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Research article

Interventions to reduce the speed of cyclists in work zones—cyclists' evaluation in a controlled environment

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Abstract: Current guidelines for work zones do not consider the needs of cyclists and pedestrians enough, which leads to unpredictable situations and a resulting higher crash risk for these road user groups. With respect to motor vehicles, speed management with various interventions is an important and well-studied measure. Their design can be hazardous for cyclists, but a systematic investigation of speed reducing interventions that are applicable to cyclists is lacking. In a controlled setting, four different types of interventions were studied regarding their effect on cyclist speed, attention, and comfort at the first encounter with the intervention and when familiar with the setup. Thirty cyclists with a variety of bicycles first rode a baseline condition to establish their desired speed, then they encountered the interventions eight times in a row. During the first encounter their speed dropped but went back to baseline levels during the following trials, regardless of intervention type. The glance behaviour showed that cyclists' attention was focused much more on the interventions themselves than beyond, which can be problematic in unpredictable environments like work zones. Comfort ratings varied widely, with interventions causing vibrations being rated as least comfortable. To conclude, speed-reducing interventions for cyclists must be applied with care and their effect weighted against potential risks of causing crashes and distraction.

Keywords: comfort, cyclists, road works, safety, speed reduction, work zone

1 Introduction

The Swedish Road Administration aims to update current guidelines for road works to better consider the conditions and preferences of cyclists. It appears to be a widespread problem that present guidelines do not take cyclists and pedestrians into sufficient consideration and road authorities and agencies around the world are struggling to find appropriate solutions to improve cyclist (and pedestrian) safety and mobility in work zones (Attanayake et al., 2017; Bilton, 2012; Shaw et al., 2016; Niska et al., 2014b). Without proper guidelines and specific instructions, it becomes the contractors' responsibility to solve the situation at site. Often, they close access to cyclists and pedestrians completely without providing alternative routes around or within work zones (Attanayake et al., 2017). The road users' behaviour then becomes unpredictable resulting in a higher risk of incidents and crashes, causing fatalities and injuries.

In Sweden, about 300 road traffic incidents at road works resulting in casualties or fatalities occur every year. In almost half of them (44%) vulnerable road users—pedestrians, cyclists or moped riders get injured (Liljegren, 2023). When analysing injured cyclists recorded between 2007 and 2012 in the Swedish national registry of road traffic crashes (STRADA), including cyclists seeking medical care at emergency departments, we found that a major part (87%) of the bicycle crashes occurring at road works are single bicycle crashes. In general single bicycle crashes represent 78% of severely injured cyclists in Sweden (Niska & Eriksson, 2013). On average almost 10 000 cyclists are injured in Swedish traffic every year and reported into STRADA. Almost 1 500 are severely injured in single bicycle crashes with about four per cent of those in relation to road works (Eriksson et al., 2022). The most common causes of single bicycle crashes at road works are cyclists falling when encountering cables, hoses, pipes etc. laid across the cycle path; loose gravel, stones or dirt from the road works; high and/or unmarked edges; large potholes, ditches or other irregularities (Niska et al., 2014b). Ninety per cent of these crashes occurred in urban areas.

To control the hazard and reduce risk at work zones the general approach is applying a 'hierarchy of controls', that is, risk elimination (such as traffic diversion), engineering controls (such as safety barriers), administrative controls (such as reduced speeds) and personal protective equipment (such as high visibility vests) (Attanayake et al., 2017). Therefore, temporary traffic control devices of various sorts are used in work zones, to warn, regulate, guide, and protect road users while also ensuring the safety of road workers. These devices are typically designed to deal with motorised traffic and can, unfortunately, contribute to the crash risk of cyclists, for example falling when hitting road signs or getting stuck with handlebars in fences (Niska et al., 2014b). In such an event, the devices can also cause injuries to cyclists, for example when falling onto sharp edges.

To gain further understanding of how height and other physical parameters and design features of temporary traffic control devices might affect the risk of injuries among cyclists, single-bicycle crashes have been simulated in the VTI crash test facility (Niska et al., 2022). The results from that study have been considered in a new national standard regulating the design of temporary traffic control devices used on pedestrian and bicycle paths (SiS, 2022). There is also a need to know how these temporary traffic control devices affect the mobility and comfort of cyclists. This determines if and how certain devices should be used to raise the awareness and improve safety, mobility, and comfort of cyclists in work zones. Speed-reducing interventions are particularly interesting to evaluate since they are often suggested and used in practice, both on roadways and on separate cycling infrastructure, although there is little support in research of their effectiveness to reduce the speed of cyclists (Berg Alvergren et al., 2019). In addition, such interventions might impose a risk to cyclists who are sensitive to obstacles or unevenness in their way.

In general, speed management is an important instrument for improving road traffic safety. Higher speeds are related to higher crash risks and contribute to the severity of impact (Vasudevan, 2021; ITF, 2018), at least regarding collisions involving motor vehicles. Research on the relationship between cyclists' speeds and crash risk is scarce (Eriksson et al., 2019). However, for cyclists not only absolute speed, but also speed variance may be an important factor. While absolute speed determines the stopping distance (AASHTO, 2012) and the kinetic energy with which a cyclist may hit obstacles or the ground in case of a collision, a high variance in speed between different cyclists may increase crash risk in areas with limited space. Therefore, homogenous speeds low enough to prevent severe impacts, but high enough to keep the cyclist stable (Schwab et al., 2012) could be a situation to aim for.

Speed management involves setting and enforcing speed limits, public education and awareness campaigns as well as engineering interventions (WHO, 2023). Engineering-based interventions include design concepts used to attain the desired speeds such as vertical or horizontal deflections (Vasudevan, 2021). The interventions based on vertical deflections, such as speed humps, create discomfort for drivers travelling at high speeds by inducing a haptic vertical movement to the vehicles passing over them. Patel & Vasudevan (2016) showed that cyclists experience greater discomfort on speed bumps than riders of powered two-wheelers, likely due to the absence of suspension and the typically harder seat. The interventions with horizontal deflections, such as chicanes, reduce speed by forcing drivers to steer left and right out of a straight travel path, often including a narrow passage. Most speed-reducing interventions are aiming to reduce the speed of motor vehicles and therefore, research on such interventions is mainly focusing on motorised traffic rather than cyclists.

