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Delivery Report for

MeBeSafe

Measures for behaving safely in traffic

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Deliverable	D3.1
WP	WP3 Infrastructure measures
Task	Task 3.2 Cyclist Nudge

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Abstract

Intersection scenarios between cars and bicycles are regarded as among the most dangerous situations in traffic, and 8 out of 10 car-bike accidents have been found to occur there. This is due to both driver and cyclist behaviour, and both aspects are addressed within the MeBeSafe project. Car drivers have reported that cyclists simply appear in front of them out of nowhere, with no time to spot them. If both cyclists and car drivers adapt their speed ahead of an intersection, there will be more time to spot each other and react.

This report describes the development of a nudge to make cyclists reduce their speed and increase their attention to traffic. It also describes various ways to influence cyclists' trajectories.

The process has involved researching current literature and holding a focus group on traffic problems, coming up with various ideas, testing the ideas and changing them based on the results and finally evaluating the most promising ones, all based on results, opinions and requirements from various stakeholders. Both visual and haptic nudges have been tried.

Six different visual nudges to reduce speed were tried. Adaptive digital speed signs showed the greatest speed reduction, but is dependent on the signs being seen. Transverse stripes placed increasingly closer together as well as progressively narrowing down the road had an equal but somewhat smaller effect (12% greater decrease than baseline scenarios). However, these latter two are completely independent of being noticed, indicating that they act upon cyclists on a subconscious level. All visual nudges were accepted by cyclists. Six different haptic nudges to reduce speed were also tried. These included softer variants of speed bumps and rumble strips, soft asphalt, spongy asphalt and coarse asphalt and an upward slope. The speed reductions were very small, and appreciation very mixed. Cyclists clearly preferred visual nudges.

In addition, trajectory-altering nudges were tried. It was found that lines when merging two biking lanes together may help make collisions less likely.

A plan was set up for how to measure the nudges' effect over time, and nudges were selected based on formulated requirements.

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2	2018-12-03	Content added regarding visual study and haptic study in Gothenburg
3	2019-03-04	Elaboration of contents
4	2019-04-09	Update from TNO regarding haptic workshop in The Hague and input on tests of visual nudging trajectory.
5	2019-05-01	Input from SWOV regarding indoor tests of visual nudging trajectory and speed.
6	2019-07-30	Draft 1 sent to reviewer
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8	2019-08-15	Draft 2 including modifications and clarifications as requested sent to reviewer
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13	2020-10-09	Final version after release for revision by the EC

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Acronyms

Term	Explanation
DoW	Description of work
MeBeSafe	Measures for Behaving Safely in traffic
P	Participant

Glossary

Term	Explanation
Nudge	Any aspect of car interiors or of road infrastructure that will mindlessly influence an individual's choosing a certain behaviour.
Visual nudge	A nudge affecting the visual sense, such as stripes, signs, etc.
Haptic nudge	A nudge affecting the haptic sense, such as rumble strips and bumps.
Rumble strips	A road safety feature to alert drivers of potential danger, by causing a tactile vibration and audible rumbling transmitted through the wheels of the vehicle.
Road stripes	A road surface marking used on a road surface in order to provide guidance to road users.

Executive Summary

MeBeSafe is a project that aims to reduce the number of accidents and fatalities on European roads through the adoption of soft measures. It will mainly use nudging, that is to say non-intrusive adjustments of how choices are presented to people, to make it more attractive to make better decisions. The project targets car drivers, cyclists and truck drivers.

This deliverable concerns the development of cyclist nudges to help cyclists adapt their speed and attention ahead of dangerous intersections, and to help them follow the best trajectory from a safety and flow perspective.

A literature study was conducted, and no previous nudges were found that targeted cyclist speed or attention. Shake-inducing layers of white paint, so-called rumble strips, have been excessively used on cyclists to reduce speed, but this is not appreciated and seems to have no effect. Several nudging measures have been tried on drivers with good success.

Focus groups were held with different types of road users to find which situations were regarded as most dangerous in traffic, and how they wanted to tackle them. Both cyclists and car drivers, as well as road users identifying in both categories, regarded intersections between cars and bikes as a major issue, and soft measures were the preferred way forward.

Ideation workshops was held to generate ideas for nudging cyclists visually, and illusions, physical alterations and projections were identified as potential candidates. Workshops for haptic nudges led to ideas for modifying surface roughness, softness, using wind resistance, dimensional modifications, dimensional speed storage, moving ground or on-bike solutions.

A number of visual nudges were tried in an iterative loop to check which had any effect. Lane narrowing, transverse stripes with progressively decreasing distance and

poles with progressively decreasing distance were found to be effective. Poles were removed for safety reasons. The other nudge types were elaborated on further to find variations, which were tested and modified. A digital speed sign was added, and in total six variations of three different types were tested on 93 cyclists in real-life scenarios. All nudges reduced speed much more ahead of intersections than in baseline scenarios and they were approved by the cyclists. The nudges had equal effect even if they were not actively noticed, and therefore seem to affect people on a subconscious level. All types of cyclists were affected. The fact that the nudges were not haptic (i.e. such as different types of rumble strips) was highly appreciated. However, only the transverse stripes seem not to reduce cyclist attention to other traffic.

Haptic nudges were developed in an iterative loop, and finally a rough surface, a spongy surface, a rubber surface, a soft bump and an upward slope (designed to reduce speed ahead of an intersection and give it back later) were designed and tested on real cyclists. Haptic nudges had much less effect on speed than did the visual nudges. They were less appreciated. Cyclists would reroute rather than be exposed to the haptic nudge.

A visual nudge to change trajectory was tested in the Netherlands, by putting a dashed centreline in the middle of a wide bike lane. This seemed to have no effect on cyclists' trajectory. One main reason seems to be that cyclists already kept to their sides. Another test was conducted to see if nudges could help prevent cyclists from running into obstacles in the street, as well as help two intersecting bike lanes merge. The latter proved successful, in that fewer dangerous interactions occurred.

A workshop was held where stakeholders relevant for the development of a nudge were identified, and their requirements for the nudge were formulated. The requirements were weighed against each other. Flat transverse stripes placed progressively closer to each other scored highest and is therefore the candidate for a longer field trial in Gothenburg, Sweden.

However, cycling is argued to differ considerably in Sweden and the Netherlands, in terms of volume of cyclists and bikes, types of bikes, and types of bike lanes, and so on. The decision was therefore to focus the field trial in the Netherlands on visually nudging cyclists' trajectory.

Contribution by each Partner

SAFER/ Chalmers University was the leader of Task 3.2 with overall responsibility for organising the work and for communication with partners involved in the task and with the core team etc. SAFER/ Chalmers University was responsible for running ideation workshops on visual and haptic nudges, a series of tests of principle designs of nudges in controlled and semi-controlled settings, and a final workshop analysing and assessing the outcome of different tests. SAFER/ Chalmers University has also provided the structure for the deliverable and was responsible for writing the main part of the deliverable, more specifically Chapters 1 to 8 and Chapters 11 and onwards.

TNO was responsible for the haptic ideation workshop that was held in The Hague and for input to the deliverable on this event. TNO was also involved in the concept test of altering cyclists' trajectory, summarised in Chapter 9. In addition, TNO participated in the workshop in which the outcome of different trials was assessed, and with a decision reached on which nudge(s) to implement in the field trials.

SWOV (Institute for Road Safety Research) provided input on the visual nudging trials performed in collaboration with TU Delft, described in Chapter 10. In addition, SWOV participated in the workshop in which the outcome of different trials was assessed, and with a decision reached on which nudge(s) to implement in the field trials.

The **Swedish Transport Administration** (STA) has participated in the work, by attending telephone meetings and taking part in workshops. STA has also been particularly involved in searching for and identifying different options for haptic nudges.

1 The MeBeSafe Project

In 2014, almost 26,000 people were killed and 300,000 seriously injured on EU roads. The major cause in most road accidents is regarded as inappropriate road user behaviour in relation to the risk posed by the situation. Road accident statistics identify several factors including lack of attention, excessive speed for the circumstances leading to loss of control and failure to spot hazards in time and impeded mental and/or physical condition due to, for example, to fatigue. Moreover, it has been found that 8 out of 10 car-bike accidents occur in intersection scenarios (Isaksson-Hellman &Werneke, 2016).

The aim of the MeBeSafe project is to develop, implement and validate solutions that direct road users (vehicle drivers and cyclists) towards safer behaviour in common traffic situations which carry an elevated risk, helping road users maintain grater safety margins. The project aims to change habitual traffic behaviour directly by using nudging, a concept adapted from behavioural economics that relates to subconsciously pushing humans in a desired direction without being prohibiting alternative choices of action. Predisposing humans to making a desired choice makes nudging measures less invasive and applicable early in a given chain of events that might lead to a critical/accident-prone situation. This is a major benefit. The project will also compare different ways of coaching and evaluate their effect on driver behaviour.

MeBeSafe is organised in a total of six work packages (WPs) (Figure 1-1).

- WP1 - **Integrated Framework** provides a theoretical framework combining theoretical behavioural change models with the concepts of nudging and coaching and identifies relevant factors to support to the design of the specific measures in WP2, WP3, and W4. This WP is completed and has been reported in D.1. Integrated Framework.

- WP2 - **In-vehicle nudging solutions** focuses on the design, development and preliminary tests of in-vehicle nudging solutions.
- WP3 - **Infrastructure measures** aims at developing and testing infrastructure nudging directed at drivers and cyclists respectively, thus increasing safe behaviour in specific situations and sections of roads/streets.
- WP4 - **Driver coaching** involves the development of driver coaching schemes, both on- and off-line, directed at professional as well as non-professional road users.
- In WP5 - **Field Evaluation** the in-vehicle, infrastructure, and coaching measures developed in WP2, WP3 and WP4 will be implemented and tested in actual traffic environments and their effects evaluated.
- Finally, WP6 **Project Management** is concerned with administering the project as well as coordinating communication and dissemination.

