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Crash tests to evaluate the design of temporary traffic control devices for increased safety of cyclists at road works

A. Niska [a,*], J. Wenäll [b], J. Karlström [a]

[a] Department of Infrastructure Maintenance, Swedish National Road and Transport Research Institute VTI, SE-581 95 Linköping, Sweden
[b] Department of Crash Safety, Swedish National Road and Transport Research Institute VTI, SE-581 95 Linköping, Sweden

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ABSTRACT

In Sweden there is an on-going process to formulate a national standard regulating the design of temporary traffic control devices used on pedestrian and bicycle paths. This paper presents results from simulated single-bicycle crashes with the purpose to create an understanding of how different features of such devices affect the risk of injuries among cyclists. A Hybrid II 50th percentile crash test dummy was placed in the saddle of a bicycle and crash tests, usually at 25 km/h, were performed. Eleven different types of road equipment were included, and different crash angles were applied, in a total of over 50 crash tests. The road equipment represented temporary traffic control devices of various kind commonly used in Sweden, but also some specifically designed for cyclists. The tests were documented with several video cameras at different angles. Slow motion pictures were analyzed with focus on mechanisms during impact and the following motion of the bicycle and the dummy. Observations regarding "body parts" in contact with the road equipment were of particular interest highlighting design features of importance such as height, smoothness of surfaces and energy-absorbing capacity. The tests show that all bicycle crashes into road equipment can cause injuries and thus the use of work zone material on bicycle paths should be avoided, if possible. Safety barriers designated to prevent cyclists from falling into a shaft must be high enough to do so and be anchored and linked together correctly to prevent them from falling and creating dangerous situations. Temporary traffic control devices should be flexible or energy-absorbing to moderate the injury outcome of a potential bicycle crash. Fences should have a fine meshed net construction to prevent bicycle handlebars from getting stuck. All road equipment should be designed without sharp edges as they could cause injuries to cyclists passing or crashing into the equipment.

1. Introduction

Road works can cause dangerous situations for both road workers and road users. In urban areas, bicyclist and pedestrian safety in work zones is a particular concern and present guidelines do not seem to be taking cyclists and pedestrians into sufficient consideration (e.g. Bilton, 2012; Shaw et al, 2016; SWOW, 2010; Niska et al. 2014).

Bicycle crashes at road works lead not only to minor injuries, but also to severe injuries and even fatalities. In an earlier study analyzing traffic incidents recorded in the Swedish national registry of road traffic crashes STRADA (Swedish TRaffic Accident Data Acquisition), we identified 288 severely injured in bicycle crashes related to road works in the years 2007–2012 (Niska et al. 2014). Not all bicycle crashes, least of all those occurring in parks and suchlike, are entered in STRADA, which makes it hard to gauge the actual magnitude of the problem posed to cyclists by road or construction works. It is clear however that a major part (87%) of the bicycle crashes occurring at road works are single bicycle crashes (SBCs). In general SBCs represents 78 per cent of severely injured cyclists in Sweden (Niska and Eriksson 2013). The vast majority, 90 per cent, occur in urban areas, and the most common causes 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. 2014). When falling due to these causes or losing control of the bicycle, temporary traffic control devices put out to warn or protect the road users, can contribute to the injuries imposed to cyclists. They might also contribute to the crash risk of cyclists, for example falling when hitting road signs or getting stuck with handlebars in fences (Niska et al. 2014). It was concluded in the study that there is a need for increased knowledge on how to adapt work zone material and

* Corresponding author.
E-mail addresses: anna.niska@vti.se (A. Niska), jan.wenall@vti.se (J. Wenäll), jones.karlstrom@vti.se (J. Karlström).

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diversion routes for cyclists, both for increased mobility and to reduce the risk of injuries (Niska et al. 2014). The problems identified was acknowledge by road authorities and manufactures of temporary traffic control devices. Prototypes of products especially designed for cyclists was developed and a committee managed by the Swedish Institute for Standards (SIS) was initiated to look into the regulations regarding the design of these devices with the objective of formulating a Swedish Standard.

A question challenging the SIS-committee was how different physical parameters and design features of temporary traffic control devices affect the risk of injuries among cyclists. The height needed to prevent a cyclist from falling over a fence or a barrier was one of the main questions. In the present study, simulated single-bicycle crashes in the VTI crash safety laboratory has been performed to elaborate on height of barriers and fences and to give insights on other parameters and design features of importance, at different vehicle impact angles. Crash tests involving bicycles are rare although some conclusions can be drawn from earlier studies including other two-wheelers, where motorcycles seem to be the most frequent subject (e.g. Dobrovolny et al., 2019; Atahan et al., 2018; Capitani and Pellari, 2012). Dobrovolny et al (2019) have studied concrete barrier containment options for errant motorcycle riders, but with the main focus on highways and not urban areas where the traffic situation might differ. Crash tests including motorcycles are also different in the aspect of speed, weight and forces, center of mass and thus the crash test scenario is likely quite different from that involving cyclists in urban areas.

In the start-up phase, SIS preformed a search for any European (CE) or international (ISO) standard without finding any current standards for temporary traffic control devices for road works on or near cycle paths and footways. The knowledge gathered from this study should thus give insights for further research nationwide on this matter. Cyclist (and pedestrian) safety and mobility in work zones seems to be a significant concern in many countries around the world, and road authorities and agencies are struggling to find appropriate solutions (e.g. Bilton, 2012; Shaw et al, 2016; Attanayake, 2017).