A different way to intervene is to use the effect of speed perception based on transversal reference marks (Gogel & McNulty, 1983). When assessing different speed-reducing interventions for cyclists in the EU-funded research project MeBeSafe, an intervention consisting of a visual pattern was concluded to be the best solution (Kovaceva et al., 2022). To nudge cyclists to slow down before an intersection, flat transversal stripes with gradually reducing gaps between them were painted across the road to provide a visual illusion of going faster than the actual speed. This intervention was found to have a small effect on leisure cyclists, but less so on commuters, which may be a result of frequent exposure. In post-exposure interviews, cyclists were generally positive about the nudge.

A physical object placed into the roadway, especially when it is connected to some uncertainty on how to deal with it, has potential to draw attention to itself and thus, away from the traffic situation (Kujala & Lappi, 2021). Thus, even though a speed reduction may give a cyclist more time to assess the situation, the speed reduction intervention may also require attention and thereby interfere with attending to the traffic situation itself. Therefore, speed reduction interventions should not only be evaluated for their potential to reduce speed, but also to which extent they still allow the cyclist to be attentive to the surroundings, which is crucial in situations like work zones with increased uncertainty.

To give guidance regarding speed-reducing interventions for cyclists at road works and to study their effect on cyclist attention, the MeBeSafe markings as well as three other interventions were evaluated in the present study. Their speed reducing effect, attention capture, as well as cyclists' subjective assessment of each intervention were studied in a semi-controlled environment.

1.1 Research questions

- Is any of the interventions capable of reducing speed over time? If so, which?
- How do the interventions affect cyclist attention?
- How do the participants perceive the interventions subjectively?
- Are there any special issues related to certain interventions in interaction with types of bicycles or participants?

2 Method

To evaluate the different speed-reducing interventions, cyclists were recruited to cycle around a test track and they were also asked to answer a questionnaire. Video cameras were mounted on the participants' bicycles, as well as around the test track.

2.1 Test track and equipment

The test track was a 7.2 to 7.5 m wide tarmac track of circa 300 m length describing a wide circle, which was ridden counterclockwise (see Figure 1). The four speed-reducing interventions were placed along the track. The physical constraints did not allow a randomisation of the order of the interventions within or between participants.

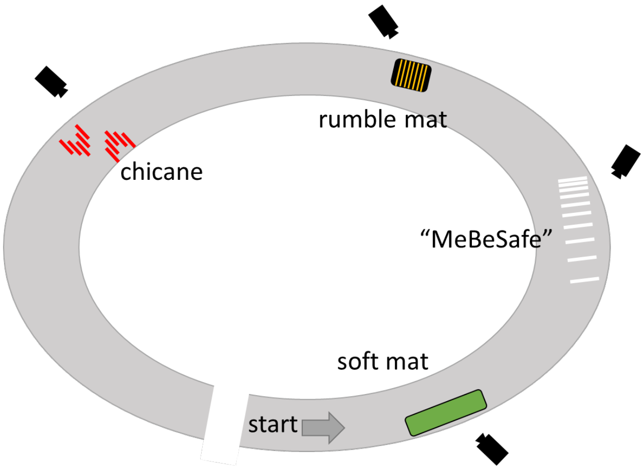

Figure 1 A schematic overview of the test track with the four speed reduction interventions and the camera positions

The four interventions included in the study represented different strategies to reduce speed. Besides that, they were included in the study, because they are either used today or have been specifically developed for handling cyclists at road works.

2.1.1 Soft mat

A soft, 13 mm thick, plastic mat of 11.1 m length and 1.25 m width was placed first (Figure 2a). The mat was a prototype which was designed as such that it created an increased need of effort for passing at the same speed. Its design also mitigates the impact of falling.

2.1.2 Visual 'MeBeSafe'

A set of 18 white stripes (15 cm wide) of 1.6 m lateral width was fixed on the track according to the pattern described in Kovaceva et al. (2022). Via the effect of an optical illusion, the decreasing distance between the stripes should create the unconscious impression of increasing speed, leading to a speed reduction. The material used was circa five mm thick, which led to an additional (although small) haptic effect (Figure 2b).

2.1.3 Rumble mat

A black, hard, rubber mat of 1.55 m length and 1.75 m width was placed on the test track. The mat contains eight yellow coloured wooden rumble strips of 30 mm width and 15 mm height, with 165 mm between the inner edges of each strip. The strips create a haptic vertical movement to the bicycles when passing over and a feeling of discomfort for the cyclist, which is expected to be mitigated by slowing down before riding over the mat. This intervention is specifically developed to reduce cyclists' speed at work zones and is already available on the Swedish market ('Ramirent GC-matta'; Figure 2c).

2.1.4 Chicane

The chicane works with a combination of Perceptual complexity and physical prevention of high speeds due to the required preciseness of the manoeuvre. This intervention is used today in some Swedish municipalities for reducing the speed of cyclists at work zones.

A chicane of ten flat traffic lane delineators was set up as shown in Figure 2d. It was placed side by side with a fence and an excavation of around 10 cm depth with sharp edges, which functioned as a natural barrier to prevent cyclists from rounding the chicane.

2.2 Participants

Participants were recruited via an ad in an open local Facebook group for people interested in questions concerning the city of Linköping as a bicycle town. Interested people were directed to a recruitment questionnaire asking about one's willingness to participate and one's cycling habits. Drop-outs were replaced by word of mouth.

A total of 30 cyclists (13 females) with a mean age of 46 years (std 12.4 years) took part in the study. The three oldest participants were 60, 64 and 77 years of age. Additionally, a girl aged 7 years on her own bicycle participated together with her parent, who also carried a younger child on a trailer bike. One participant had two young children in a cargo bike.

The participants were asked to bring their own bicycles to the test, resulting in a variety of bicycles included: 13 comfort bikes (Dutch style), two road bikes, two mountain bikes, ten trekking/hybrid bikes, two pedelecs, four cargo bikes (three of them three-wheeled) and one longtail.

2.3 Procedure

Participants were run in groups of two to six on two consecutive days in autumn 2021. Upon arrival to the test site, participants were informed about the purpose of the study. They then signed an informed consent form, their bicycles were equipped with an action camera and a microphone, and the bicycles were measured and categorised by type, tyre width, handlebar width and weight. Within each group, one or two participants were equipped with eye tracking glasses (Pupil Labs Invisible, Berlin, Germany). Nine participants in total wore eye trackers. It was not possible to equip more participants, as only two sets of eye trackers were available and in some groups there was only one participant who did not need their own prescription glasses.

