can surprise the road users. For more information on use of rumble strips in Norway, see 4.1.3.

4.2.4. Sweden

Traffic signals should only be used in urban areas with speed limit of 70 km/h or less. (*VGU001* 5.11)

Reflectors, both on delineator posts and on barriers, placed directly before and after an intersection should be yellow, as opposed to the normal white reflector. (*VGU001* 13.2.2.1.1) and ((*VGU001* 13.2.2.2)

On roads without delineator posts, in a T-junction with refuge islands, delineator posts should be placed on a road stretch from about 100 m before to 100 m after the refuge island. (*VGU001* 13.2.2.1.3)

In urban areas, intersections should be lit. (*VGU001* 14.1.2.2.1) Signalized intersections should be equipped with road lighting of at least 15.0 lx illuminance. (*VGU001* 14.1.1.2.1)

Intersections where few vehicles turn and intersections where the complexity is small do not have to be lit. (*VGU003* 14.1.1.2.1) Large complexity can be intersections with a large traffic flow, an intersection which is difficult to detect, understand or get an overview of in darkness, and intersections with multiple lanes. (*VGU003* 14.1.1.2.1)

Intersections with large complexity (intersections that differ from normal design, have a large share of connecting, diverging and varying traffic during night-time and drivers exposed to a larger share of annoying lighting) should be equipped with road lighting. For roads with at least 70 km/h, the illuminance should be at least 15.0 lx and for roads with 60 km/h or less, the illuminance should be at least 10.0 lx. (*VGU001* 14.1.1.2.1)

To have safe intersections, the speed should not exceed 70 km/h at risk of side collision. (*VGU003* 6.4.3)

Road signs in intersections should be used for information and guidance through the intersection and should in general be distributed so that they are not concentrated in the intersection where the road user attention should be towards other road users. (*VGU003* 13.1.15)

Often guiding lines (Swedish: ledlinjer) are used in intersections with refuge islands and where there is a risk that turning vehicles will be driving in the wrong direction. (*VGU003* 13.2.1.3.4)

Stop lines and yield lines should be placed at least 1.0 m from the crossing road. In signalized intersections, the distance between stop line and pedestrian crossing/pedestrian passage/bicycle passage/bicycle crossing should be at least 2.0 m. (*VGU003* 13.2.1.4.1)

Yield lines should be designed as in Figure 6 (*VGU003* 13.2.1.4.2):

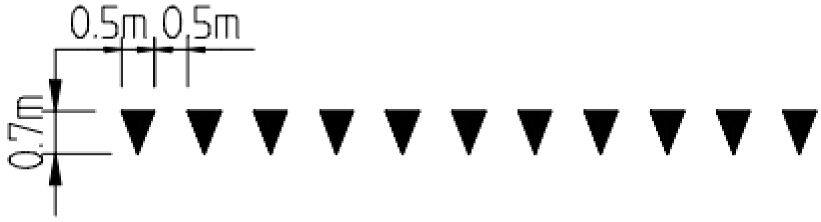

Figure 6. Yield line design.

Advance information of yield or stop duty as a road marking can be used 100-200 m before yield or stop line, for instance when the regulations in an intersection have changed, where there is a limited view of the intersection or otherwise difficult to observe the intersection, see Figure 7. (*VGU003* 13.2.1.5.1)

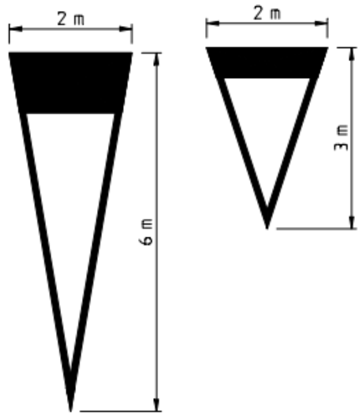

Figure 7. Advance information of duty to yield. The larger symbol should be used at speeds exceeding 60 km/h.

Road marking symbols as road numbers can be used in complicated intersections, where it is difficult for the road user to have the time to read localisation signs and where it helps to make a correct choice of path. (*VGU003* 13.2.1.5.14)

4.3. Crossings with vulnerable road users

4.3.1. Denmark

4.3.1.1. Pedestrian crossings

Pedestrian crossings should be illuminated, either by the regular road lighting or by special illumination. On roads without road lighting or where the average horizontal illuminance is less than 7.5 lx or the semi-spheric illuminance is less than 5.0 lx , the pedestrian crossing should be lit by a special lighting to 30 lx horizontal illuminance on the crossing. On roads where the average horizontal illuminance is 7.5 lx or more, or the semi-spheric illuminance is at least 5.0 lx, only pedestrian crossings on critical positions should have special lighting, for instance at midblock crossings, where the crossing is not visible from an adequate distance or other complicating circumstances. Special road lighting can be omitted if the pedestrian crossing is signalized, near a roundabout or if it crosses a road adjacent to a road with higher priority. (*Vejbelysning* 5.9) The road lighting should be placed so that the side of the pedestrian that the drivers approach is illuminated. (*Vejbelysning* 7.3.8)