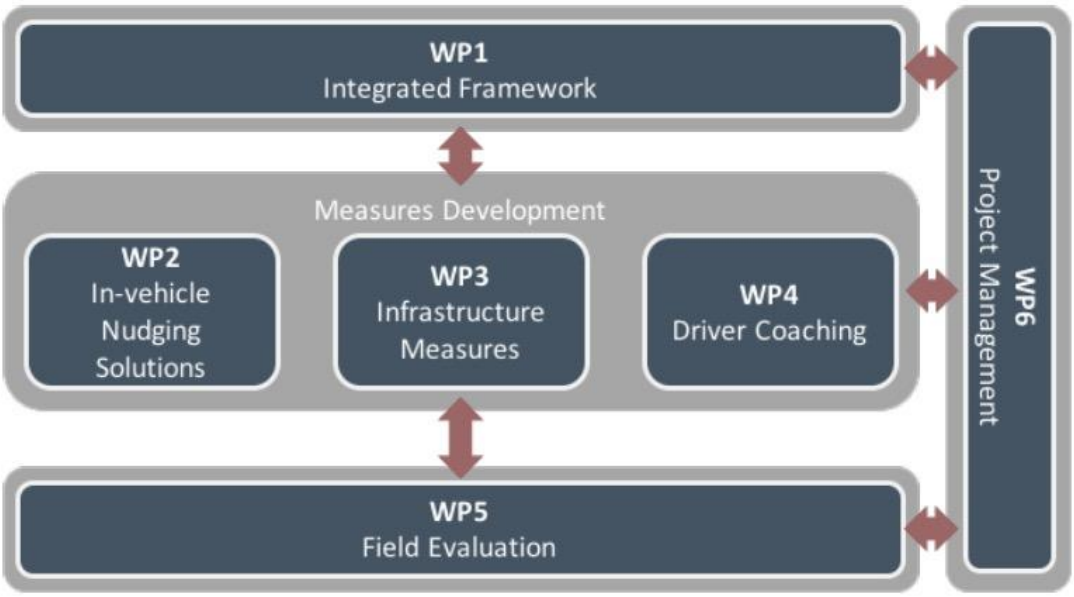

Figure 1-1. MeBeSafe is organised in six work packages.

2 Scope, Structure and Accomplishment

2.1 Scope of deliverable

The scope of deliverable D3.1 is to describe the work accomplished in Task 3.2., i.e. development of infrastructure measures to nudge cyclists to reduce their speed and choose a safer trajectory at critical intersections. More specifically the deliverable provides a description of an iterative design process including generating ideas, turning the ideas into concepts, validating them in tests involving users and assessing the outcome of the different tests, and the choice of final concepts. The work aims to provide input to the field trial that will be performed in WP5.

2.2 Structure of deliverable

The report is structured as follows:

- Chapter 1 introduces the aim and overall organisation of the MeBeSafe project.
- Chapter 2 provides an overview of the scope and structure of this deliverable, as well as a description of the main activities undertaken to accomplish the work.
- Chapter 3 summarises the findings of a complementary literature study of nudging in a traffic context.
- Chapter 4 gives an overview of focus groups with different types of road users to gain insights into which traffic problems they find most urgent, and which measures they want to use to mitigate them.
- Chapter 5 describes three ideation workshops, where ideas on how to nudge cyclists were generated, based on previous knowledge.
- Chapter 6 describes the first exploratory study to check which visual nudges could be used to affect cyclists.

- Chapter 7 describes the refinement of the visual cyclist nudges and tests involving 93 cyclists in real traffic.
- In Chapter 8 the development and testing of haptic nudges to affect cyclists is described.
- Chapter 9 provides insight into a test aiming to visually nudge cyclists to change their trajectory, by adding a centreline to a wide bike lane.
- Chapter 10 describes a second test to nudge cyclists visually, in this case by making it easier for intersecting bike lanes to merge.
- In Chapter 11, the process to evaluate the respective nudges is summarised.
- Chapter 12 provides a summary, discussion and conclusion.

2.3 Accomplishment of work in WP3.2

The work in Task 3.2. was accomplished as illustrated in Figure 2-1.

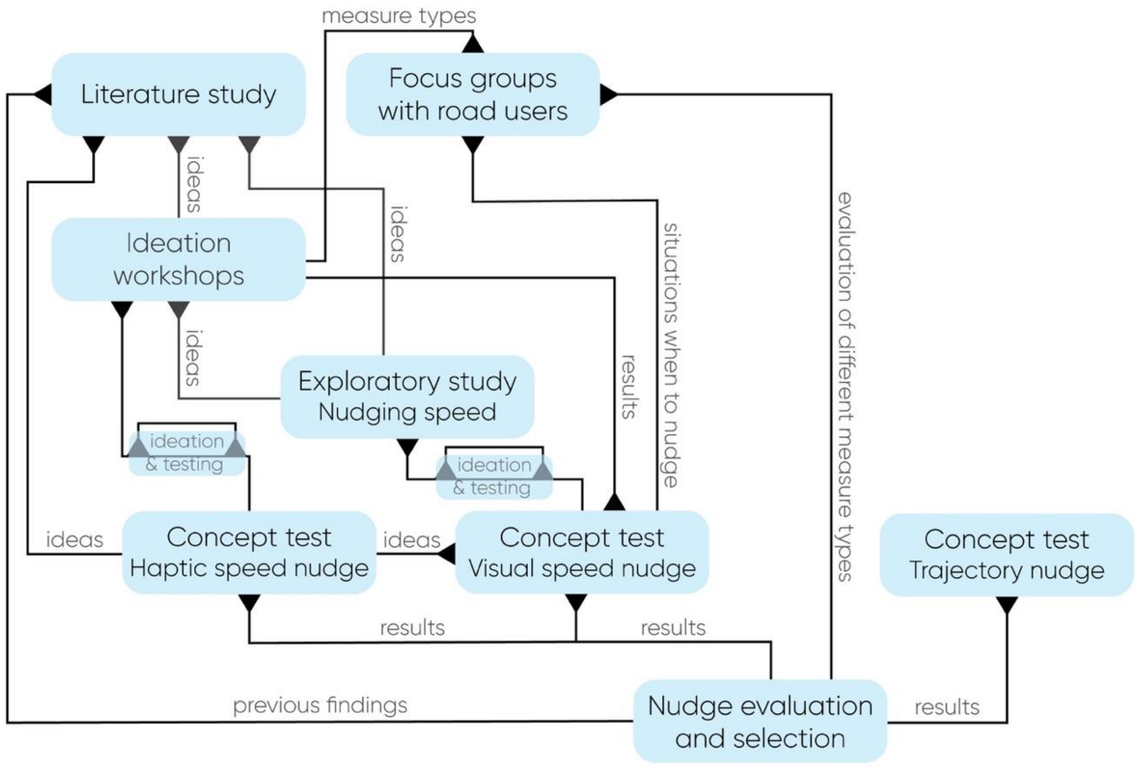

Figure 2-1. Overview of work in Task 3.2.

- A **literature study** was performed in order to gain insights into previous use and assessment of different types of nudges and to understand which nudges might be based on this information and be more or less feasible for MeBeSafe.
- **Focus groups**/workshops were held with different types of road users (car drivers, bicyclists, and road users who use both car and bicycle) to understand which problems they found most challenging in traffic and which types of measures they (would) prefer.
- **Ideation workshops** were held to iteratively generate ideas for visual and haptic nudges respectively that could be used in trying to affect cyclist speed and trajectory.

- Promising nudges from the ideation workshops were first tested in a series of iterative **exploratory use trials** to examine whether or not they appeared to have any effect or not on bicyclists' behaviours.
- The most promising nudges were then tried in **quasi-experimental tests** with real cyclists to ensure effect as well as cyclists' acceptance of the measures.
- Ideas for nudging cyclists haptically were tried on a more experimental scale, to see if there is any potential for implementing these types of measures.
- Ideas for nudging trajectories by steering cyclists away from obstacles were evaluated at an indoor facility in the Netherlands.
- Finally, a **workshop** was undertaken to assess the outcome of the respective trials and to reach consensus regarding which nudges to implement and test in the planned field trials.

3 Literature Study

This chapter summarises the results of a complementary literature study on nudging different categories of road users.

3.1 Aim

The literature study was undertaken in order to gain insights into previous trials with and effects of different types of nudges and to see which nudges might be feasible for the MeBeSafe project, based on this information.

3.2 Method

Existing literature was searched through different digital sources (incl. Google Scholar, Elsevier, Science Direct, the Chalmers Library Search, etc.). Terms used in the search included 'nudging', 'nudging bicyclists', 'bicyclist behaviour', 'nudging cars', 'speed reduction', 'illusion nudge' , 'transverse stripe', rumble stripes', etc. References including empirical evidence of any impact of different types of nudges were included.

3.3 Results

Infrastructure nudging has previously been applied although, as it seems, with a focus on car drivers. However, few scientific articles have been published on the topic. Most of the available information stems from newspaper reports; some of which include quantitative results and some which do not. Typically, these types of studies do not compare different versions of the same nudge. Each nudge is tried once in one configuration and the results are then compared without considering the impact of detailed design elements.