Together with one of the experimenters the participants rode around the test track once, receiving explanations of where to ride during baseline and during treatment. During this test run and the baseline phase, the visual MeBeSafe-intervention was covered, and the chicane was not in place.

2.3.1 Baseline

The participants were sent onto the test track individually, with a time gap large enough to prevent them from catching up to each other. They were encouraged to make verbal comments about their ride. Each participant passed the interventions in the following order: soft mat – MeBeSafe – rumble mat – chicane. During baseline, the participants rode parallel to the interventions. Three baseline trials per participant were run.

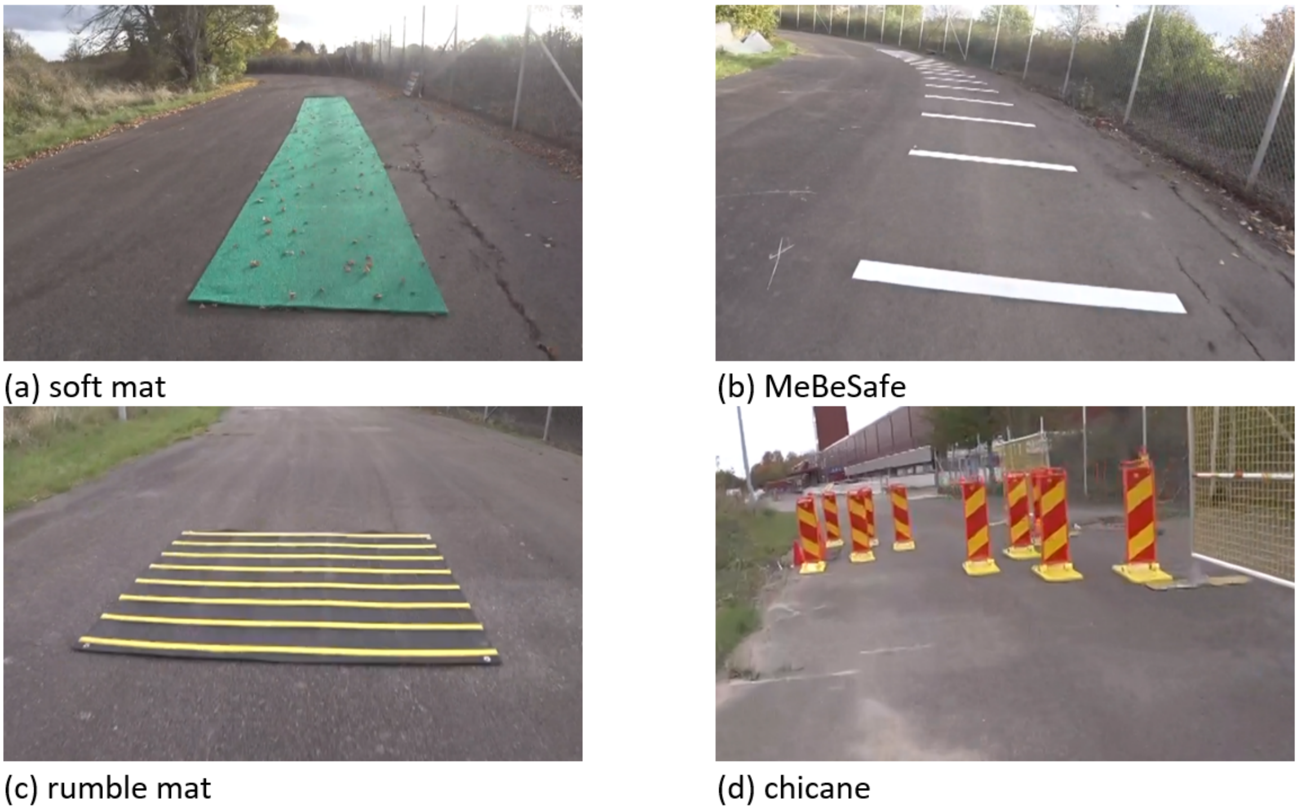

Figure 2 The four interventions seen from the point of view of an approaching cyclist

2.3.2 Treatment

Before the treatment trials were begun, the MeBeSafe-intervention was uncovered, and the chicane was set up. The participants then rode eight treatment trials, with a similar procedure as in the baseline, except that they now rode over or through the interventions. Again, verbal commentary was encouraged.

2.3.3 Subjective evaluation

After finalising the treatment trials, the participants were asked to fill in a digital questionnaire about their subjective opinions considering the interventions. They ranked the interventions for their potential to reduce speed sustainably, for their comfort, perceived risk, and overall impression. They also noted by way of multiple choice how they had acted to deal with the interventions. The choices were ‘apply extra effort before intervention’, ‘apply extra effort on/in intervention’, ‘coasting before intervention’ (coasting meaning freewheeling, i.e. rolling without pedalling), ‘coasting on/in intervention’, ‘brake before intervention’, ‘brake on/in intervention’, ‘set foot down’, ‘dismount’, ‘hold on to things’, ‘stand up on pedals’, ‘normal behaviour, nothing special’, ‘other (specify)’.

2.4 Analyses

For each passage of each intervention the indicators detailed in Figure 3 were extracted based on manually coding the video films with the software Noldus Observer XT 16 (Wageningen, NL) and on the data from the eye tracker. The mean speed from intervention start to end was calculated from the duration on and the length of the intervention. For each passage it was determined whether the participant coasted, braked visibly or stood up on the pedals in the approach phase or on the intervention. For the approach phase this was coded as absent or present, as different camera angles made it difficult to identify an equal approach start across groups. For the duration of the intervention, the percentage of time spent coasting, pedalling and braking was calculated. Also, percentage of time spent seated, standing up or jumping was extracted. Braking was identified either as backpedal braking for bicycles with coaster brake or as a visible hand movement in combination with coasting, or otherwise visible retardation that could only have been achieved by braking actively, again in combination with coasting.

One of the eye tracking devices had a loose connection, affecting all data from one participant and leading to partial data loss for two more participants. Altogether, complete or partial data were obtained for eight participants. Given the low quantity of data, no inferential statistics were computed, and analyses were partially made in a semi-qualitative manner.