As special illumination the road sign E17 pedestrian crossing can be used together with yellow flashing beacons. (*Vejbelysning* 7.3.8)

Pedestrian crossings can be signalized if the amount of VRUs is large (more than 200 pedestrians and cyclists crossing the road as a total of the averaged hourly traffic for the four most intense hours of the day, if the total averaged hourly traffic for vehicle drivers exceeds 600 during the same hours). (*Trafiksign* 2.4.3)

For signalized intersections with pedestrian crossings, the stop line for cars should be 5 m in advance of the pedestrian crossing. (*Afmærkning* 1.2)

4.3.1.2. Cycle crossings

Road lighting is recommended in intersections between roads and paths. If cyclists should yield then stop or yield signs, yield lines, bumps and/or ramps could be used. (*Trafiksikkerheds…* 8.5.2)

4.3.2. Finland

4.3.2.1. Pedestrian crossings

Pedestrian crossings can be signalized if the speed limit is 60 km/h or less (*Finlex* 2 kap.3§) and should be signalized if the speed limit is more than 50 km/h. (*Finlex* 3 kap. 36§)

Pedestrian crossings at a maximum of 30 m from a signalized intersection should be signalized. (*Finlex* 2 kap. 6§) A pedestrian crossing with a refuge island and that is situated at least 10 m from an intersection and where a maximum of two lanes are directed from the intersection, can be signalized when the intersection is not. (*Finlex* 2 kap. 4§)

Pedestrian crossing signs are used either alone or together with road marking (see Figure 8). (*Finlex* 3 kap. 36§) Road marking only can also be used for pedestrian crossings. An unsignalized pedestrian crossing is not marked if the speed limit exceeds 50 km/h. (*Finlex* 4 kap. 44§)

Figure 8. Road marking "pedestrian crossing" and road sign "pedestrian crossing". From https://vayla.fi/sv/trafikleder/material/digiroad/lamna-uppgifter-om-trafikanordningar-till-trafikledsverkets-informationssystem/anvisning-for-vaghallare-for-enskilda-vagar/beskriving-av-informationen-som-ska-levereras

A pre-warning sign for a pedestrian crossing is used if it is either impossible to discern a pedestrian crossing in an adequate amount of time, or on roads where pedestrian crossings are rare, or where the pedestrian crossing is the first in the beginning of a road stretch or in an area with several pedestrian crossings. (*Finlex* 3 kap. 32§)

If there is a stop line for motorised vehicles in front of a pedestrian crossing, the distance between the stop line and the pedestrian crossing should, if possible, be at least 5 m. (*Finlex* 4 kap. 44§)

4.3.2.2. Cycle crossings

Cycle paths that cross a right-turning traffic direction (where the traffic has been separated from an intersection) should be marked on the road. A yield sign should be used for the right-turning traffic crossing the cycle path. (*Finlex* 2 kap. 5§)

Cycle crossings at a maximum of 30 m from a signalized intersection should be signalized. (*Finlex* 2 kap. 6§)

For places where motorised vehicles should yield where cyclists cross the road, a sign for duty to give way for cyclists should be at hand, together with road marking that defines the continuation of a cycle path (see Figure 9). (*Finlex* 3 kap. 33§)

Figure 9. Road marking "continuation of cycle path" and road sign "duty to give way at a place where cyclists cross the road". From https://vayla.fi/sv/trafikleder/material/digiroad/lamna-uppgifter-om-trafikanordningar-till-trafikledsverkets-informationssystem/anvisning-for-vaghallare-for-enskilda-vagar/beskriving-av-informationen-som-ska-levereras

4.3.2.3. Pedestrian passages

A warning sign for pedestrians can be used for places where pedestrians may cross the road or another place on the road that is not marked as a pedestrian crossing. (*Finlex* 3 kap. 32§)

4.3.3. Norway

To increase traffic safety for pedestrians and cyclists, urban intersections should be designed for achieving maximum speeds of 40 km/h. (*N100* B.8) Pedestrian crossings and crossing pedestrian or cycle paths shall be lit to reduce the accident risk at night. (*N100* D.6.1)