The goal of MeBeSafe as a whole is to increase traffic safety by developing and implementing nudges. For cyclist nudges, the decision was to try to affect speed. However, this is but one of the ways in which traffic safety can be increased. There are for instance a number of traffic rules and regulations that are broken due to misunderstandings or deliberately broken (more often by people driving cars than by people walking or biking, despite what public discussions might imply, see e.g. Vejdirektoratet, 2019). One possibility of nudges is to nudge people to behave according to these rules and regulations, e.g. make it clearer who is to give way in a certain situation or nudge towards a correct lane positioning. Considering the implications of the Deliverable D1.1 of the MeBeSafe project, If the breaking of traffic rules and regulations are intentional, a "type two nudge", targeting system 2 and hence people's reflective decision-making processes is recommended. if the breaking is unintentional, a "type one nudge", targeting system 1 and i.e. automatic processes would be feasible. However, there are indications that "type one nudges" may have only short-term effects. The most commonly discussed intervention strategies in literature are those that target system 2. Overalll though very limited information has been found on the topic of nudging traffic safety, other than trying to nudge car drivers to comply with speed limits (see section 3.3.1).

3.3.1 Nudging car drivers

A number of approaches have been used to nudge car drivers to reduce their speed, and many of these have been found to have an effect. It has also been found that if several different approaches are used together, they lose part of their effectiveness. This indicates that only one type of nudge should be tried at a time (Jamson, Pyne, and Carsten, 1999, cited in Katz, 2007).

An important distinction to make in relation to infrastructure nudging for cars (or any other vehicle), is what actually constitute a nudge and what is more of a "shove" (see French, 2011). There are many measures for slowing down cars that have been implemented that fall into the shove category, such as speed bumps and chicanes. However, as the focus in MeBeSafe has been nudging, research on these other types of measures have not been included in the literature review.

Rumble stripes have been used since at least the 1970s to slow down traffic and/or to make car drivers alert when they leave their lane. These measures could be argued to be of the “type two nudge” in that the car driver is made aware of the situation and has to make a conscious decision to steer or slow down, rather than unconsciously reacting to the nudge (which would be the case in a "type one nudge"). Although transverse rumble strips have proven to have some impact on car drivers' behaviour (e.g. Muhamad et al., 2019; Thompson et al. 1973; Zaidel et al., 1986), the same solution does not seem to work for cyclists. In cars, the purpose of the rumble stripes is to create noise and vibrations that alert the driver, but for bicycles the effect is that the whole bike shakes in a way that is perceived as dangerous (for more on rumble stripes for bicyclists, see secion 3.3.2 on nudging bicyclists).

Another measure that could be argued could be viewed as a nudge is the narrowing of lanes or streets to affect speed. This is an area that still is undergoing much research. While some researchers claim that narrower lanes result in lower speed, the data is still very inconclusive as it is difficult to factor out other differences between two scenarios with varying lane width (see e.g. Deller, 2013).

One of the most common infrastructure nudges is transverse stripes across the lane spaced progressively closer and closer to create an illusion of increased speed and thereby nudging the driver to reduce speed (Selinger & Whyte, 2011). Transverse stripes have been found to reduce car speeds, although more so for drivers not already familiar with the surroundings (Selinger & Whyte, 2011). This suggests that if the drivers are familiar with the environment, they will to a certain extent use previous knowledge of this environment and possible risks when deciding which speed to adopt. Another, often-cited, test in Chicago where transverse stripes were introduced found that accidents were reduced by 36% (Damani, 2017). A Chinese simulator study by Ding et al. (2013) found that raised thermoplastic transverse stripes (i.e. with a haptic effect) could reduce the speed of cars by 10 km/h, whereas longitudinal markings (i.e. not crossed by vehicles, therefore without haptic effect) reduced speed somewhat less.

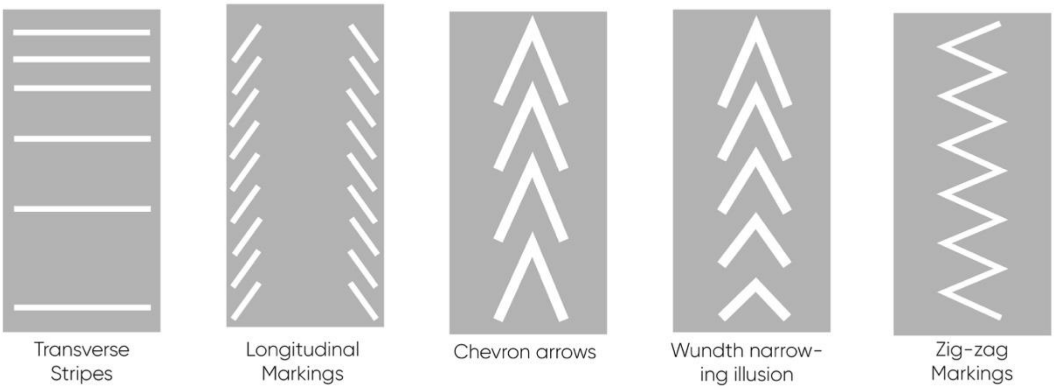

Figure 3-1. Some common lane mark nudges with effect on cars according to previous studies.

So-called **longitudinal markings** usually do not get closer and closer together, but are instead painted on the side of the road at an angle – to create an illusion of the road narrowing down and thus also that speed is increasing. Here, different angles of the same nudge have been tried and an angle of 15° has been found to be most effective in reducing speed (Wan, Du, Yan & Chen, 2017). A similar nudge is a Wundth narrowing illusion, consisting of arrows becoming increasingly pointed. These have been found to reduce speed, but less so than transverse stripes (Jamson, Pyne, and Carsten, 1999, cited in Katz, 2007).

Chevron arrows are instead painted in the middle of the road. These have been found to slow down cars, for instance a study where they were painted on exits from major roads found a speed decrease of 20 km/h (Drakopoulos & Vergou, 2001) and similar results were described by Hallmark et al. (2007).

Other illusions of increasing speed have been constructed by trees being planted beside the roads with progressively decreasing gaps between each tree. One such configuration, in Norfolk, England, was found to give an average speed reduction for cars of 2 mph (≈3.2 km/h) (Damani, 2017).

The creation of **illusions of three-dimensional objects** on the road is another approach to reduce speed. A zebra crossing, with the appearance of three-dimensional jersey barriers has been reported to eliminate accidents in a dangerous area in India (Olewitz, 2016). There has also been (claimed) attempts to paint illusions of children running after a ball in the middle of the street, cut-out silhouettes of people dying in car accidents and fake policemen (Moskvitch, 2014). However, the ffects of these (claimed) interventions are unclear.

Zigzag marks on a road are not intended as illusions, but rather aim at drawing attention in another way. Nevertheless, they have been found to reduce car speed, even after one year of usage (Damani, 2017).

A certain type of light embedded in the street close to a zebra crossing, flashing when pedestrians are about to cross, has also been found to be effective. Results indicate speed reductions of 2-5 km/h, with a doubled rate of giving way to pedestrians, reduced pedestrian-car conflicts and fewer pedestrians crossing the road outside the zebra crossing (Hakkert, Gitelman & Ben-Shabat, 2002).

Putting up **roadside posters** reminding drivers to keep the speed down is less intrusive but relies more on the conscious effort of the driver. Effects of such measures have also been found to be temporary, completely vanishing soon after they have been put up (van Schagen, Commandeur, Goldenbeld & Stipdonk, 2016). Words (such as "SLOW") painted on the road have not been found to reduce speed at all in an American study (Corkle, Giese & Marti, 2001). Dynamic speed signs, showing the speed of the driver, have been found to reduce speed by 1-10 mph (or 1.6-16 km/h) (Hallmark et al. (2007). Dynamic speed signs have been found to be more effective if the actual speed is provided in colour (e.g. red coloured numbers for high speed and green for low speed), and even more effective if complemented by a message (e.g. "SLOW" for high speeds and "THANK YOU" for low speeds) (Gehlert, Schultze & Schlag, 2012).

Making the lane more curved or colouring sections of the road are two other approaches found to reduce average car speed (e.g. Hallmark et al. (2007)). Another, but potentially dangerous measure is to reduce the driver's visibility at intersections. A study on cars found that speed could be reduced by up to 30% for a prolonged period of time if visibility was decreased. Drivers indicated that safety had not decreased, and no severe crashes were detected in the area during the test (Charlton, 2003).

Another potential nudge, relying on conscious attempts, was described by the Nudge blog in 2008. They cited a Japanese road fitted with bumps so that it appeared to play music when driving at a certain speed. This was described as potentially reducing speed or making drivers change lane, although no measurements are available from the actual road ("Singing in the lane", 2008).

3.3.2 Nudging bicyclists

There have been some attempts to use nudging to impact cyclists, but very few have been described in scientific literature. Only one previously published study was found to actually deal with cyclists and nudging. This Chinese study by Zhang and Wu (2013) found that cyclists could be nudged to wait at a red traffic light by putting up sunshield tents. The effect was noticeable on sunny days, but also in cloudy weather.

There are several videos posted online where lines are drawn to divert cyclists and change their paths (e.g. Urish, 2017). Although without scientific rigidity, these 'quick and dirty' trials appear to work. Many other interventions, referred to as nudges, have been used for cyclists around the world without reports on their effect. The city of Copenhagen has tried to put up **footrests** at light-controlled intersections to prevent cyclists from crossing, but it is uncertain how well it worked (Lusk, 2015). In Belgium trials have been conducted to use **digital signs** telling cyclists to speed up, slow down or maintain their current speed to reach the next intersection at green light. This may be more of a "hug" than a nudge however. No measurements have been made but a calculation found that such measures could theoretically increase traffic flow by up to 40% (Collado, 2017).

There have been some trials aimed at slowing down cyclists, but most of these have not been well-received. These can be described as more of a 'shove' than a nudge. For example, parks in London have tried **transverse rumble strips** to curb cyclist speeding, but cyclists are reported to take detours over the grass instead of crossing the strips (Lydall, 2017). The same effect was found on a bridge in Portland where rumble strips were set up close to a bus stop. Cyclists were found to stray into the vehicle lanes instead of crossing the 3.2 mm strips, despite these causing less of a rumble than at other places on the bridge (Maus, 2013). There is no clear consensus about what the effects are at places where detours are possible dubious (see e.g. Brown, 2015).