Aim: When designing and constructing road equipment, the manufacturers need to know the dimensioning parameters such as height, vehicle impact angles, speed and forces. The aim of this study was to create an understanding of how height and other physical parameters and design features of temporary traffic control devices might affect the risk of injuries among cyclists.

2. Material and methods

Parameters that need to be taken into consideration in the design of temporary traffic control devices, such as falling height, angles, and forces, have been elaborated on through simulations of single-bicycle crashes in the indoor facility of the VTI crash safety laboratory. These simulations have been conducted using a Hybrid II 50th percentile crash test dummy placed in the saddle of a bicycle. The tests were documented with several video cameras at different angles, including high-speed video cameras, to be able to study the falling motion in detail.

2.1. Instruments, equipment, and test procedure

To be able to perform crash tests with bicycles, a specially designed rig was constructed. It consisted of a reinforced plywood board with a metal construction to keep the crash test dummy and the bicycle in position during the propulsion phase of the rig (Fig. 1). The crash test dummy was hereby supported by the construction behind its back - at the torso - and under the arms. The rig slid on rails and was driven by a cable system connected to two electric motors with the capacity to generate accelerations from 0 to 110 km/h at 47 m. The speed can be set with an accuracy of 0.1 km/h. During testing, the actual speed is measured using photocells to control the exact sampling rate. When the desired speed and position was reached the rig was stopped, but the bicycle with the crash test dummy continued to roll freely forward, at the right speed before the “crash”. The aim was to “deliver” the bicycle with the crash test dummy in a repeatable way at the same spot in each test. A partly similar construction and procedure have been used in earlier studies simulating single-bicycle crashes at VTI (Niska & Wenäll, 2019). Otherwise, the indoor facility of the crash safety laboratory is mainly used when crash testing child restraint systems[1].

Fig. 1. Hybrid II 50th percentile crash test dummy on a bicycle mounted on the rig specially constructed for the purpose of performing simulated single-bicycle crashes.

The road equipment to be tested was placed on wooden boards in front of the position where the rig was stopped. Different types of road equipment, mainly temporary traffic control devices, were included in the tests and several test scenarios were performed for each equipment (Table 1). The equipment included can be divided into three different categories: concrete barriers, fences, and other devices. Concrete barriers aim to prevent vehicles from entering the work zone, falling into a shaft, or hitting workers at the site, and are mainly designed to withstand impacts of cars and trucks. Fences are usually installed to discourage pedestrians and cyclist to enter a work zone. Other devices included were mainly signs used to guide or redirect the traffic.

The standard set up used in most of the tests included a “commuter bicycle” (Nishiki Pace for men) with closed frame, at 25 km/h. The chosen speed represents a high average cycling speed in Sweden (Eriksson et al, 2019) and is also the limit-speed for electric assistance of pedelecs. We also experienced it to be the maximum speed possible due to the practical limitations of the test equipment and space available. One additional test was performed at 15 km/h and seven tests using an open frame bicycle with a more up-right seating position, i.e. a lady’s bicycle (Marvil 3 Speed Solhaga Classic 3), at 20 km/h in one case and otherwise at 25 km/h. In our former study simulating single-bicycle crashes (Niska & Wenäll, 2019) we elaborated on different speeds and included three types of bicycles in our testing. In this study we chose one speed and one of the bicycles as standard, to limit the number of variables in the analysis. However, for curiosity reasons we added just a few tests with another bicycle and a different speed. Four different crash angles were applied in the tests: 8, 20, 45 and 90°. Since there is no standard procedure for crash testing road equipment with bicycles, we chose to follow the standard procedure (EN1317-2:2010) for crash testing safety barriers with motor vehicles including vehicle impact angles of 8 and 20°. The impact angles chosen were also meant to represent different crash scenarios with 8° representing cycling along and swirling into, for example, a fence, and 90° representing a straight

[1] https://www.vti.se/en/research-areas/crash-safety-testing/child-car-seats/

Table 1

The crash test scenarios performed for each road equipment included in the study. "C" indicates a test performed with the commuter bicycle and "L" a test with the lady's bicycle. The figure indicates the speed set in the test, e.g. 25 km/h.

Road equipment		Height (meter)	Crash angle			
Type	Product		Straight hit, 90°	45°	20°	8°
Concrete Barriers	GP Link without wooden board	0.87	L20			
	GP Link with wooden board	1.1	C25			
	GP Link with wooden board	1.4	C25			
	GP Link with wooden board	1.8	C25			
	REBLOC, Concrete barrier	0.74	C25	C25	C25	C25
	REBLOC with ATA bicycle net	2.1			C25	C25
	REBLOC with ATA bicycle net and fabric	2.1	C25	C25	C25	
	TA-barrier	1.1	C25 (two tests)	C25	C25	C25
	TA-barrier with Worxsafe Pedestrian/Bicycle Fence	1.65	C25	C25	C25, L25	C25
Fences	Ramudden crowd barrier	1.1	C25	C25	C25, L25	C25, L25
	Jonsered SafePass GC Barrier	1.4	C25	C25	L25, C25	C25
	Construction fence	2.0	C25	C25	C25, L25	C15, C25, L25
Signs and other devices	Flat traffic lane delineator with rubber base	1.0	C25			
	Foldable flat traffic lane delineator	0.95	C25			
	Concrete block	0.45	C25			
	Concrete block with signpost	0.45	C25			

hit into an obstacle. The 45-degree angle was added upon request from the SIS committee to illustrate a hit into, for example, a barrier placed in a curve. In total, the different angles chosen were considered to represent different possible crash scenarios (from along-side cycling to a straight hit) within reasonable limits with respect to the number of tests needed. In total, over 50 simulations of single-bicycle crashes were performed in this study.