Glances were analysed for the situation in which the participants were most familiar with the baseline setting (BL3), their first and second encounter with the intervention (Tr1, Tr2), and when they were familiar with the intervention (Tr7) but not yet in their last trial. The next-to-last trial was chosen for the comparison, as participants might behave differently knowing they were on their last round. For the four interventions, the number of glances was counted starting with the first glance on the intervention and ending with the last glance on the intervention. The percentage of glances on the intervention, as well as to the left, right, in front of or beyond the intervention was determined (coloured patches in Figure 3). For the baseline trial, the first-glance position from Tr1 and the area corresponding to the location of the intervention was used.

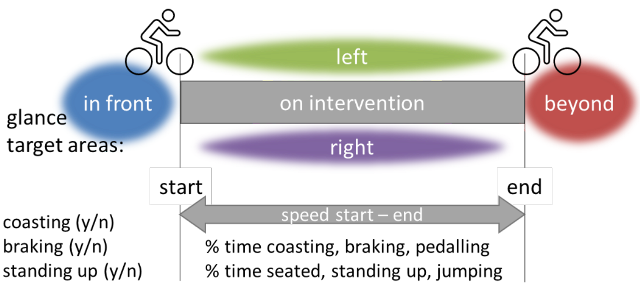

Figure 3 Schematic illustration of the data extracted from the films and the gaze tracker per passage of each intervention (y/n = yes/no)

3 Results

The overall mean baseline speed was 19.0 km/h (min 9 km/h, max 38 km/h, std = 4.6 km/h), but mean baseline speeds differed significantly between locations of the four interventions, likely due to the layout of the test track ($F(3, 371) = 17.5$, $p < .001$). The mean baseline speed at the location of the soft mat (17.1 km/h) and the rumble mat (17.8 km/h) were lower than at the location of the MeBeSafe intervention (21.1 km/h) and the chicane (20.0 km/h). For this reason, speed comparisons were only made within each intervention.

An analysis of variance of gender and trial, with the fixed factor 'gender' nested under the random factor 'participant', showed that men rode 2.8 km/h faster than women on average ($F(1, 29) = 4.6$, $p = .041$), and that participants varied significantly in their average speed ($F(29, 1307) = 66.7$, $p < .001$). Trial also affected speed significantly ($F(10, 1307) = 19.7$, $p < .001$) and will be explored in more detail below. A similar analysis showed that the type of bicycle affected speed significantly as well ($F(6, 24) = 3.1$, $p = .022$), with road bikes being the fastest, followed by pedelecs. Mountain bikes and trekking/hybrid bikes were ridden at similar speeds, as were comfort bikes and cargo bikes. Note, however, that the bicycle types were not equally distributed across genders, and the number of bicycles per category varied substantially.

3.1 Speed per intervention

Analyses of variance of mean speed on the intervention, with the fixed factor 'trial' and the random factor 'participant', were conducted per intervention (Table 1). In each case, both factors were significant. Post-hoc tests for 'trial' showed that in all cases, the average speed in the first treatment trial was lower than during the three baseline trials and all other treatment trials. In some cases, the average speed in the second treatment was still lower than for the remaining trials, but higher than in the first treatment trial. From the third treatment trial onwards, while nominally slightly lower, average speeds did not differ significantly from the baseline trials nor from each other.

As the range for baseline speeds was large, participants were grouped by their mean speed in BL3 into three equal groups. Analyses of variance for trial and the speed groups showed that all speed groups followed the same pattern as described above at their level of speed, with no interaction effects between speed group and trial (Figure 4). Throughout, the slowest third was approximately 5 km/h slower than the medium group, which was around 2 km/h slower than the fastest group. Though not significant, the speed drop from BL3 to Tr1 tended to be largest for the fastest group, but went up to baseline level again at the latest in Tr3, with mean speeds well above 20 km/h.

In some cases, especially the rumble mat and the chicane generated speeds that could be considered too low. The distribution of cases per intervention and treatment passage with a mean speed of below 10 km/h is presented in Table 2. This cutoff was chosen loosely

Table 1 Mean speed and standard deviation for BL3, the first and second treatment trials and across treatment trials 3–8 per intervention, including F- and p-values for the analyses of variance comparing all eleven trials per intervention

	Speed BL3	Speed Tr1	Speed Tr2	Speed Tr3–8	F(10, 300)	p-value
Soft mat	17.4 ± 3.3	14.4 ± 3.3	16.1 ± 3.1	16.9 ± 3.8	9.55	< .001
MeBeSafe	21.7 ± 4.7	17.0 ± 3.6	20.1 ± 4.3	19.9 ± 4.3	13.10	< .001
Rumble mat	18.2 ± 4.1	13.6 ± 4.8	15.2 ± 5.4	17.1 ± 5.9	6.86	< .001
Chicane	20.7 ± 4.9	15.0 ± 4.9	16.7 ± 4.9	18.5 ± 5.5	11.52	< .001