4.3.3.1. Pedestrian crossings

At roundabouts, pedestrian crossings should be at least 5 m in advance of the yield line at the roundabout and they can be raised or marked physically where there are many pedestrians or risk of vehicles driving through at high speed. (*N100* D.1.2.6) Speed-reducing measures include speed bumps, speed cushions, road narrowing and chicanes. (*V127* 5.1)

Pedestrian crossings can be regular or raised. At intersections, the pedestrian crossing should be placed either 1-2 m (small detour for pedestrians) or 5 m (possible for a vehicle to stop without hindering intersecting traffic) from the intersecting road. (*N100* D.2.6.1)

No pedestrian crossings should be established in residential areas with 30 km/h. In centre areas with speed limit 30 km/h pedestrian crossings should be established in crossings where there are many crossing pedestrians per hour (more than 40) or AADT exceeding 8000. (*N100* D.2.6.1) No pedestrian crossings should be established where the sight distance is less than 1.2 times the stopping distance[1]. (*N300-2* 140)

At speed limits of 40 or 50 km/h pedestrian crossings should be established if either the amount of pedestrians is more than 20 and the amount of vehicles is more than 200 at the dimensioning hour, or the amount of pedestrians is more than 10 and the amount of vehicles is more than 800 at the dimensioning hour. (*N100* D.2.6.1)

Pedestrian crossings on roads with speed limit of 60 km/h should be signalized. No pedestrian crossings should be established on roads with speed limit exceeding 60 km/h. (*N100* D.2.6.1) For

[1] Stopping distance is here defined as the necessary distance to an object for a driver to detect it, react, evaluate whether he or she should brake and brake until the vehicle has stopped. (*V120* 5.1.2)

midblock pedestrian crossings with speed limit 60 km/h the centre line should be a barrier line at least 35 m in advance of the crossing. (*N302* 8.1)

Pedestrian crossings should be lit (*N100* D.6.1) and either be illuminated by intense lighting or increased lighting. Unless there are specific reasons, intense lighting is chosen. For intense lighting, white light with good colour rendering should be used. The vertical illuminance in the middle of the pedestrian crossing should be at least 20 lx in lanes towards the pedestrian crossing and at least 10 lx in the opposite direction. The minimum horizontal illuminance of the pedestrian crossing should be 80 lx. An area of each side of the pedestrian crossing, where pedestrians arrive, should also be adequately lit and on the right side in the driving direction the vertical illuminance should be at least 10 lx at 3 m from the pedestrian crossing. The average luminance level of the road before and after the pedestrian crossing should be at least 1.00 cd/m^2. (*N100* D.6.3)

Road lighting for pedestrian crossings can be dimmed at night-time, as long as the relative difference in lighting between the before/after and pedestrian crossing is maintained. (*N100* D.6.3)

Stop lines should be positioned at least 2 m before pedestrian crossings at intersections and single pedestrian crossings. (*N303* 4.6)

Figure 10. Signs that can be used at pedestrian crossings. At raised pedestrian crossings, skilt 109 should be used to warn drivers. From V127.

The road marking in Figure 11 must be used at pedestrian crossings and it can be used without the pedestrian crossing sign 516 given in Figure 10. (*N302* 8.1) In city centres with many pedestrian crossings, the traffic sign 516 can be omitted for pedestrian crossings at intersections. The same applies to pedestrian crossings over a side road in other intersections where the speed towards the pedestrian crossing is low, especially if the placement of the sign conflicts with the yield sign. (*N300-3* 516) Before pedestrian crossings that are not raised or signalized, the warning sign 140 in Figure 10, including information of the distance to the pedestrian crossing, can be used. (*N300-3* 516; *N300-2* 140) The warning sign should be used for pedestrian crossings in areas that are not obviously urban areas. It shall be used when the sight distance to the pedestrian crossing is less than appr. 42 m for speed limit 30 km/h, appr. 55 m for 40 km/h and appr. 68 m for 50 km/h. (*N300-2* 140)

Figure 11. Road markings at pedestrian crossings. From V127.

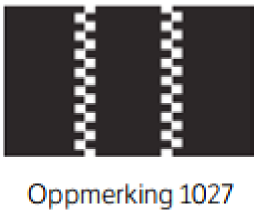

Figure 12. Road marking that can be used at raised pedestrian crossings. From V127.

Rumble strips can be installed as a warning of an upcoming pedestrian crossing that can surprise the drivers. For more information about use of rumble strips in Norway, see 4.1.3.