The selection of road equipment included in the study aimed to comprise temporary traffic control devices commonly used at road works in Sweden but also to represent a variety in respect of design – mainly height. We also wanted to include products specifically designed for cyclists, some of which were only prototypes. Photos of the products included can be found in the result section: Ramudden steel barrier (Fig. 3, left picture), Jonsered SafePass GC Barrier (Fig. 5, right picture and Fig. 7, left picture), Construction fence (Fig. 4, left picture and Fig. 6), REBLOC (Fig. 2, REBLOC with ATA bicycle net and fabric (Fig. 4, right picture) TA-barrier (Fig. 3, right picture and Fig. 5, left picture), TA-barrier with Worxsafe Pedestrian/Bicycle Fence (Fig. 7, right picture), or in the Appendix. When used in work zones, a lot of the products are often linked together in longer constructions. To simulate this in our indoor-facility, single products had to be anchored with straps, particularly in the tests with smaller angles.

2.2. Method of analysis

Slow motion pictures were analyzed independently by three researchers focusing on the kinematics of the crash test dummy and the bicycle. At critical moments in each crash test scenario the video recordings were studied in detail, frame by frame from different angles, to determine the course of events in the crash. In the analysis, it was decided to focus on mechanisms during the first moment of impact, i.e. handlebars getting stuck in a fence, and the following motion of the bicycle and the crash test dummy. Observations regarding "body parts" in contact with the road equipment were of particular interest emphasizing construction and design features of importance such as height, smoothness of surfaces and energy-absorbing capacity. The most important aspect for barriers and fences was their ability to prevent an errant cyclist (the dummy) from flying over and therefore this outcome was emphasized in relation to height and crash angle. The possible injury outcome in each scenario was also assessed based on the video recordings. It was a qualitative method of analysis including a certain amount of subjectivity. However, the observations from each independent researcher were discussed and summarized into a conclusion for each test. In cases of discrepancy about details in the assessment between the researchers, the video recordings were studied all over again focusing on the details in question until an outcome was decided that could be agreed upon. This procedure improved the method with respect to repeatability, although being subjective to begin with.

3. Results

When studying the kinematics in the slow-motion pictures from the crash tests, several factors could be noticed regarding the design and dimensions of the road equipment included in the study. First of all, it can be concluded that the height of the barriers/fences is important (Table 2). Barriers lower than one meter, i.e. REBLOC and GP Link, are not high enough to prevent a cyclist from falling over and down into a shaft (Fig. 2). Barriers or fences equal to or higher than 1,4 m always stopped the crash test dummy from flying over, although in one case with a straight hit into the construction fence, the fence turned over (Table 2). For barriers or fences with the height of 1,1 m the outcome varied depending on crash angle, design, and probably also the speed of the bicycle (Fig. 3). A rise in approach angle were related to a higher tendency for the dummy to fly over (Table 2). For example, placements preventing the risk of a straight crash into the equipment are preferable as crashes in smaller angles are more likely to result in less severe injuries. At lower heights and angles the dummy slid on top of the railings of the barriers/fences and often ended up hanging over the device (Table 2).

For barriers or fences equal to or higher than 1,4 m the crash dummy had an impact on the head, either into the fence/net or the upper railing. However on ATA:s REBLOC with a soft net and fabric the energy-absorbing properties made the impact less severe even though the upper railing potentially could cause a risk for a head injury for a taller