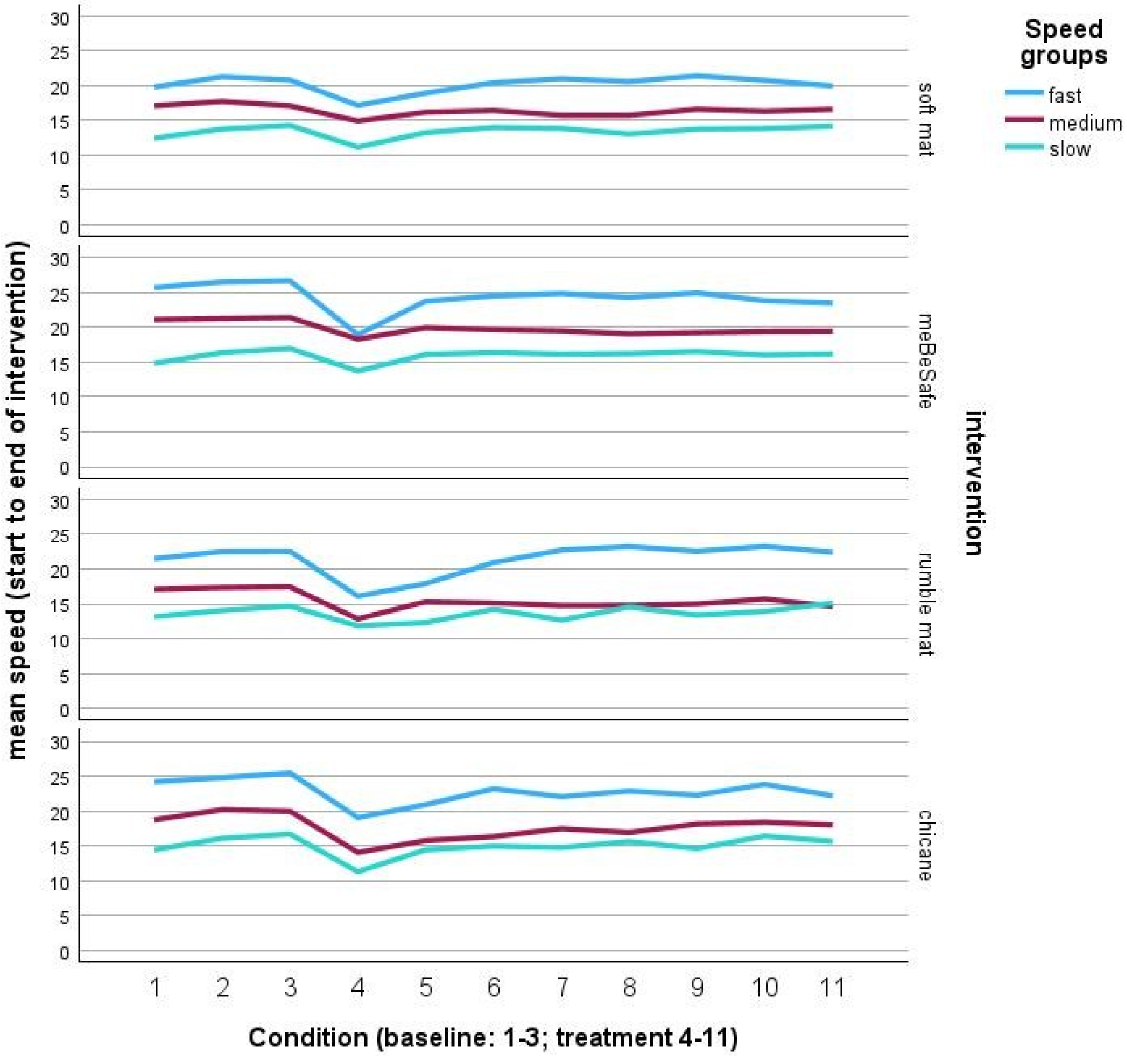

Figure 4 Mean speed of different speed groups of cyclists for each intervention and trial

Table 2 Number of cases out of 31 passages per treatment trial and intervention in which a mean speed below 10 km/h was measured during the passage of the intervention

	Tr1	Tr2	Tr3	Tr4	Tr5	Tr6	Tr7	Tr8	TOTAL
Soft mat	3	1	0	0	0	0	0	0	4
MeBeSafe	1	0	0	0	0	0	0	0	1
Rumble mat	8	5	3	4	5	6	3	4	38
Chicane	4	1	1	1	1	2	1	1	12
TOTAL	17	7	4	5	6	8	4	5	55

based on Kooijman et al. (2009) with the steering angle decreasing for increasing speeds and Schwab et al. (2012) showing that bicycles become self-stabilising at around 10 km/h. Mean speeds below 10 km/h did practically not occur during baseline (0.8% of the cases), while they did in five per cent of the treatment cases. Of those 55 cases, 40 per cent affected cargo bikes and 53 per cent affected comfort bikes. In the comfort bike group, the average rider age for passages under 10 km/h was 50.4 years, whereas it was 43.5 years for the faster passages ($F(1, 376) = 5.04$; $p = 0.025$).

3.2 Behavioural adaptation per intervention

Cyclists can make use of different forms of behavioural adaptation to the interventions, either in preparation before reaching the intervention or while in or on the intervention. The employed strategies differed between interventions and participants. Table 3 shows the frequency with which participants coasted or braked before and on the interventions, and the percentage of participants who reported to have done so. The absolute values differ more for braking than for coasting, but overall, the patterns were similar, except for braking before the chicane, where considerably more participant reported braking than what was observed.

Analyses of variance showed that coasting and braking were deployed differently depending on the intervention (all $p < .001$, see Table 3 for F-values). Bonferroni-corrected post-hoc tests showed that the cyclists were more likely to coast and brake before reaching the rumble mat and the chicane than before the other two interventions. The same was true for coasting and braking on the intervention, even though braking was more common before than on the intervention. The cargo bike riders were more likely to brake before (40.6% of the treatment passages) and on (25% of the treatment passages) the rumble mat than riders of all other bicycle types. They never stood up on the pedals when passing the rumble mat, whereas that strategy was used in just above 20% of the passages by the riders of other bicycle types. Of the braking events in the chicane, 68% were executed by the four cargo bike riders and the rider of the longtail.

In addition, almost ten percent of the participants reported exerting some extra effort before reaching the soft mat, one third said they did so on the soft mat, and just above twenty percent did both. One third did not report any specific tactical action. Half of the participants reported standing up on the rumble mat, which was observed in almost 20% of the cases. Apart from that, two participants reported setting a foot down or dismounting in the chicane. According to the observational data, this occurred only during the first treatment passage for both participants and was related to not understanding how to navigate the chicane.

3.3 Visual information sampling

The absolute average number of glances from the first to the last glance on the intervention area varied from 13.3 to 27.5, with most glances at the MeBeSafe-intervention (23.6), respectively for trial Tr1 (21.6). During baseline, the percentage of glances on the intervention areas was smaller (34.1%) than during treatment (72.4–83.4%). Figure 5 shows that during treatment the percentage of glances on the intervention area (blue bars) decreases with increasing familiarity for all interventions but the chicane, for which the percentage increases. Thus, except for the chicane, the absolute number of glances to other areas than the intervention is almost the same for all treatment trials, but decreases with familiarity for the chicane. In comparison to the baseline, substantially fewer glances are directed at other areas in any of the treatment cases. The decrease of the absolute number of glances over time (red line) for treatments reflects the increase in speed over treatment trials.