There is a lack of scientific evaluations of rumble strips designed to affect cyclists. One study, commissioned by public authorities in Sweden, found that rumble strips for cyclists had no effect on speed, but were considered as uncomfortable (Ljungblad, 2017). Other studies have examined more general effects of road surface structures. Vibrations have been found to be uncomfortable without affecting the ability to control the bicycle (Torbic, El-Gindy and Elefteriadou, 2003). Cyclists are found to prefer smooth pavements over rougher surfaces (Stinson and Bhat, 2005; Ayachi, Dorey and Guastavino, 2015). The correlation between perceived comfort and vibrations is so well established that several studies measuring the comfort of biking lanes use vibration as the only measurement (Bíl, Andrášik and Kubeček, 2015).

Rumble strips and their effect on cyclists have been researched where such strips are applied to the edges of roads to prevent cars inadvertently driving off the road and to help reduce speed (Godley, Triggs & Fildes, 2002; Hallmark et al., 2007). Cyclists biking on the side of such roads have been found to regard these strips as uncomfortable and dangerous. If there are gaps in the rumble strip edge, where the asphalt ceases to rumble, this affects the cyclists. Larger gaps have been found to increase cyclist speed and make cyclists venture onto the car lane from the edge outside the strips (O'Brien, Jackson, Vosburgh & Findley, 2015).

Another approach reducing cyclist speeding is the design of a **square roundabout** in the Netherlands (Crow Fietsberaad, 1999). However, a study found the sharp turns to be dangerous and that they reduced the traffic flow (van Minnen, 1999).

Other studies have explored which road characteristics tend to affect cyclists' speed. A study by Parkin and Rotheram (2018) found that cyclist speed increased downhill by 0.86 km/h for every 1 % gradient and decreased uphill by 1.44 km/h for every 1 % gradient. Separate bike lanes have in general been found to increase cyclist speed (Strauss & Miranda-Moreno, 2017), although an Italian study found the opposite (Bernardi & Rupi, 2015). In mixed traffic, the presence of heavy goods vehicles has been found to reduce bicycle speed, whereas the presence of cars, motorcycles and trucks does not (Bernardi & Rupi, 2015).

The presence of pedestrians in a bike lane has been found to reduce cycling speed by 10-27%, whereas the presence of other cyclists could give 5% lower speed compared to cycling in an empty lane (Bernardi & Rupi, 2015). Having pedestrians nearby could increase or decrease cyclist speed depending on their location (Kassim, Ismail & Woo, 2017).

Wider bike lanes have been found to result in higher cyclist speed (Strauss & Miranda-Moreno, 2017). For example, a study by Vansteenkiste et al. (2013) found that bicyclists reduce both their preferred speed and the speeds they regard as fast and slow respectively when the lane got narrower (40 cm vs 25 cm vs 10 cm), but that the effect was limited. Children were slower in narrower lanes, but showed otherwise similar behaviours to adults (Vansteenkiste, Cardon & Lenoir, 2015). A study of bikes in a virtual simulator, where users only pedalled and did not control the steering revealed higher speeds in narrower lanes, but this was believed to may be an effect of the virtual rendering (Gade, Gallagher, Maidan, Patel & Deutsch, 2016). Car drivers have instead been found to decrease their speed by 1-3 km/h with every foot in street width (Parsons Transportation Group, 2003).

Similarly, longer road segments give higher speed, especially if intersections are not equipped with signals (Strauss & Miranda-Moreno, 2017). When there are signalised intersections, cyclists are found to maintain higher speeds when approaching a green light, and even higher if the light turns yellow (Kassim, Ismail & Woo, 2017).

Cyclists in bike lanes have also been found to go faster on their way to and from work or school (Strauss & Miranda-Moreno, 2017). Younger drivers and males are likely to have higher speeds, and when the temperature is between 10-20°C, cyclist speed is at its highest (Strauss & Miranda-Moreno, 2017).

Studies of cycle safety connected to infrastructure are quite common and some important results are presented here. Cyclists have been found to be more predictable when there is a bike lane (Schramm & Rakotonirainy, 2009), although more than 40% may still choose the road (Bernardi & Rupi, 2015). Visual separation between cyclists and pedestrians has been found to make cyclists less attentive to intersections and zebra crossings (Mantuano, Bernardi & Rupi, 2017). A Chinese study found cyclists more likely to run red lights if pedestrians are doing the same (Ling & Wu, 2004).

Parkin and Rotheram (2018) found that cycling in the middle of a car lane is associated with being involved in more crashes, and that women, younger people, more experienced and high-intensity cyclists are more likely to do so. Wider car lanes and roads with less car traffic are connected to more severe cyclist injuries, as the cars generally drive at higher speed on such roads (Schramm & Rakotonirainy, 2009).

Lane keeping was found to be low when biking lanes were narrowed down (to 10 cm), but it was better if riders cycled at their preferred speed rather than at a slow speed (Vansteenkiste et al., 2013). Cyclists also look more at the lane when it gets narrower and divert their attention between a goal straight ahead and the lane itself. Objects on the sides are more often ignored (Vansteenkiste et al., 2013). It has also been found that cyclists pay more attention to a road of lower quality (Vansteenkiste, Zeuwts, Cardon, Philippaerts & Lenoir, 2014a).

When cyclists cross a road they are likely to encounter other traffic participant (e.g. passenger cars) approaching them. A Chinese study by Ling & Wu (2004) measured the lag, tha is the time between a cyclist reaching a certain point on the road and a car reaching the same point. It was found that the average lag was 2.93 seconds, with 0.5 being the minimum value. A larger gap was found necessary when cyclists turned left (in right-hand traffic).

When entering a curve, cyclists have been found to anticipate the curve and then use compensatory behaviour within the curve. Those travelling at higher speed try to use curvature matching whereas those with lower speed instead try to look where they are going and adjust accordingly (Vansteenkiste et al., 2014b).

3.4 Summary and Implications

The main implications of the literature study are that:

- There is some knowledge on the effects of nudging car drivers to behave in a certain way. Car drivers have been found to respond to nudges by visual illusions.
- There is limited experience of nudging cyclist behaviour. However, measures affecting the haptic sense (e.g. rumble strips) appear to receive negative reactions.
- Overall, only one type of nudge should be tried at a time to get the best result.

- o Many different factors influence the speed of cyclists and the design of any nudge must consider these carefully.

4 Focus Group Interviews/Workshops with Road Users

This chapter describes three focus group interviews/workshops that were held with different types of road users, to identify which situations were perceived as the most critical ones in traffic and which types of measures were preferred. The focus groups were all held in Gothenburg, Sweden. Focus Group 1 consisted of road users using bicycles and cars, Group 2 bicyclists only and finally Group 3 car users.

4.1 Aim

The aim of the focus group interviews/workshops was to identify which types of scenarios are considered most challenging for different types of road users and which types of solutions they find most appealing – nudging or harder measures.

4.2 Method

Potential participants were recruited in different ways. Several targeted advertisements were placed in social media to find persons in Gothenburg who were cyclists or car drivers and links were posted in relevant groups. In addition, one type of flyer was put on 1500 cars around the city, and another type on an equal number of bicycles. Those interested were directed to a survey, where they filled out their travel habits, how often they drove cars, rode bicycles or used public transport. Based on this information distinct groups could be formed. Those using both cars and bikes several times per week were invited to Group 1 (i.e. for the mixed workshop), those using bikes several times per week and who drove cars less than once a month or never were invited to Group 2, while those driving cars several times per week, and who never biked or who biked less than once per month were invited to Group 3.

The focus groups/workshops were run according to the same process. The participants were first asked to identify difficult traffic situations in general as well as difficult situations involving car–bike interactions and then the participants voted for the two situations they found most problematic. The two situations that received the most votes, of which one had to be a bike–car scenario, were chosen for further work. The participants then worked in groups to come up with solutions for how both car users and bike users could (be made to) change their behaviour. The prospect of nudging was compared to that of legal measures and prohibitions.

4.3 Results

4.3.1 Difficult traffic situations

The respective focus groups/workshops identified very different situations. The most problematic situations (including the specific focus on bike–car interactions) were grouped in categories, depending on who was exposed to the problem and who was believed to cause it. In cases where the responsibility was placed on several parties, these were treated as different situations.

The Cyclist Group identified problems for cyclists solely, the Motorist Group identified problems either for car drivers or pedestrians and the Mixed Group mainly identified problems for cyclists (Table 4-1).

In identifying who caused the problems, cyclists were focused mainly on cars, whereas both the Mixed Group and the Motorist Group identified an equal number of problems caused by bicyclists and cars. In the Mixed Group, an equal number of situations was found to be caused by pedestrians.

Type of problem proposed by road user category	Mixed Group	Cyclists	Motorists
Bike is problem for bike	2	1	
Infra problem for bike	6	9	
Pedestrian problem for bike	5	3	
Bike problem for pedestrians	1		2
Pedestrian problem for car			2
Infra problem for pedestrian			2
Car problem for bike	5	7	
Bike problem for car	3		10
Infra problem for car	1		12
Car problem for car			12
Bus problem for bike		1	
Bus problem for car			1
Others problem for car			1
General behaviour problems	4	3	1
Rules	1	7	2
Total	28	31	45
Problem for which type of road user	**Mixed Group**	**Cyclists**	**Motorists**
Problems for bike	18	21	0
Problems for car	4	0	38
Problems for pedestrians	1	0	4
Total	23	21	42

Road user assumed causing problem	Mixed Group	Cyclists	Motorists
Problems caused by bike	6	1	12
Problems caused by car	5	7	12
Problems caused by pedestrians	5	3	2
Total	**16**	**11**	**26**

Table 4-1. Type and number of problems identified in the focus groups/workshops.