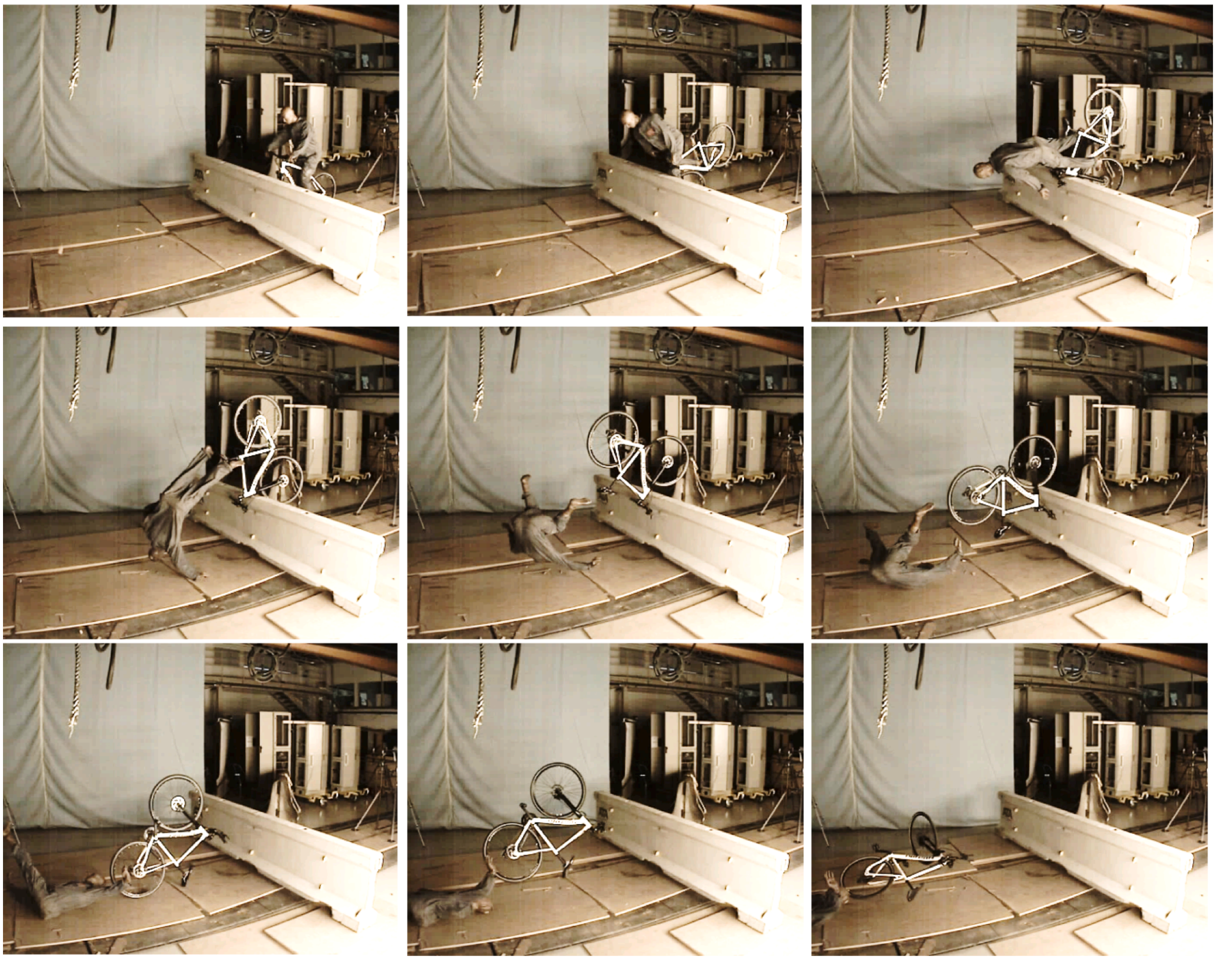

Fig. 2. A straight crash into a REBLOC Concrete barrier in 25 km/h, resulting in a somersault over the barrier for both “cyclist” (75 kg) and bicycle.

Fig. 3. The outcome of a 45-degree crash into Ramudden steel barrier (at the left) and a straight crash into a TA-barrier (at the right), both in 25 km/h.

Fig. 4. To the left the crash dummy hits the head at impact with the construction fence. To the right the crash dummy's head hits a soft net with fabric that absorbs the energy from the impact.

Fig. 5. A scenario with a straight crash into a single TA-barrier (at the left) and a Jonsered SafePass GC Barrier (at the right), both in 25 km/h.

rider or a different bicycle set up (Fig. 4).

It was also found that the anchoring of the barriers/fences is highly important for the outcome of a bicycle crash. A crash into a single barrier or an unattached fence could result in the product turning over. In one case, with a single TA-barrier, the head of the dummy was hit by the upper railing as the barrier turned over in a straight crash with the bicycle (Fig. 5., left picture). Such a scenario would probably result in a fatal outcome - the weight of the TA-barrier is over 400 kg. The crash tests including fences showed that they often moved several meters, even when they had been anchored with straps (Fig. 5., right picture). This must be considered when placed at the edge of a shaft.

When crashing into a fence at smaller angles (8 and 20°) the design of the bicycle, in particular the handlebars, seems to be of importance. The commuter bicycle with straight handlebars was more prone to get stuck in the fences than the ladýs bicycle with handlebars being bent backwards (Table 2 and Fig. 6). When the straight handlebars on the commuter bicycle got stuck in the fences, the front wheel was turned 90° resulting in a sudden stop with the dummy flying over the handlebars and landing on its head (Fig. 6). The handlebars of the lady's bicycle slid along the fence for several meters, but eventually the handbrake got stuck in the fence and the dummy usually fell sideways from the bicycle with a first hit to the shoulder or hip.

Some of the products specifically designed for cyclists gave the desired effect by moderating the injury outcome. For example, the Jonsered SafePass GC Barrier with a fine meshed net constitution resulted in a lower tendency for handlebars to get stuck in the fence. The more flexible construction (in comparison with stiffer fences like the Ramudden steel barrier) also seemed to be somewhat less aggressive during impact. The Worxsafe Pedestrian/Bicycle fence mounted on the TA-barrier prevented the "cyclist" from flying over the barrier. However, the design of these fences was not optimal regarding some other aspects. In several of the crash scenarios the head, face and/or neck of the crash test dummy hit the non-flexible railings of the net, with a risk of severe injuries (Fig. 7). In other cases, "body parts" got stuck in the joint between the fences or slid along the upper railing of the fence or barrier (Fig. 8). This indicates that a smooth upper surface is advisable