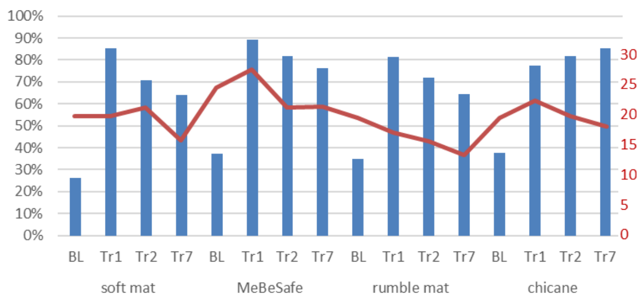

Figure 5 The blue bars indicate the average percentage of glances on the intervention area per intervention and trial (y-axis on left side). The red line indicates the average absolute number of glances from the first to the last glance on the intervention (y-axis on right side).

Across interventions, Figure 6 (left) shows that glances on the track in front of the intervention, that is, in the near field, are common in all trial conditions. Glances beyond the intervention and to the left of the intervention are more common during baseline than when the interventions are present, while glances to the right of the intervention are rare in general. Across all

Table 3 Behavioural adaptation strategies according to observations and self-reports

		Soft mat	MeBeSafe	Rumble mat	Chicane	F(3, 950)
Coasting before	Observed	14.3%	15.3%	80.5%	72.1%	199.1
	Reported	9.7%	16.1%	29.0%	48.4%	
Coasting on	Observed	8.2%	15.3%	73.9%	81.5%	255.2
	Reported	16.1%	16.1%	48.4%	51.6%	
Braking before	Observed	0.0%	0.4%	17.8%	3.0%	37.9
	Reported	6.5%	9.7%	41.9%	58.1%	
Braking on	Observed	0.0%	0.4%	7.1%	8.2%	12.2
	Reported	0.0%	0.0%	6.5%	3.2%	

Observed: percentage of occurrence of the behaviour across all treatment trials for all participants
Reported: percentage of participants who reported having employed the strategy when asked after the data collection
F-values: comparison between the interventions

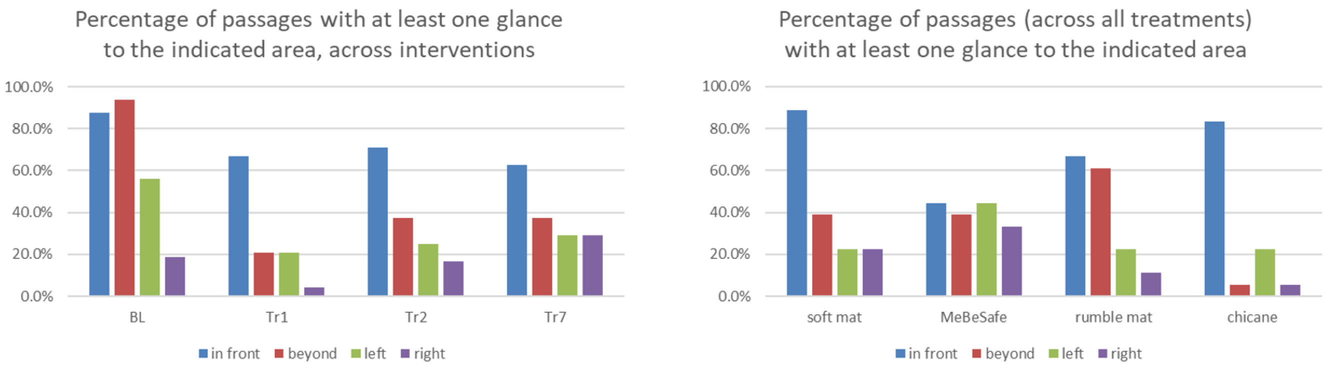

Figure 6 Percentage of passages during which at least one glance in the specified directions occurred: comparison between the trials (left) and between the interventions (right)

analysed treatment trials glances beyond the chicane are less common than beyond the other interventions (Figure 6, right).

3.4 Verbal comments

Around a quarter of the participants provided verbal comments on the interventions while cycling, although not all interventions were commented equally often. All comments during the first and last treatment ride were transcribed.

The soft mat was unanimously described as increasing resistance, which was also felt by pedelec riders. One person with a cargo bike commented that it was hard to predict what the effect would be, but as the bike had three wheels, that was not a worry. In the last treatment ride, one person commented that the mat did not feel like an obstacle anymore, and another person called it 'boring'.

The MeBeSafe-intervention was generally not seen as being an obstacle. Only one person mentioned that the markings were getting narrower and narrower, apart from that only the slight bumpiness was mentioned, which was a result of the thickness of the marking material used. One person mentioned that the paint applied in a curve would be scary, as it can get slippery. In the last treatment ride, only few comments were made, all in agreement that the intervention had no effect on the ride.

The rumble mat was generally described as rough. One person with a cargo bike reflected that sleeping children in the basket of the bike would certainly wake up on this intervention. Another person was at first worried about sharp edges, but was relieved that the rumble strips were not of metal. Another person concluded that it was best to stand up on the pedals, and an additional comment was that here one would definitely want to slow down. In the last treatment ride, people still commented that it was uncomfortable to ride over at high speed (even though they did anyway), and that they had to hold on to objects kept in the bicycle basket, as they would otherwise risk to jump out.

The chicane received the most diverging comments in the first and last treatment ride. The overall notion in the first treatment ride was that it was difficult to understand where to cycle and that it looked like an impermeable wall under approach. People with cargo bikes commented that they had to slow down a lot to get through. In the last treatment ride, people mentioned that in this case it made a lot of difference to have ridden there a few times, and that once you knew it, it was easy enough to deal with, given there was no other traffic going through.

3.5 Acceptance per intervention

Most interventions were not rated by the cyclists as reducing speed well in a sustainable fashion, with the highest ranks for the soft mat, followed by the chicane (Figure 7). The MeBeSafe-stripes, closely followed by the soft mat, were experienced as the most comfortable, with the rumble mat receiving the lowest rank. The chicane was ranked as the most dangerous intervention. Overall, the participants preferred the soft mat as a speed-reducing intervention, followed by the MeBeSafe-stripes.