Some situations were identified by more than one group (Table 4-2). The overlap was mainly between the Mixed Group and the Cyclist Group. However, the problem of bike lanes and car roads crossing each other was identified in all groups. This was therefore deemed to be a highly problematic issue.

	Mixed Group	Cyclists	Motorists
Cycling in bike lane when pedestrians walk there as well	x	x	
Cycling in bike lane when pedestrians cross the lane	x	x	
Cycling in mixed pedestrian-bike lanes	x	x	
Cycling in a roundabout with cars	x	x	
Cycling in bike lanes where car exits cross the lane	x	x	
General negative mood in traffic	x		x

Table 4-2. Problematic situations per road user group

4.3.2 Problems to tackle

The three groups chose different problems to tackle. The Mixed Group chose cycling through roundabouts and car exits crossing bike lanes. The Cycling Group also chose car exits crossing bike lanes and pedestrians walking on bike lanes. The Motorist Group tackled the opposite problem of bikes in pedestrian lanes or any type of cycling close to pedestrians, as well as getting cars and buses to stop at the right places so that intersections are not blocked. There is therefore some overlap in the situations.

4.3.3 Solutions to problems

The solutions proposed by the participants were categorised into different types of interventions, and according to whom they were aimed at. The different types were based on the nomenclature of hug/nudge/shove/smack (cf. French, 2011) but adapted to the characteristics of the respective proposals and the conclusions drawn from previous studies on nudges. The different categories were as follows, with explanations and examples as proposed in the focus group interviews.

- **Hugs**, i.e. giving an actual reward to an individual person for behaving well (e.g. reduced congestion charges for car drivers who let cyclists pass before them).
- **Soft nudges**, aiming to gently push a person into behaving in a way that is better mainly for society (e.g. colouring bike, pedestrian and car lanes in different colours and then colouring intersections in the colour of those with priority).
- **Rough nudges**, aiming to change behaviour in a similar way but using measures that are less subtle, (e.g. putting up cattle grids for cars crossing a bike lane).
- **Information**, such as neutrally informing the road user of the situation (e.g. putting up mirrors at crossings with an obstructed view).
- **Instructions**, presenting information to try and force a person into certain behaviour (e.g. signs for pedestrians telling them not to walk in bike lanes).
- **Clarifications**, such as changing the rules (e.g. making the rules clearer regarding when cyclists are allowed to bike against one-way traffic).
- **Prohibition**s, prohibiting certain behaviour (e.g. prohibiting all left turns).

- **Smacks**, in the form of actively punishing road users not adopting the correct behaviour (e.g. nails shooting up in the road when cars approach cyclists).

These types of interventions ranged from 'softer' to 'harder' in terms of how much individual freedom the interventions take away from the road users. The soft measures were regarded to be hugs, nudges, and information. Hard measures were regarded to be mandates and smacks. The categorisation in Table 4-3. gives an overview of the types of measures that were most appreciated by the different types of road users.

		Mixed Group	Cyclists	Motorists
'Soft' measures	At car drivers	5	6	3
	At bicyclists	8	4	8
	At car drivers and bicyclists	3	0	1
	At pedestrians	0	6	1
	At pedestrians and bicyclists	1	0	4
	At car drivers, pedestrians and bicyclists	0	2	0
	Total number of measures	***17***	***18***	***17***
		Mixed Group	**Cyclists**	**Motorists**
'Hard' measures	At car drivers	2	4	6
	At bicyclists	1	2	2
	At car drivers and bicyclists	3	0	0
	At pedestrians	1	0	0
	At pedestrians and bicyclists	0	0	0
	At car drivers, pedestrians and bicyclists	0	1	2
	Total number of measures	***7***	***7***	***10***

Table 4-3. Overview of suggested measures aimed at different types of road users.

All groups proposed more 'soft' than 'hard' measures. In addition, the Mixed Group suggested more soft than hard measures for both cars and bikes. The Cyclist Group came up with more soft measures for cyclists, car drivers and pedestrians. The Motorist Group proposed more hard than soft measures for cars and more soft measures for cyclists.

The suggestions for measures appeared to be linked to the participants' image of other road users and of themselves. The motorists declared for example that cyclists rarely followed traffic rules. They therefore assumed that 'carrots' would likely work better than 'sticks' when trying to change cyclists' behaviour. The cyclists confirmed this notion: they often did not follow rules when they found them unnecessary, such as stopping at red lights when the traffic is calm. As the cyclists saw themselves as not following rules when deemed unnecessary, and also believed car drivers break rules and do not stop for bicyclists when they should, their suggestions mainly involved hard measures at the same time as they believed that rules and regulations will not work. The motorists saw themselves as rule followers (with a few exceptions, such as minor speeding). Rules were believed to be the basis of a functioning road system and the motorists were therefore more inclined to suggest hard interventions for (other) motorists. However, many of these interventions involved changing the rules to clarify situations. Still, many drivers thought that soft measures were a good way to change behaviour in several cases.

Aggression and a bad mood in traffic were raised in all groups. Motorists claimed to meet cyclists who get angry with them every day in traffic (e.g. shaking their fist or giving the finger). The cyclists argued that many car drivers do not show any consideration for bicyclists, for example by parking or stopping their cars in bike lanes.

Both car drivers and cyclists found themselves to be unfairly treated by or in comparison with other groups of road users. Cyclists found car drivers to act inconsiderately and they mentioned bike lanes ending without a continuation and signs telling bicyclists to "watch out for cars", whereas cars are not told to watch out for cyclists. Car drivers mentioned cyclists having priority over cars without car drivers being able to spot the cyclists. The motorists generally believed that many cyclists insist on their right, no matter what. It was believed that cyclists often darted out in front of cars, just because they have priority. Car drivers generally wanted cyclists to behave in a more controlled way, and cyclists wanted cars and pedestrians to move out of the way to make space for the cyclists. Some of the bicyclists wanted to have traffic signs and road marks for bikes as well, to have them regarded as a serious mode of transport, whereas others wanted to keep as much freedom as possible.

4.4 Summary and implications

All groups proposed more soft measures than hard measures and all appreciated softer measures which implied that nudging could be a feasible approach. However, the motorists were not always certain if nudging would work for everyone. Motorists are in general so used to rules that the usage of rules was seen as a natural step. Nevertheless, there was an expressed acceptance of softer measures such as nudges, as long as they could be proven to have an effect.

All groups identified problems with cars and bicyclists intersecting each other's routes, and this was regarded as one of the major problems in traffic, confirming that this is a situation that should be tackled.

In general, the focus group interviews/workshops exposed an ongoing conflict between bicyclists and car drivers. Both regard the other group as more privileged. It is therefore very important that any measure aimed to make cyclists adapt their speed and increase attention is not seen as intrusive or as favouring car drivers. Therefore, the nudges developed and implemented must not remove any of the cyclists' freedom. The cyclists must furthermore accept that the measure is legitimate, and this can be done by choosing intersections that have been found to be dangerous.

5 Ideation Workshops

This chapter describes three ideation workshops that were organized to generate ideas for potential nudges, both visual and haptic. Two of the workshops were held in Gothenburg, Sweden and one of the workshops was held in The Hague in the Netherlands.

5.1 Aim

The aim of the workshops was to gain insight into which types of nudges could potentially could be used to affect cyclist behaviour in subsequent trials.

5.2 Method

The workshops were executed in different ways but were all focused on generating as many ideas as possible using different creativity techniques (brainstorming, brainwriting, etc), followed by a session where these ideas were evaluated, categorised and morphed into a limited number of ideas that were judged as feasible to test further.

5.2.1 Workshop 1 – Visual nudges in Gothenburg

The workshop was held over two days and involved ten participants. Six were researchers from Chalmers/Safer, two were representatives from the Swedish Transport Administration, one was a researcher from Cranfield University, and one represented a provider of technical solutions for road safety. During Day 1, the participants were introduced to the aim of the MeBeSafe project, the framework developed in WP 1 and different types of nudges. The participants were then asked to brainstorm in groups to generate ideas. The ideas were presented and explained to the other groups who were then asked to assess the ideas that they believed in the most. During Day 2, new groups were formed and asked to develop further on the best ideas from Day 1 taking into consideration the feasibility of implementation.

5.2.2 Workshop 2 – Haptic nudges in Gothenburg

The second workshop was a one-day event. It involved three researchers from Chalmers/Safer, one representative from the municipality of Gothenburg, and two representatives from the Swedish Transport Administration. This time brainwriting (e.g. Wilson, 2013) was used to support ideation. The participants were invited to individually generate ideas on how a haptic nudge could reduce a cyclist's speed ahead of an intersection and draw them on a piece of paper. The ideas were then passed on to each of the other participants, who altered and refined them step by step. The ideas were presented to the participants and sorted into relevant categories before the participants were asked to vote for the idea(s) that they believed were feasible and at the same time had some potential.

5.2.3 Workshop 3 – Haptic nudges in the Hague

The workshop in The Hague involved eight participants from TNO, SWOV and Chalmers/Safer respectively. In this workshop, the results from the Swedish workshops were presented. In addition, differences in cycling cultures between Sweden and the Netherlands were discussed. Two scenarios were then formulated for which the participants were to generate ideas for haptic nudging. The first concerned speed reduction ahead of an intersection and the second speed reduction when high-speed cyclists approach low-speed cyclists. Ideas were sorted into categories.

5.3 Results

The results from the three workshops are summarised in two sections, one on visual nudges and the other on haptic nudges.

5.3.1 Visual nudges

The workshop resulted in three main types of nudges.

- **Illusions:** in the form of stripes or trees placed progressively closer to give an illusion of increased speed, trees of progressively larger size to give an illusion of decreased lane width, road marks to symbolise a downward slope, or lights blinking to give an illusion of something approaching (Figure 5-1);

- **Physical alterations:** in the form of narrowing down the lane to make cyclists instinctively reduce speed, by restricting the field of vision or using a portal where cyclists have to go;

- Active **projections** of messages or images on the ground or a speed that the cyclist should follow to get a green wave. These types of nudges were developed in all the groups. Other types of nudges not fitting into the categories were deemed impractical or detrimental to safety.