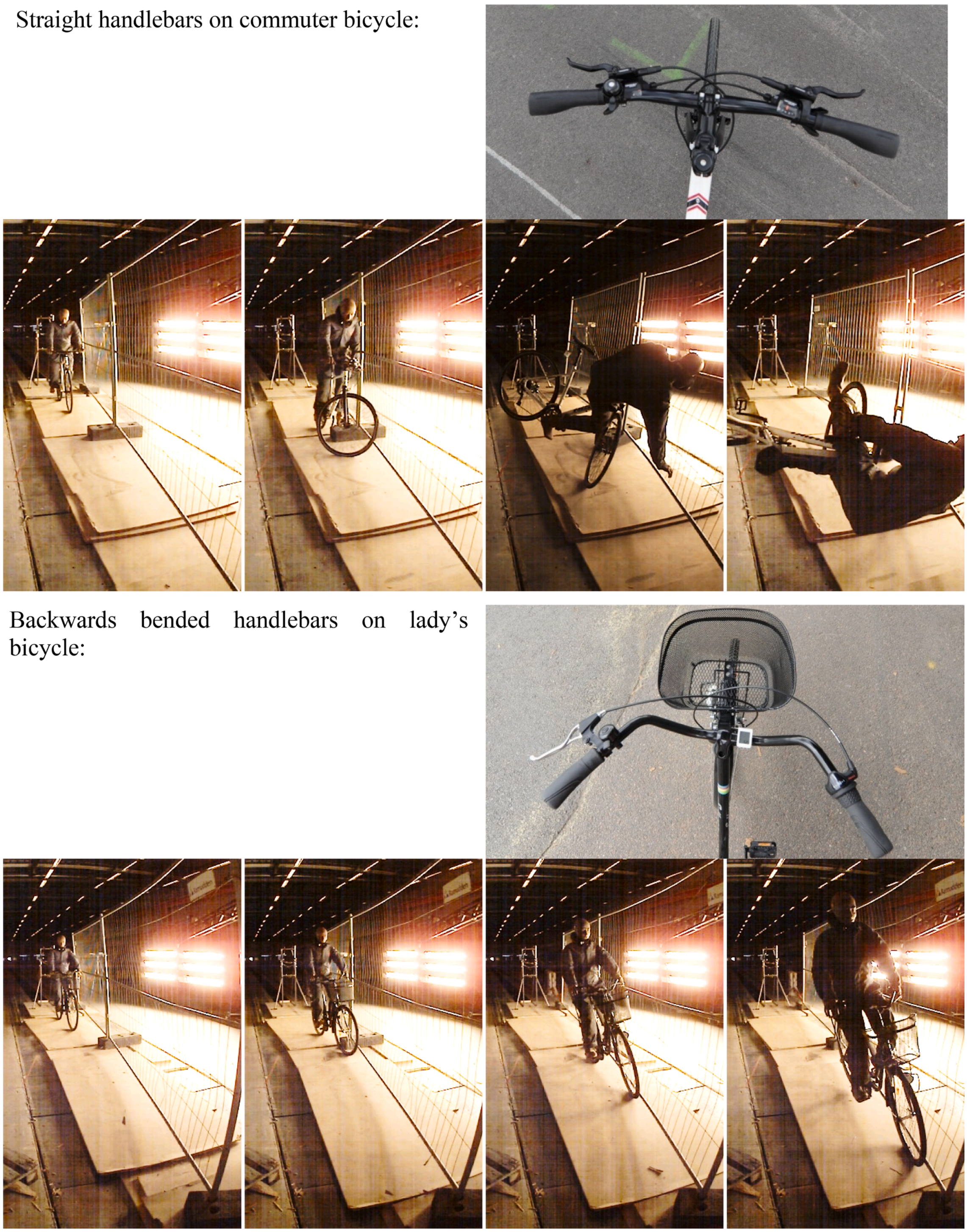

Fig. 6. An eight degree crash into a construction fence in 25 km/h with a commuter bicycle with straight handlebars in comparison with a lady's bicycle with backwards bended handlebars.

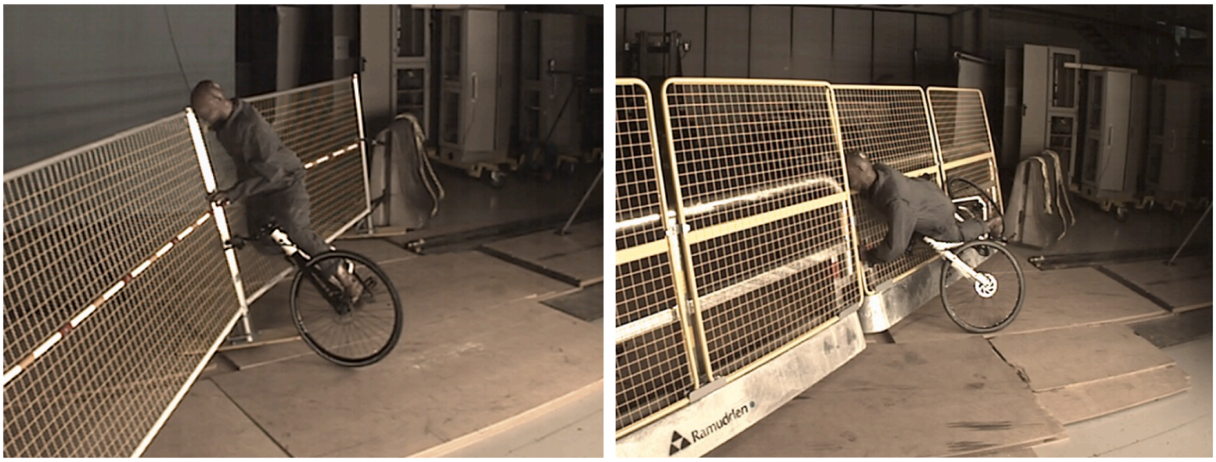

Fig. 7. Examples of cases when the head hit the railings of the fences.