4.3.3.2. Cycle crossings

Cycle paths should not be placed throughout a roundabout. D.1.2.6 in N100

Cycle paths in parallel with the road are not marked with road markings in an intersection where the right-hand rule applies. On cycle paths in parallel with the road the road marking “cycle crossing” (Figure 13) should be used in an intersection passing a side road where the yield rule applies, and also through a signalized intersection. The road marking should not be used where the cyclist should yield. 8.3 in 302

When drivers on a side road should yield to cyclists on a cycle crossing, the road marking “cycle crossing” is also used, together with yield line and yield sign including information of crossing cyclists for drivers. 8.7 in 302 When drivers on a side road should yield to both pedestrians and cyclists, the combined road marking “cycle crossing and pedestrian crossing” is used (Figure 14), together with appropriate yield signage (yield line and yield sign including information of crossing cyclists) for drivers. 8.5 in 302

Figure 13. Road marking 1026.1 ”cycle crossing”. From N302.

Figure 14. Road marking 1026.2 ”cycle crossing at pedestrian crossing”. From N302.

4.3.3.3. Pedestrian passages

Pedestrian passages can be relevant when pedestrians are likely to cross the road on that location or where a passage will increase accessibility without increasing the accident risk. At a pedestrian passage the kerb on both sides of the road is phased to the level of the road. Pedestrian passages are not recommended on roads where speeds exceed 65 km/h. Measures that can be considered to enhance pedestrian passages are refuge islands, road lighting and rumble strips. 6 in V127

4.3.4. Sweden

4.3.4.1. Pedestrian crossings

Pedestrian crossings are not allowed on roads where the posted speed limit exceeds 60 km/h. (*VGU001* 10.2.7.1) Pedestrian crossings can be signalized or unsignalized. At unsignalized pedestrian crossings, the roadway should have maximum one lane in each direction. (*VGU003* 10.3.7.1) Pedestrian crossings should have a refuge island. (*VGU003* 10.3.7.3)

Pedestrian crossings should be lit. (*VGU003* 10.3.7.4) When lighting a pedestrian crossing at an unlit road, the horizontal illuminance should be at least 7.5 lx for areas of driving, whereas for pedestrian areas the horizontal illuminance should be at least 5.0 lx and the vertical illuminance at least 1.5 lx. (*VGU001* 14.1.2.4)

On roads with road lighting, a higher illumination class should be used on a road stretch of 50 m before to 50 m after the marked pedestrian crossing and at a width of at least 5.0 m of the side area at each side of the roadway. Separate road lighting for pedestrian crossings can be used (if the regular road lighting does not make it possible to achieve a satisfying negative contrast between the pedestrian and the background) by letting vertical lighting illuminate the side of the pedestrian that is turned towards the motor traffic (creating a positive contrast). The vertical illuminance should be at least 20 lx on the middle of a pedestrian crossing and it should be higher than the horizontal illuminance on the pedestrian crossing, although not too high and it must not make drivers experience glare. (*VGU003* 14.1.2.4)

The speed at pedestrian crossings shall be secured to 40 km/h or less (*VGU001* 6.4.6) and should be secured to 30 km/h. (*VGU003* 6.4.6)

In signalized intersections, the distance between stop line and pedestrian crossing/pedestrian passage/bicycle passage/bicycle crossing should be at least 2.0 m. (*VGU003* 13.2.1.4.1) The distance between a yield or stop line at an intersection and a passage for vulnerable road users should be at least 5.0 m to allow for a vehicle to be positioned between the passage and the line, or otherwise the yield or stop line should be placed before the pedestrian crossing. (*VGU003* 13.2.1.4.2)

4.3.4.2. Cycle crossings

The speed at cycle crossings shall be secured to 30 km/h or less. Secured speed at pedestrian passages as well as at cycle passages shall be considered. (*VGU001* 6.4.6)

No cycle crossings are allowed on roads where the posted speed limit exceeds 60 km/h. Cycle crossings cannot be regulated by traffic signals. (*VGU001* 10.3.8.3) Cycle crossings should be marked by the road sign in Figure 15 and by road markings for cycle passage (white squares on both sides of the crossing, see Figure 16) and yield line for drivers (before the crossing from the driver perspective, see Figure 17). The speed should also be secured to 30 km/h by raised pavement or similar. (*VGU003* 10.3.8.3)

Figure 15.Retrieved from https://www.transportstyrelsen.se/sv/vagtrafik/Trafikregler/cykeloverfart/

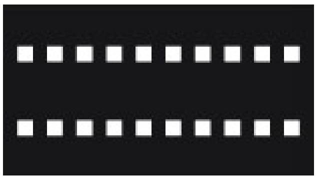

Figure 16. Road marking for cycle passages and cycle crossings. Retrieved from [*https://www.transportstyrelsen.se/sv/vagtrafik/Vagmarken/Vagmarkeringar*](https://www.transportstyrelsen.se/sv/vagtrafik/Vagmarken/Vagmarkeringar)