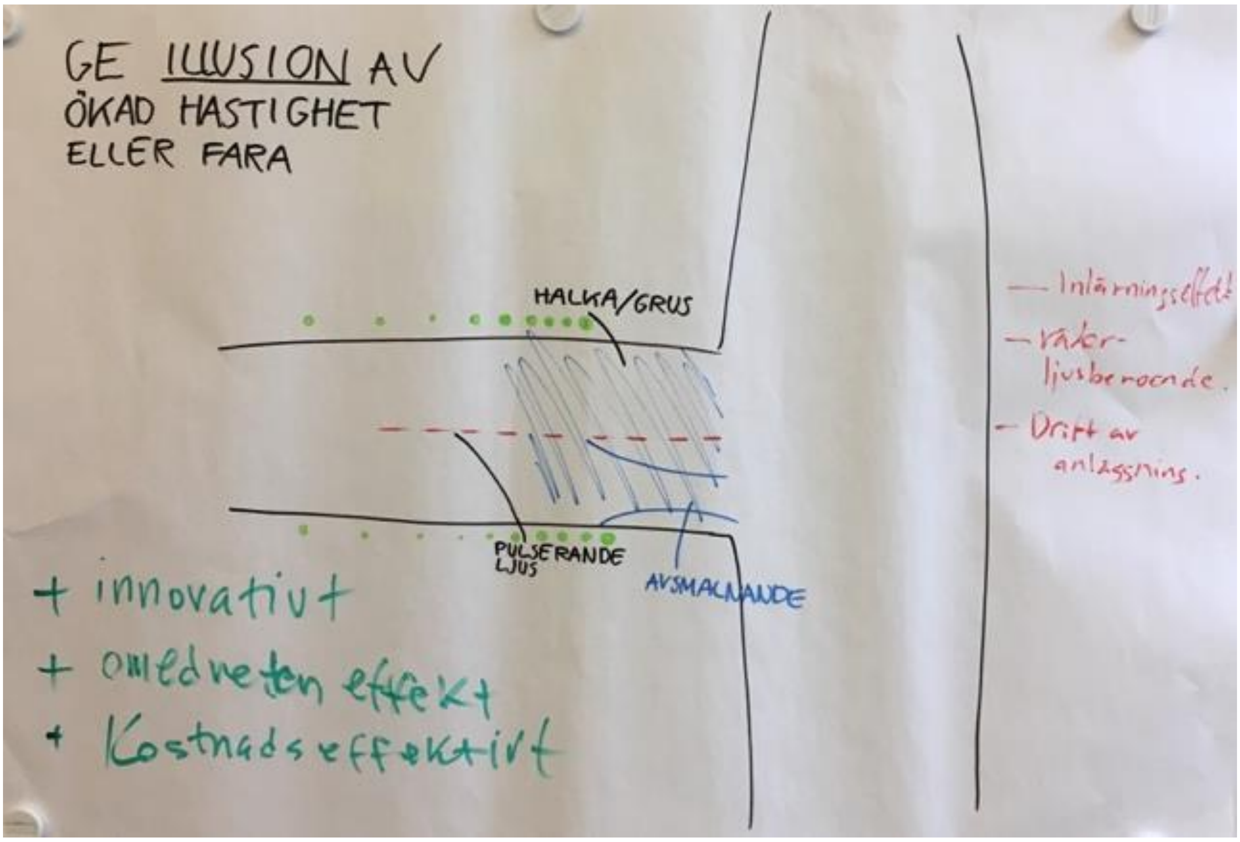

Figure 5-1. Example of ideas for visual nudges.

5.3.2 Haptic nudges

The workshops in Gothenburg and The Hague led to very similar results, with one main exception. Both found comparable haptic ways to decrease speed, but the discussions during the workshop in The Hague also involved suggestions for wider biking lanes and cyclists overtaking others.

The main categories for haptic nudging were:

- Modified **surface roughness**, such as glued gravel, shaggy asphalt and rubber balls on the ground;
- Modified **surface softness**, such as soft asphalt or spongy asphalt;
- **Wind resistance,** such as large blowing fans;
- **Dimensional modifications**, such as grooves, soft bumps or small bumps;
- **Dimensional speed storage** such as upwards slopes towards an intersection and downwards slopes away from an intersection;
- Moving ground or moving objects;
- **On-bike solutions** such as using vibration in the bicycle sat or handle bar to communicate negative behaviour (thus requiring a specific type of bike).

For cyclists with different speed norms in The Hague, some other ideas were elicited, such as fast routes through a city with smoother road surface material, passive speed compliance in the middle of the lane through a convex lane shape, or two-directional biking lanes everywhere.

5.4 Summary and Implications

The workshop on visual nudges generated several promising ideas on how to nudge cyclists. However, active projections were found to be impossible to implement, as the type of projection available today cannot be seen in direct sunlight.

Whereas the workshop on visual nudges was conducted in Sweden with only Swedish participants the workshops on haptic nudges were carried out in Sweden and in the Netherlands. These reached very similar conclusions in terms of which haptic measures could be used to nudge cyclists' behaviour.

For the haptic nudges, wind resistance was not deemed a feasible option, for example real-life winds would probably have much greater impact. Implementing solutions where the ground moved was found to be too dangerous to even test in reality and vibrating on-bike solutions were too specific as such solutions would only target those cyclists who acquire a new bike with these features.

The remaining ideas for nudges were all taken forward to early testing after the respective workshops.

6 Explorative Study – Visual Nudges

This chapter describes the process and results of the very first stage of the development and evaluation cycle. This included an explorative study conducted at Chalmers/Safer, Gothenburg, Sweden to investigate the potential of different ways of nudging cyclists.

6.1 Aim

The aim of the explorative study was to gain insight into which of the nudges from the workshop could be used in future evaluations and what design parameters influenced the outcome.

6.2 Method

The study was carried out by testing a range of different approaches and design versions in 'quick-and-dirty' trials. The first tests were based on the findings from the workshop on visual nudging (described in Chapter 6), but also included experiments on the effect of varying colours, images painted on the ground, cut-out silhouettes, auditory nudging and attempts to influence trajectory. Different concepts (Figure 6-1) were tried and refined in iterative loops.

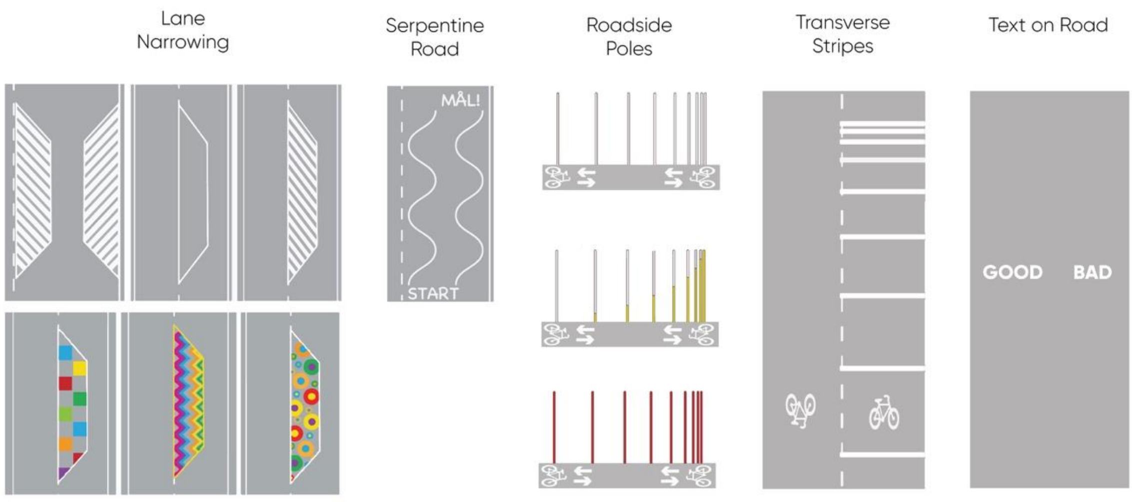

Figure 6-1. Some of the nudges in the explorative study.

The first iterations were carried out in a controlled indoor environment (a large garage), in which 12 participants were invited to bike along a defined route. The following iterations were performed outdoors at different locations in real traffic where a larger number of random bicyclists were studied. The effect of the these designs on cyclists' speed was documented by measuring time over a fixed distance.

6.3 Results

The explorative study found that several types of visual nudges had potential to influence cyclists' behaviour.

- **Visual nudges** appeared to have the best effect when they lasted for at least 20 metres.
- **Transverse stripes** placed progressively closer seemed to have potential to influence speed. Only one version was tried, where the gap between the stripes narrowed by one third for each stripe (Figure 6-2). The speed of bicyclists were documented without and with stripes at two different locations, Vasagatan (n=110) and Korsvägen (n=100) in the centre of Gothenburg. The speed was reduced from 5 m/s to 4 m/s in the first case and from 6 m/s to 5 m/s in the second case. Stripes seemed to have the best effect when white.
- **Poles** beside the road placed progressively closer had a similar effect. The speed of more than 100 bicyclists was measured with and without the poles and average speed was reduced from 5 m/s to 4 m/s. Poles appeared to have better effect when in other colours than white.

Figure 6-2. Stripes were tested as one way of influencing cyclists' speed.

- **Lane narrowing** was mainly tried as a means to alter bicyclists' trajectory. To be able to measure if a cyclist's trajectory was altered by the nudge, the lane was narrowed down towards one end of a bike lane at two locations (Vasagatan and Gibraltargatan) in the centre of Gothenburg. Several different patterns and colours were tried within a cordoned area. Although the effect was small, brighter colours (bright white, yellow, etc.) appeared to have the best effect. Out of 89 observed bicyclists, 22% biked across the area, 65% avoided it but did not appear to change trajectory and 12% made obvious changes in trajectory to avoid crossing the area (Figure 6-3). In these cases, the narrowing appeared to have an effect also on the bicyclists' speed.