Table 2
The results from the crash test scenarios performed for each road equipment included in the study

Road equipment		Height (meter)	Crash angle			
Type	Product		Straight hit, 90°	45°	20°	8°
Concrete Barriers	GP Link without wooden board	0.87	Flying over*			
	GP Link with wooden board	1.1	On top			
	GP Link with wooden board	1.4	Stopped			
	GP Link with wooden board	1.8	Stopped			
	REBLOC, Concrete barrier	0.74	Flying over	Flying over	On top	On top
	REBLOC with ATA bicycle net	2.1			Stopped	Stopped/SH
	REBLOC with ATA bicycle net and fabric	2.1	Stopped	Stopped	Stopped	
	TA-barrier, coupled	1.1	On top	On top	On top	On top
	TA-barrier, single	1.1	Turning over			
	TA-barrier with Worxsafe Pedestrian/ Bicycle Fence	1.65	Stopped	Stopped	Stopped; Stopped*	Stopped/SH
Fences	Ramudden crowd barrier	1.1	Turning over	Flying over	On top/SH; On top*	Stopped/SH; Stopped*
	Jonsered SafePass GC Barrier	1.4	Stopped (hit on top)	Stopped (hit on top)	Stopped*; On top	Stopped/SH
	Construction fence	2.0	Turning over	Stopped	Stopped/SH; Stopped*	Stopped/ SH**; Stopped/SH; Stopped*
Signs and other devices	Flat traffic lane delineator with rubber base	1.0	Running over			
	Foldable flat traffic lane delineator	0.95	Sudden stop			
	Concrete block	0.45	Flying over			
	Concrete block with signpost	0.45	Turning over			

Consecutive tests in the same test scenario are separated with a semicolon. “Stopped” means that the barrier/fence stopped the crash test dummy from flying over. “On top” means that the crash test dummy either slid along or landed and stayed on top of the barrier/fence. “Turning over” means that the equipment and the crash test dummy turned over in the crash. “SH” indicates that the handlebars got stuck in the fence/net resulting in a sudden stop. *lady’s bicycle, **speed: 15 km/h.

Fig. 8. Examples of “body parts” hitting the upper railing of the fences.

when designing road equipment, to moderate the injury outcome in a bicycle crash.

4. Discussion

From the crash test video recordings, it is obvious that the design of the road equipment is important for the outcome of a bicycle crash. Barriers designated to prevent cyclists from falling into a shaft must be high enough to do so. In the scenarios we have tested, 1.1 m seems to be sufficient in most cases, but not always, while barriers of 1.4 m were high enough. The minimum height needed is thus somewhere in between. The barriers should also be flexible, or rather energy-absorbing, to moderate the impact forces and hence the injury outcome. Fences should be designed (e.g. have a fine meshed net construction) to prevent bicycle handlebars from getting stuck in the fence, which could happen on a narrow bicycle path when a cyclist is avoiding conflicts with oncoming road users. All road equipment should be designed without sharp edges as they could cause injuries to cyclists passing or crashing into the equipment. Besides the design itself, there is also a potential in adjusting current guidelines and requirements regarding the placement of road equipment on bicycle paths. For example, placements preventing the risk of a straight crash into the equipment are preferable as crashes in smaller angles are more likely to result in less severe injuries.

As all bicycle crashes into road equipment can cause injuries, it is of outmost importance to take actions to prevent the crashes in the first place. Thorough planning can minimize the time cyclists are exposed to an accident risk at road works. New techniques to perform maintenance measures could also reduce the time and space needed to complete the work needed (Nicholls, 2013). Already in the design and the construction phase of a bicycle path the risk can be reduced – for example by avoiding putting sewage pipes under the bicycle path construction. If not necessary, the use of temporary traffic control devices on bicycle paths should be avoided, for example by using road markings instead to guide or redirect cyclists. Warning the cyclists of obstacles ahead must be done early enough to serve time to react. The conspicuity of the road equipment is important in this respect and can be improved by using fluorescent coloring, reflectors and/or lighting. In this case it should be recognized that bicycle lighting might not be sufficient to reach the desired effect of reflectors (Kircher & Niska, 2021). Led lighting etc. is therefore preferable, especially in darkness and at poor visibility conditions. Visibility and conspicuity of temporary traffic control devices for cyclists needs to be further studied.

In addition, measures to lower the speed of the cyclists passing a construction site might be effective. This is however difficult as speed reducing measures themselves can impose a risk to cyclists (Niska & Eriksson, 2013). However, the aim should be to create a diversion route for cyclists bypassing the work zone with the same quality as the bicycle path, if that is not possible, then lowering of the cyclist speed should be considered. Diversion routes and speed reducing measures for cyclists should be further studied. At lower speeds, cyclists have more time to brake or make evasive actions. Furthermore, the speed of the cyclist might influence the outcome of a possible crash situation. In the crash tests we performed, we did not elaborate enough with the bicycle speed to be able to draw conclusions regarding its effect on the outcome. However, physical laws establish that the force is related to the square of the velocity, and a higher crash force is more likely to cause severe injuries. In a numerical simulation of a motorcycle crash into a roadside barrier, Capitani and Pellari (2012) have indeed shown a quadratic dependence of impact severity, represented by injury indexes, on impact speed (and crash angel).

Crash tests including bicycles are scarce and when performed they usually simulate collisions with motor vehicles (Watson, 2010), and not single-bicycle crashes. No standard procedure is therefore available and a study like this is a matter of trial and error both when it comes to the method, procedure and analyses of the results. The long-time experience of the personnel at the VTI crash test laboratory performing crash test of various kind was crucial in this case. Crash tests involving motorcycles (e.g. Dobrovolny et al., 2019; Atahan et al., 2018; Capitani and Pellari, 2012) give some guidance with similarities being a two-wheeler, but with a major difference in crash test speed, weight and forces.