4 Discussion

None of the interventions reduced absolute cycling speed sustainably. All interventions included in this study had similar temporary effects on cycling speed. The mean speed was reduced in the first encounter, but this effect was short-lived, with mean speeds returning to approximately baseline values after one or two encounters. Here, the quick return to baseline speeds may be exaggerated compared to a real-traffic situation, as the riders repeated the trials within minutes from the previous trial, such that memory was fresh. Also, the simplicity of the surroundings and the absence of an actual work zone may have contributed to this effect. While it is recommended to investigate the progression over time in a realistic situation, it is likely that the first encounter cannot be taken as representative for the following encounters. This makes it hard to draw conclusions from an observational study in a real-traffic situation, like the earlier evaluation of the MeBeSafe intervention (Kovaceva et al., 2022), as the previous experience of a passing cyclist is not known. In a real situation where people who are familiar with the conditions and people who encounter the situation for the first time likely are mixed, the novelty effect will apply only to some people and therefore it will not lead to a uniform speed reduction.

In a work zone, where the availability of space can be limited, it is expected to be safer if cycling speeds are homogeneous and not too high. A very low speed can even be dangerous, as it can compromise stability (Kooijman et al., 2009; Schwab et al., 2012), which requires more lateral space for balancing and increases the risk of falls. However, the four tested interventions did not equalise speeds compared to baseline. The initial speed did not affect the rate of reduction, meaning especially that cyclists who rode at a slower pace in baseline reduced their speed equally much as the fast cyclists. Thus, the speed variance in the areas of the interventions did not change. Speed reductions to below 10 km/h affected mostly cargo bike and comfort bike riders. At least for cargo bikes with three wheels, this does not hamper stability, but given the dimensions of a cargo bike, it is likely to affect the speed of following cyclists, as possibilities to pass the cargo bike may be slim. For the comfort bike riders, it appears that older riders are more likely to end up at very low speeds, which is not desirable, as older cyclists can be especially at risk of losing their balance and falling when the speed is low (Twisk et al., 2017).

In the present setup, the interventions drew a large share of the glances in the treatment trials. This also affected to which extent the areas around the intervention were monitored. In baseline, participants frequently checked the wider surroundings, notably they looked far ahead at least once for almost every passage. This changed markedly in the treatment trials. Especially for the first encounter (Tr1), most glances were directed at the intervention, and it was unlikely that the participants sampled any visual information from beyond the intervention. For the following treatment passages the percentage of glances on the intervention decreased for all interventions but the chicane. Presumably this is due to the decreasing novelty effect. However, to navigate the chicane at speed, it probably requires intensive visual sampling, such that the surroundings are sampled less not only on the first encounter but also over time. If one intention with speed-reducing interventions is to help cyclists gain time to evaluate the upcoming situation, then the results cast doubt on the effectiveness of the interventions included in this study, and particularly the chicane. Here, the surroundings were rather uniform and uninteresting, which can be a partial explanation for the high visual attraction of the interventions. Still, the divergent result for the chicane indicates that interventions that demand

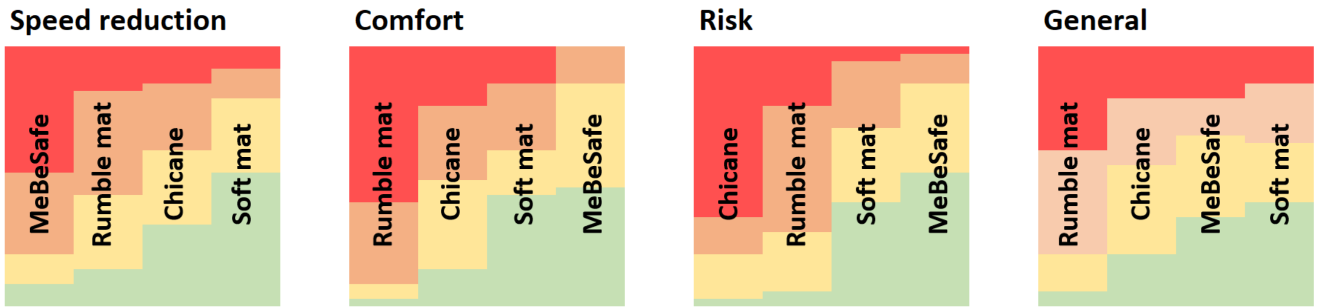

Figure 7 Subjective rankings for how well the interventions reduced speed sustainably, how comfortable they were, how risky they appeared, followed by a general rating (from green to red: Rank 1 to Rank 4)

visual sampling for manoeuvring can capture attention rather than directing it to the critical situation. It still needs to be investigated in real traffic whether enough information from critical areas is sampled.

The cyclists' perception of the different interventions can play a role in how effective they are in the long run, as people could devise strategies to avoid the interventions or treat them in unintended ways. The soft mat was generally perceived positively, not only for comfort and perceived risk, but also for its speed reducing effect. Spontaneous comments while cycling indicated that the extra effort required was experienced as a slight disturbance. The visual effect of the MeBeSafe intervention was commented upon by one person only, otherwise cyclists mostly noted the slight vibration effect due to the thickness of the stripes. So, while the intervention was liked for not being a disturbance, its speed reducing effect was questioned. The rumble mat was perceived as the most uncomfortable of all interventions and already in the study provoked avoidance mechanisms, with one person trying to jump over it. The chicane was associated with the greatest risk, and especially during the first encounter there was confusion about how to approach it. This was also reflected in the spontaneous comments that it makes a big difference to have seen the setup once. The feeling of being an obstruction with a cargo bike was conveyed.

While the measured speed changed in a similar way for all four interventions, the participants behaved differently in other aspects than speed adaptation—effects on attention were different, and the subjective perception varied between participants. In the present study situation, with no real hazards in the environment, there was no obvious reason for the cyclists to decrease their speed except as a result of the intervention, so the effects observed here can likely be ascribed to the intervention only. Based on this, it can be speculated how the interventions could work on site in real traffic. It must be noted that the speed reducing effect is not the main purpose of the interventions, but rather to increase the safety and security of cyclists and road workers. Hence, a speed-reducing intervention that could increase the risk of injuries, a crash or other disruptions that are hard to predict for others could not be considered effective, although having a speed reducing effect.