Figure 6-3. Example of narrowing the cycle lane by painting different patterns.

Other tests with trajectories were accomplished by implementing a **serpentine biking lane,** which affected the trajectory of a few bicyclists but the speed of most. It is likely, however, that this reduction in speed was a result of the nudge drawing the bicyclists' attention away from surrounding traffic – many of the bicyclists were noticed to look down at the nudge.

Another test was performed in an area with mixed traffic, the consequence of ongoing construction work at the site. Lines were here drawn to divide pedestrians and bicyclists moving in various directions (Figure 6-4). This solution has been tried before in other contexts and this test confirmed that there is an effect. Traffic flow increased and pedestrians and bicyclists chose their paths according to the dividing lines.

Figure 6-4. Example of visual nudges implemented at a construction site.

6.4 Summary and Implications

The results of the exploratory study implied that transverse stripes or poles placed progressively closer can influence cyclists' speed. In addition, narrowing the lane appeared to decrease the speed of cyclists. Furthermore, the study indicated that white stripes and regular types of marks work better than novel colouring or paintings. White stripes are likely to be more connected to 'real' road marks in bike lanes, while other colours may be regarded as something that should not be there. Transverse stripes and a gradual narrowing of the road were therefore taken for further evaluation in Concept Test 1.

Physical poles were not considered for further evaluations. These could be regarded as intrusive and will block areas that could be used for other purposes in a crowded city. Accidents could occur should someone fall over them, and they may be a particular problem for visually impaired road users.

7 Concept Development and Test 1: Visual Nudging of Speed

This chapter summarises a quasi-experimental study was performed with cyclists in central Gothenburg aimed at determining whether visual nudges affect cyclist behaviour at all and how much their behaviour is affected.

7.1 Aim

The aim of the concept development and test was to further determine if, and what type of, visual nudges can affect cyclist behaviour in a positive way and to understand which factors contribute to observed effects (if any).

7.2 Development of concept nudges

The ideas for visual nudging that were found to be the most promising in the explorative study (see Chapter 7) were chosen for further development following an iterative design and evaluation loop. The development of nudges included transverse stripes and lane narrowing. In addition, a digital speed sign was introduced as a reference; the reason being that it is commonly used for reducing car drivers' speed in different contexts.).

7.2.1 Transverse stripes

In order to determine the respective configurations, distinguishing features were listed for each type of nudge. For transverse stripes, the features considered are listed in (Table 7-1).

Feature	Possible manifestations
Total distance from start to end	Distance-compliant with stripe distances
Distance from end to intersection	Distance
Initial gap between stripes	Distance
Number of stripes	Distance
When gap sizes start to decrease	Immediately, after a few gaps
Function for narrowing the gaps	Decrease by a specific constant distance Decrease by a specific constant percentage Decrease by a constantly decreasing/increasing percentage, Decrease by a specific constantly decreasing/increasing percentage where the rate of decrease/increase changes
Difference between initial and final gap size – total gap decrease	Percentage - compliant with number of stripes, initial gap and change

Table 7-1. Distinguishing features for transverse stripes.

In order to determine which two configurations to include in the concept test, different options were developed and evaluated in iterations. For this purpose, a 'bike lane' was created in an office corridor as a testing facility (Figure 7-1).

This type of easy access evaluation facility was considered essential in order to run short tests with easy accessible test persons, and to be able perform trials regardless of weather conditions.

A number of configurations were modelled, first digitally and then tested in the corridor, in order to determine the length of the nudge from start to end. A distance of approximately 20 metres was found to fulfil the criteria, that is the same length as found in the explorative study.

Figure 7-1. The cycling lane in the office corridor where different configurations were tried out.

It was hypothesised that by using different but constant percentages for a decreasing gap width between stripes, the change would be more or less apparent and could either act as an illusion of cycling faster, i.e. a type 1 nudge, or as a symbol for the cyclists to reduce speed, i.e. a type 2 nudge.

Two metres were decided as a feasible initial gap size as it allows for a number of gaps, short enough for the cyclist to repeatedly run over stripes but large enough for small differences in gap width not to be noticed. For the first transverse stripe nudge, Transverse I, a decrement of 3.5% per gap was decided upon, resulting in a total of 12 gaps, a total decrement of 32.4% and a total length of 19.9 metres. The difference in gap sizes appeared impossible to spot by the cyclist passing over even when he/she knew they existed. For the second transverse stripe nudge, Transverse

II, a decrement of 7.25% per gap was found feasible. This principle resulted in 17 gaps, a total decrement of 70% and a total length of 19.9 metres. This difference in gap size could be noticed if actively searching for it but seemed small enough not to be noticed otherwise when biking. It was found to be the largest decrease that may still act as an illusion, with a potentially greater effect on speed given the larger decrease (Figure 7-2).

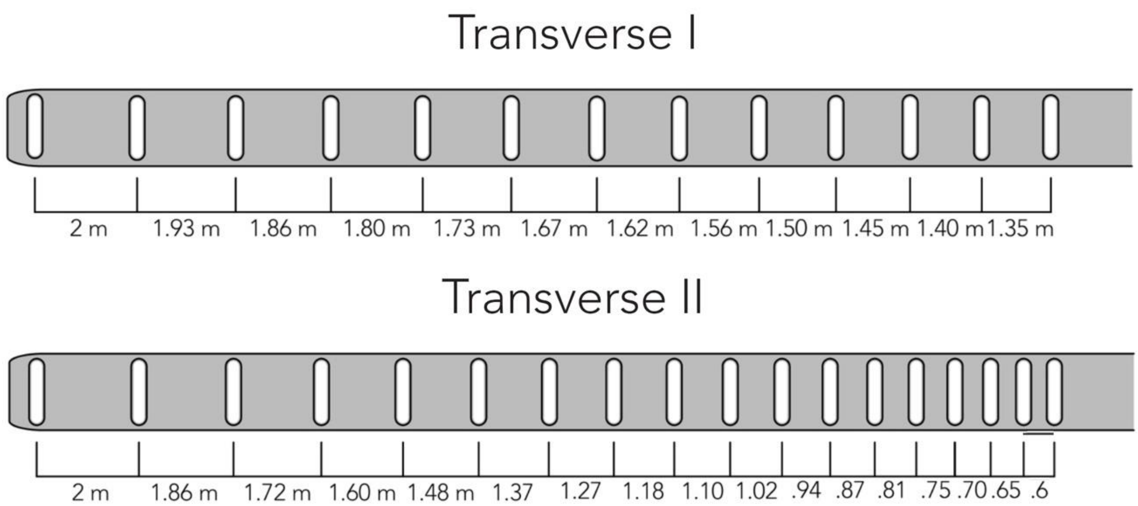

Figure 7-2. Illustration of the two designs for reducing speed with transverse lines.

7.2.2 Lane narrowing

In addition, lane narrowing could potentially work as a symbol or an illusion. For lane narrowing nudging, the features that were considered in the design are listed in (Table 7-2).

Feature	Possible manifestations
Total distance from start to end	Distance
Total distance when narrowing occurs	Distance
Approach to narrowing down	Right side, left side, both sides
Final width	Distance

Extent of final width	Reached before intersection and kept constant for a distance, reached at intersection, reached before intersection and then increasing
Function of width decrease	Linear, convex, concave, other function
Coverage of blocked area	No cover, stripes at set distance, stripes at varying distance, all white
Longitudinal multiples	Narrowing down before intersection only, increasing width after intersection as well
Latitudinal multiples	Affecting one lane, affecting both lanes (in duo-directional roads)

Table 7-2. Distinguishing features for lane narrowing

Several design–evaluation cycles were completed, varying the features listed. In this process it was deemed important to narrow down the lane from both sides, as this would steer the cyclists into a safer trajectory. The width was only to decrease in the lane heading towards the intersection. Different lengths were tried, and 20 metres was found suitable also for this type of nudge too. It was also determined that narrowing down the lane over a distance of 20 metres, with stripes covering the cordoned area every 30 centimetres, had most potential. A 25% decrease of the width was to be barely noticeable and a 50% decrease was more noticeable but still not intrusive.

However, bike lanes vary in width and this must be taken into consideration when deciding what nudges to test. The lanes in Gothenburg were found to vary between 120 cm (duo-directional) and 140-160 cm (single direction). The less apparent nudge, Narrow I, would remove 25% of the width. Removing 25% of the widest lane would make it as wide as the narrowest lane, but it was still believed to create an illusion. The more apparent nudge, Narrow II, would narrow the lane to 50% of the least wide lane, i.e. to 60 cm (Figure 7-3). Cutting the width to half was found to have less effect on the rider's perception if the lane is very wide. For a wide lane, more than 50% had to be removed. However, removing more than 50% of a narrow lane would result in it being too narrow to be usable.

Simple white lines seemed most effective to cover the blocked area in the exploratory study (Chapter 6), and different versions were tested. One stripe every 30 centimetres was found appropriate to emphasise the actual change and the fact that the area really was blocked (Figure 7-3).