The test method used has its limitations and the results should therefore be considered as giving directions for further studies rather than providing decisive conclusions. First of all, the crash test dummy is developed for crash tests in cars and not for bicycle crash testing. It is therefore difficult to place in the saddle of a bicycle, and as concluded in our earlier study with simulated single-bicycle crashes (Niska & Wenäll, 2019), the method is sensitive to minor changes in dummy placement. However, the new rig constructed before the crash testing in this study was more stable than the one used previously, which made it possible to perform the crash tests more effectively. Even though most tests were performed at a speed of 25 km/h, the construction endured several crashes before it had to be repaired. Another limitation is the lack of sensor data. The HYB II dummy used is instrumented with an accelerometer in the head, and in our former bicycle crash study (Niska & Wenäll, 2019) we analyzed accelerometer data including HIC values. In the present study that was practically impossible to perform with the available equipment and the variety of the products tested. As a substitute we tried to collect accelerometer data with a Hövding collar (hovding.com) with the airbag inflation function disconnected. Unfortunately, it malfunctioned after just a few crash tests and thus we had to rely solely on the qualitative results from the video recordings. Repeated tests of each scenario could have improved the reliability of the results, but as crash tests are costly, we considered it more important for the aim of this study to be able to test as many different products as possible instead of performing repetitions of the same scenarios. Also when comparing with other studies (e.g. Capitani & Pellari, 2012; Atahan et al, 2017) one can conclude that it is common practice to perform only one single crash test of each scenario.

In the previous study (Niska & Wenäll, 2019) where we used another rig mounted on the sledge used for crash testing child restraint systems, the bicycle ran on the glossy painted concrete floor. In this study the bicycle ran on wooden boards instead. Neither of the options are optimal in respect of representing actual road surfaces, usually of asphalt. That influences, for example the level of friction and hence the tendency for the road equipment to slide on the surface. The wooden boards also moved due to impact, but our belief is that it did not influence the outcome in most cases. When we could see that it did, we repeated the test. The solution we chose made it possible to place the road equipment and perform the testing in the indoor facility. Another option would have been to do the testing in the outdoor facility of the VTI crash safety laboratory. That would have made the testing more sensitive to the weather conditions and a lot more expensive to conduct.

In a crash laboratory test, you need to take control of the uncertainties that influence the outcome of the test. This has the implementation that you chose a specific speed, a specific angle, specific installation methods, impact points etc. It has also the implications that you have to reject some of the factors that might be present in a real-world crash – like driver avoidance actions, cyclist equipment e.g. a helmet, influence from surroundings, soil and surface parameters, temperature, slippery road conditions etc. The important thing is to construct a test situation which is repeatable over time and at several locations, controlling all parameters that will influence the outcome. The bicycle and the crash test dummy used, the speed, the angle, the surface and the installation itself are all parameters that will affect the outcome. Another choice might give a different result. For a crash test, it is rare to find parameters that will include all possible future crashes. In most cases, the crash test is designed to reflect only one or a few common crash types. Equally important is to define the validation criteria. What is a good outcome and what is an unacceptable outcome? Once you can effectively define the difference between fail and success of a test, you can start defining a relevant test setup aiming at finding just that important difference in behavior. There will always be real crashes outside the settings of the test setup. However, despite the discrepancy from real world situations, the performed crash tests have generated important insights regarding the design and usage of road equipment in general and temporary traffic control devices in particular.

5. Conclusions

From the simulated bicycle crashes performed in this study, we can conclude the following:

- All bicycle crashes into road equipment can cause injuries and hence visibility, planning and road design are important to prevent the crashes to occur.
- If not necessary, the use of temporary traffic control devices on bicycle paths should be avoided.
- Barriers designated to prevent cyclists from falling into a shaft must be high enough to do so. Barriers of 1.1 m does not always seem to be sufficient while those of 1.4 m are high enough.
- Barriers must be anchored and linked together correctly to prevent them from falling and creating dangerous situations.
- Temporary traffic control devices should be flexible or energy-absorbing to moderate the injury outcome of a potential bicycle crash.
- Fences should have a design that prevents bicycle handlebars from getting stuck in the fence.
- When designing fences, the existing difference in the design of handlebars should be considered.
- All road equipment should be designed without sharp edges as they could cause injuries to cyclists passing or crashing into the equipment.

CRediT authorship contribution statement

J. Niska: Conceptualization, Project administration, Funding acquisition, Formal analysis, Writing – original draft, Writing – review & editing. **J. Wenäll:** Methodology, Validation, Investigation, Formal analysis, Writing – review & editing. **J. Karlström:** Formal analysis, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix: Photos of road equipment not included in the result section

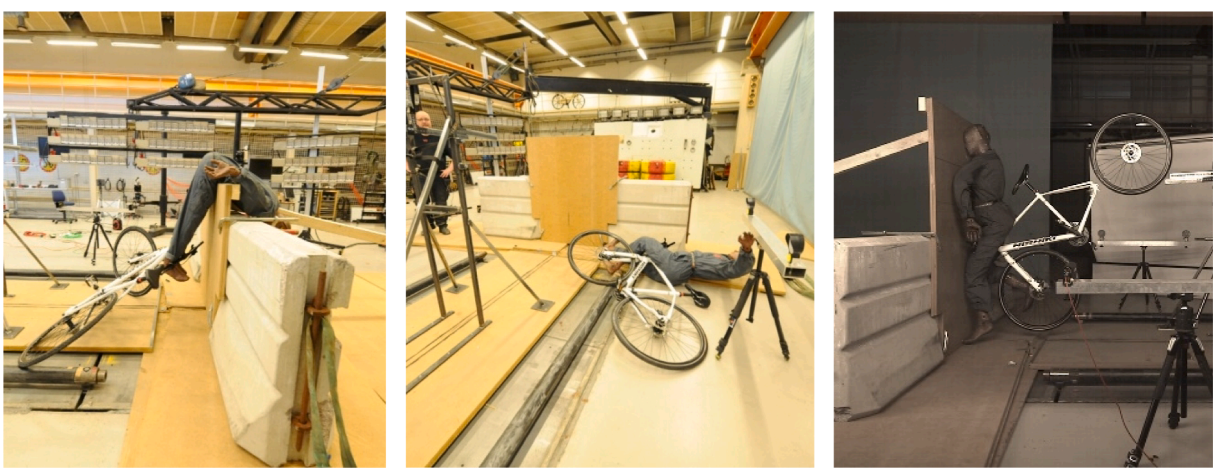

Fig. 9. Bicycle crashes into GP-link with wooden boards (from left to right): 1.1 meter, 1.4 meter and 1.8 meter.