For the soft mat, many participants reported exerting extra effort, which reduced or cancelled out the speed reduction. This indicates that cyclists are unwilling to lose momentum and rather put in some more effort at least briefly to maintain their desired speed (Fajans & Curry, 2001; Castro et al., 2022). The longer the mat, the more likely it is that it will lead to a speed reduction eventually. Once the novelty effect is overcome, a potentially remaining speed reduction achieved by the required additional power is likely to remain over time. Stronger cyclists will be affected less and later than weaker cyclists, who are also likely to have a lower initial speed. E-bikes are a special case in that the electric assistance may effectively counteract the increased demand on effort, and the share of e-bike users is on the rise. Nevertheless, of the interventions tested in this study the soft mat can be considered the most promising intervention for reducing the speed of cyclists without impaired comfort or increased crash risk. In a real work zone situation, it is possible that the increased rolling resistance of the soft mat could be an effective and relatively safe way to raise cyclists' awareness of an oncoming situation where a reduced speed is recommended.

The intended optical illusion effect of the MeBeSafe-intervention should work equally on riders of e-bikes and conventional bikes. While the literature reports on cases where this type of intervention had some effect (Denton, 1980; Kovaceva et al., 2022), even though not confirmed here except for the novelty effect, there may be practical difficulties in implementing it in the context of a work zone. The visual effect is presumably reduced in a cluttered environment and when the lateral space is limited. As the effect is visual, the intervention needs to be seen, which can be hampered by grit or dirt from the road work, in darkness and for higher traffic densities. Also, there is a risk of decreased friction if the intervention is implemented with road markings (Niska et al., 2014a).

The rumble mat is meant to achieve a speed reduction by providing an unpleasant vibration sensation, and not surprisingly it received the lowest ranking for perceived comfort. Wider tyres and a lower tyre pressure (Olieman et al., 2012), suspension (Gadsby & Watkins, 2020) and the bicycle geometry (Gao et al., 2018) can affect the degree of unpleasantness. A lower speed does not necessarily increase the rider's experienced comfort, but can prevent adverse consequences, such as personal belongings jumping out of a basket. Objects in baskets jumping out or being rattled around, or children waking up can not only be a nuisance, but may also cause cyclists to stop and pick up the fallen objects, rearrange the load, or take care of the children, which could lead to incidents with other cyclists in a busy situation. Notably, the rumble mat was the only intervention that consistently led to at least ten per cent of passages occurring at a speed below 10 km/h, which is potentially unstable for two-wheelers and could lead to falls. The various compensatory strategies employed by the participants, like standing up, holding on to their belongings, or even attempting to jump over the length of the mat, testify not only to the unpleasantness of the intervention, but could also indicate that other cyclists' behaviour could be difficult to predict, which increases the probability of incidents and might entail that cyclists will look for alternative and potentially unintended routes.

The chicane differed from the other interventions in that it limited the lateral space and forced the participants out of a straight trajectory. For some participants the first encounter was qualitatively different in that they had to figure out how to get through, which could lead to unpredictable behaviour in a real-world setting. Even though this was then known in the following passages, the chicane still required a high portion of glances such that it could be navigated at the desired speed. This means that less visual capacity can be devoted to what is going on around it, such as oncoming traffic. The physical barriers on the sides could pose a risk for wider bicycles like cargo bikes or mountain bikes with wide handlebars, causing falls or getting stuck with a part of the bike.

The differences between the reported and observed instances of braking, coasting and other interventions can partially be affected by some difficulty in recognising whether a person had coasted or also braked. However, participants could change their strategy over time, and the reported behaviour may be the one that had left the strongest impression in their encounter with the intervention—probably in the first test trial. For example, braking was very common upon the first encounter with the chicane, but less so in later trials.

The four interventions aimed at achieving speed reduction with different means—through increasing the necessary power, a visual effect that should induce an unconscious speed reduction, by discomfort, and by a deflection of the trajectory in combination with a narrowing of the available space. Given the different approaches, it is surprising that the overall effect on speed was so similar. This could mean that the interventions created uncertainty and therefore increased complexity in the first encounter. Vlakveld et al. (2015) showed that cyclists reduce their speed in more complex situations. Here, however, the cyclists quickly got to know the interventions and their effects in an otherwise simple environment, so speeds increased again. In real work zones complexity may differ, depending on the size and type of the work zone. Physical features like limited space or a rough surface may in themselves lead to reduced speed, and a complex and unpredictable environment at the work zone may also have a speed reducing effect. To assess whether speed-reducing interventions have any additional sustainable effect, they would need to be tested in more realistic situations. Such a test should also assess their effect on the cyclists' attention, that is, whether their ability to monitor other traffic and relevant aspects of the work zone is hampered.

5 Limitations

The study was conducted on a test track where there was no other traffic nor any obstacles except for the tested interventions. Thus, the situation did not correspond to what would have been encountered in real traffic. The participants knew this and therefore may have focused less on the surroundings than they would have otherwise. This can also have affected their choice of speed, which may have been lower in real traffic. However, chances are high that the novelty effect and the following decline in the speed reducing effect would have persisted. It may also be the case that the decline in effect would have been slower in reality, as the participants were exposed to the interventions several times in much quicker succession than they realistically would have been in real traffic. The share of glances directed at the intervention may be higher than it would have been in reality, especially at reduced speed, as the amount of relevant targets present influences the glance distribution (Kircher & Ahlström, 2023, 2024).

The participants in the study brought their own bicycles and were recruited for diversity in demographic factors and bicycle types. The observed differences in speed could therefore be due to the bicycle type, the person riding the bicycle or a combination of both. The diversity of participants and bicycle types illustrates the breadth in the population of cyclists and was intended to catch issues that might occur for a subset of bicycles and riders only, but the small group sizes also make generalisations to certain bicycle and rider types difficult.

6 Conclusions

In line with earlier studies, this study concludes that it is difficult to reduce the speed of cyclists sustainably, or to reduce the variance in speed between cyclists. Some interventions might have an initial effect, probably mainly since cyclists slow down to gain time for figuring out how to handle the intervention, but as the cyclists get used to the interventions the speed reducing effect disappears. As the main purpose of speed-reducing interventions is to increase the safety of road users, an intervention that could increase crash risk should not be considered effective, although it may have a speed reducing effect. Interventions that require a large amount of visual capacity to be navigated will leave less time for the cyclist to monitor the surroundings, which is especially problematic in potentially unpredictable environments like work zones.

CRediT contribution statement

Katja Kircher: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Visualization, Writing—original draft, Writing—review & editing. **Anna Niska:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing—original draft, Writing—review & editing.

Declaration of competing interests

The authors have no interests to declare.

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Ethics statement

The study has been ethically approved by the Swedish Ethical Review Authority [2021–03508].

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