Figure 17. Yield line. Retrieved from [*https://www.transportstyrelsen.se/sv/vagtrafik/Vagmarken/Vagmarkeringar*](https://www.transportstyrelsen.se/sv/vagtrafik/Vagmarken/Vagmarkeringar)

4.3.4.3. Pedestrian passages

Passages for pedestrian, cyclist, and moped traffic on roads with speeds of 60 km/h or less should be designed for safe interactions (*VGU001* 6.4.5) and where separated passages cannot be used, the speed 40 km/h should be secured. (*VGU003* 6.4.5)

At pedestrian passages the kerb is phased to the road level and they are not marked with any road marking or road sign. (*VGU003* 10.3.7.7)

Pedestrian passages on roads with reference speeds of 60 km/h or more shall be equipped with a refuge island (Figure 18) (*VGU001* 10.3.7.7), which should have a width of at least 2.0 m. (*VGU003* 10.3.7.7)

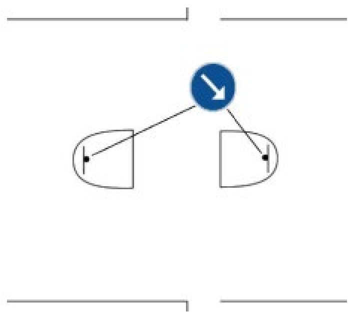

Figure 18. Example of a pedestrian passage with refuge island. From TRV publikation 2021:001.

4.3.4.4. Cycle passages

No cycle passages are allowed on roads with posted speed limit of more than 60 km/h. (*VGU001* 10.3.8.1) Cycle passages are established to indicate where it is appropriate for cyclists and drivers of low-speed mopeds (maximum 25 km/h) to cross a road. Cycle passages are marked with road markings for cycle passage in the shape of white squares on both sides of the passage path (*Transportstyrelsen*). The kerb should be phased to the road level. Midblock passages should be equipped with a refuge island. Cycle passages on roads with posted speed limit of 60 km/h should be secured to 40 km/h. Cycle passages can be signalized or unsignalized. (*VGU003* 10.3.8.1)

5. Final discussion and conclusions

This report is intended to be used by road authorities and traffic researchers in the Nordic countries. A literature review has been carried out on driver behaviour in connection to use of road equipment in curves, intersections, and crossings with vulnerable road users. An overview of the current regulations (early 2021) in Denmark, Finland, Norway, and Sweden are given to let the reader look up and reflect on the regulations.

Most of the studies referred to in the literature review are not from the Nordic regions, and hence the generalisability of their results must be considered.

If a new design of road equipment is of interest to try in Denmark, Finland, Norway, or Sweden, then maintenance issues should be assessed and evaluated in combination with evaluation of road user behaviour. Road equipment that is positioned in or on the road may for instance be exposed to functionality decrease or stop functioning totally in relation to winter conditions and road maintenance.

In addition, the studies referred to are often carried out in optimal circumstances, i.e., in daylight conditions on days without precipitation. In the Nordic countries rain, snowfall, fog, and darkness are examples of other situations that prevail and need to be studied so that the introduction of a certain measure function, or at minimum does not have any dangerous side-effects during adverse conditions. It is important that the road equipment is used in a consistent manner.

Many studies have been conducted in a simulator. As simulator studies have their advantages of repeatability, of making an initial evaluation of a measure, and for comparing different measures against each other, they should be complemented by studies on real road. Hence, introduction of a new type of road equipment on the road should be followed up.

Some research gaps that were detected in the literature study were the following:

- Research on other vehicles than private cars. For example, more studies on motorcycles are recommended to investigate whether road equipment used has any detrimental effects.
- Research on performance of road equipment in adverse weather conditions, such as winter, rain, and snowfall aspects.
- Night-time studies of performance of road equipment in connection to curves. It is important that curves, especially sharp ones, are visible both in daylight and at night-time, to avoid surprises.
- Cycle crossings and passages in relation to driver behaviour and road equipment. These crossings and passages have not been examined to any larger degree.

In conclusion, it is important that road equipment is used in a consistent manner, for all road users to understand what they should expect and avoid surprises.

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Our operations cover all modes of transport, and the subjects of pavement technology, infrastructure maintenance, vehicle technology, traffic safety, traffic analysis, users of the transport system, the environment, the planning and decision making processes, transport economics and transport systems. Knowledge that the institute develops provides a basis for decisions made by stakeholders in the transport sector. In many cases our findings lead to direct applications in both national and international transport policies.

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