Fig. 10. The outcome of a 20-degree crash into REBLOC Concrete barrier with ATA Bicycle net without the fabric.

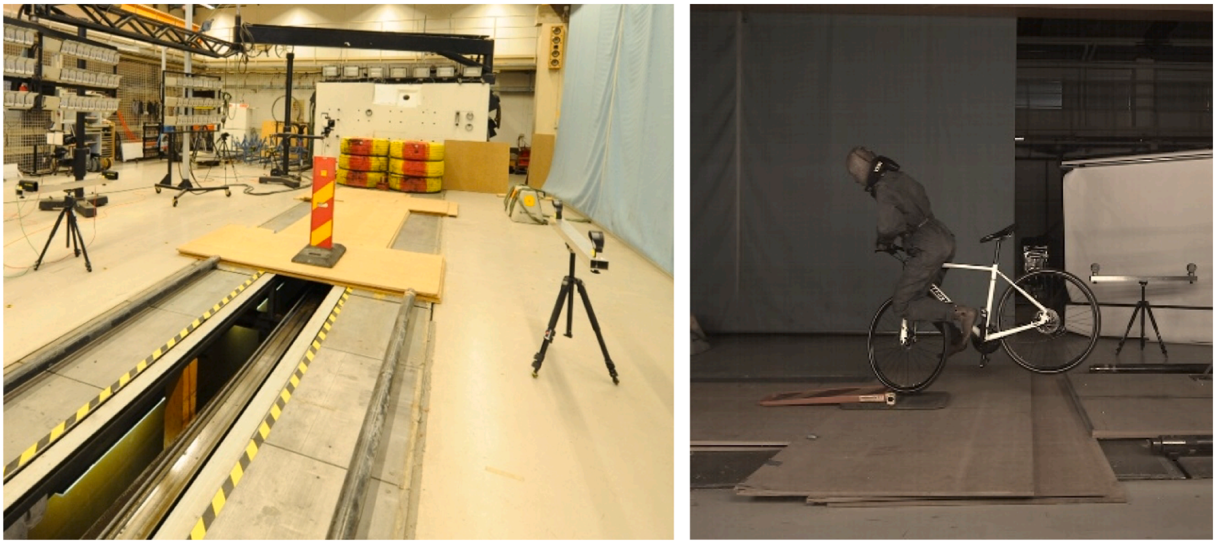

Fig. 11. The road sign with rubber base to the left and the foldable road sign to the right.

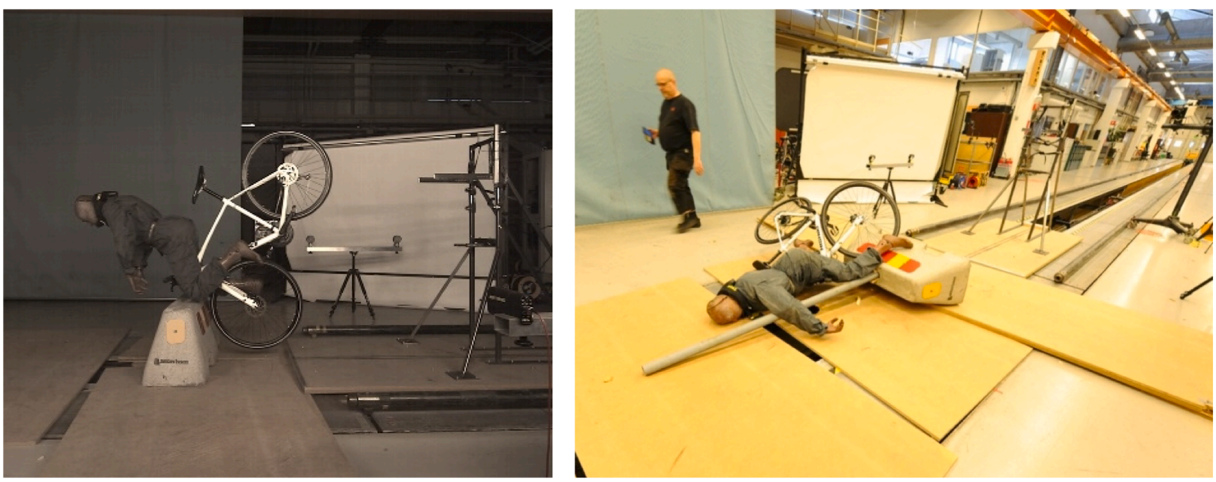

Fig. 12. Bicycle crash into a concrete block without and with a signpost.

Appendix A. Supplementary data

A video recording of a presentation at the ICSC 2020 (2021) including a selection of the crash tests can be found here: 38 'Crash tests to evaluate the design of temporary traffic control devices for ..' Anna Niska – YouTube. The video recordings from each crash tests to this article can be found online at https://doi.org/10.1016/j.aap.2021.106529.

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