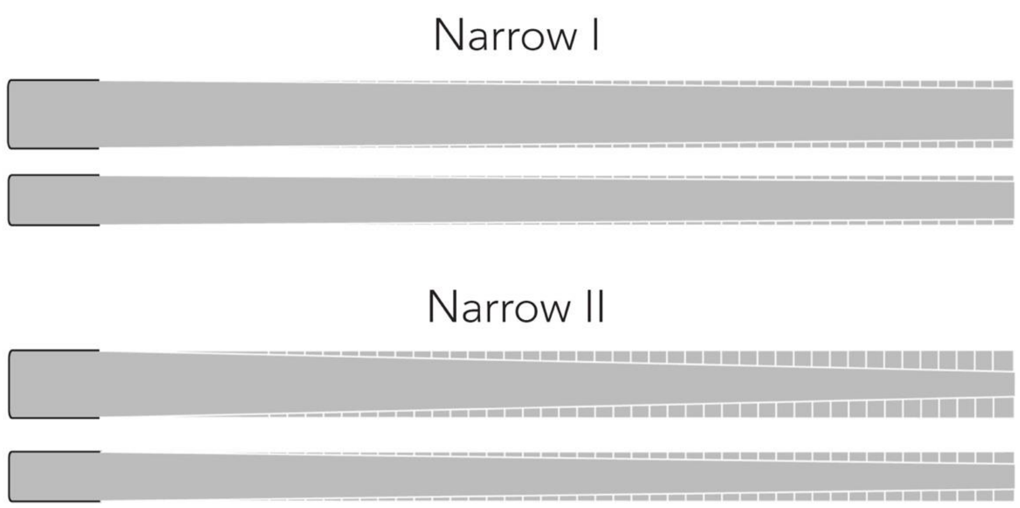

Figure 7-3. Illustration of the two designs for reducing speed by narrowing the bike lane.

7.2.3 Digital speed signs

Digital speed signs can vary in numerous ways, it is the type of sign that provides the delimitations. Table 7-3 describes different features that can be varied in a digital sign. All these factors can significantly influence the results.

Feature	Possible manifestations
Communication start time	When discovering cyclist, at a certain distance (possibly related to speed)
Mode of speed presentation	Actual speed, ideal speed, difference from actual and ideal speed
Speed presentation differentiation	Different colours, different sizes
Speed differentiation limits	Certain values in km/h (same or different for speed presentation and message)
Number of speed differentiation limits	Certain numbers (all coupled to messages or not)
Message use	Text, Image, none
Valence of message	Positive, Neutral, Negative, different for different steps,
Spatial message differentiation	Different message for different distances to sign, same message over entire distance
Speed-related message differentiation	Same all the time, different if going from fast to slow or slow-slow or slow-fast etc
Actual wording/image of message	Large variance
Update frequency	All the time, at certain distances
Distance from sign to intersection	Distance
Sign roadside placement	Left side, right side, above road
Sign size	Different sizes and proportions
Height placement	Different heights

Table 7-3. Distinguishing features for the digital sign.

In the trials in Gothenburg, the sign used was an Evolis Solution (https://amparosolutions.se/produkter/evolissolution/)(dimensions 70x70cm). This sign can communicate the actual speed of the fastest passerby it can detect, it can present speed in green, yellow or red numbers as soon as it detects it, and the speed can be coupled to a message, either as text or as an ASCII image. Given these preconditions, a number of different solutions were tried out before decisions were made on which versions were to be tested.

One of the signs, DigiSign I, was more 'nudgy'. This meant that for low speeds, the cyclist's speed was displayed in green and no message was presented. For higher speeds, speed was displayed in orange and a message "Farlig korsning" ("Dangerous Intersection") was shown (Figure 7-4).

The other sign, DigiSign II, was designed to be more imperative in nature and used three manifestations. For low speeds, actual speed was displayed in green with a positive reinforcement text: "Tack!" ("Thank you!"). For medium speeds, speed was shown in orange with a message "Sakta ner" ("Slow down"). For high speeds, the sign displayed the cyclist's speed in red and with a clear imperative message: "Bromsa!" ("Brake!") - as complementary information.

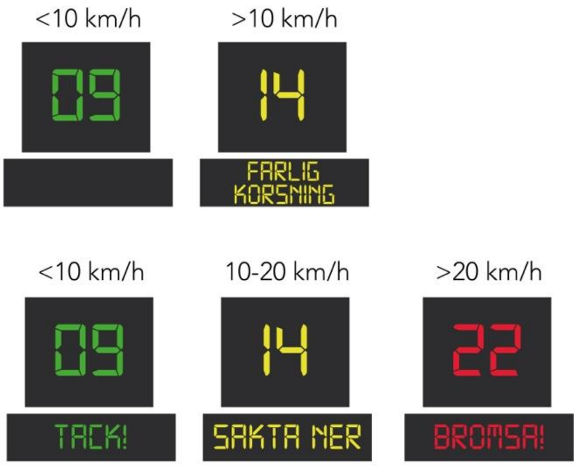

Figure 7-4. Illustration of the two designs for reducing speed by display of information in a digital sign.

7.3 Test of concept nudges

7.3.1 Method

All three types of nudges were to be tested in two different configurations respectively. The study therefore involved six nudges and one baseline. All of them were tested at three different positions, called stations, along a defined route. Baseline conditions were tested twice at each station to obtain a larger sample.

Eight different tests were carried out over eight days. The test track was prepared in the morning and tests were run in the afternoon. Figure 7-5 provides an overview.

	Day 1	Day 2	Day 3	Day 4	Day 5	Day6	Day7	Day 8
Station I	F - Narrow 2	A - Baseline	H - Transverse 2	E - Narrow 1	G - Transverse 1	A - Baseline	D - DigSign 2	C - DigSign1
Station II	A - Baseline	G - Transverse 1	A - Baseline	C - DigSign1	D - DigSign 2	F - Narrow 2	E - Narrow 1	H - Transverse 2
Station III	G -Transverse 1	E - Narrow 1	C - DigSign1	H - Transverse 2	A - Baseline	D - DigSign 2	A - Baseline	F - Narrow 2

Figure 7-5. Study design

The sequence assured that no test included more than one nudge of each type of nudge and that each nudge was tested once at each station. The purpose was also to mix the ordering of apparentness. To diminish the effect that one nudge may have on other nudges, some tests included only less apparent nudges, others more apparent and some a mix of both.

7.3.1.1 Test persons

Potential participants (Ps) were recruited via campaigns running as targeted advertisements in social media and displayed on posters and as flyers on bikes. The intent was not stated, only that there would be a study on biking and safety, and that Ps should bike a kilometre during working hours and would be compensated. Interested cyclists filled in a questionnaire on age, gender, biking frequency, car use, accident involvement and situations found correlated to accidents by Hezaveh et al. (2017). Those found to bike at least once a month were invited to book a time.

The tests included a total of 93 participants (Ps) between 18 and 75 years old (mean age=37). Fifty-nine percent were male and 41% female. A majority (88%) had a driving licence, but only 14% used their cars regularly several times per week. About one out of four Ps had been involved in a bike accident during the past three years. (For more detailed information on the profile of the Ps, see Appendix 1b).

7.3.1.2 Equipment

The Ps used their own bikes, to ensure that they would bike as normal as possible. In those cases where they could not bring their own cycle, one was provided.

The bikes were fitted with a Garmin Virb Ultra 30 Action Camera (https://www.garmin.com/en-GB) that documented each P's route and logged speed, location and distance. Ps were also fitted with a helmet featuring a camera to log their gaze behaviour. This data was used to discern overall gaze patterns at the intersections and potentially whether or not the cyclists looked at the nudges.

7.3.1.3 Test route

Potential test routes were sought in the city of Gothenburg. The criteria were that the route should be fairly smooth, without rumble stripes or painting on the ground. It should moreover be around 1000 metres long, contain a minimum of three real intersections and have enough space between them for cyclists to build up a cruising speed. The route should also start and end at the same place.

One such route was found (Figure 7-6) located in central Gothenburg, starting and ending at Korsvägen. It includes both duo-directional and single lane roads, is approximately 800 metres long, traversing three streets (Södra Vägen, Berzeeligatan and Skånegatan), the latter two single lane.

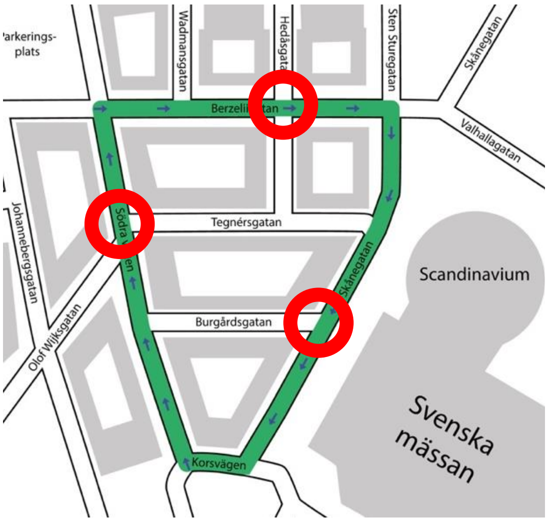

Figure 7-6. Test route in the centre of Gothenburg,

Station 1 was located along Södra Vägen before Tegnérsgatan, Station 2 along Berzeeligatan before Hedåsgatan and Station 3 along Skånegatan before Burgårdsgatan (intersections shown in Figure 7-6). The stations were evenly spread out along the route and the lanes ahead of the respective intersections are fairly straight and without any obstructing artefacts.

7.3.1.4 Test procedure

The Ps were welcomed by a test coordinator and introduced to the route. They were told to cycle as normally as possible, handed the special helmet and the equipment was fitted to their bike. They were not informed about the specific purpose of the test until after it was completed, only that the study concerned cycling and safety.

Each P was subjected either to two nudges and a baseline or to three nudges; no P experienced more than one nudge of the same type (Figure 11) to avoid any learning effects.

After biking the route, the Ps were asked if they had seen anything special and told to pinpoint this on a map of the area. If a nudge was mentioned they were asked what they thought was its purpose, if and how it had affected them and what they thought of it. They were also asked to fill out a questionnaire about how they perceived the nudges. In addition to open questions, the questionnaire included a semantic differential scale. The Ps were asked to rate their experience according to six different items: “comfortable-uncomfortable”, “safe-unsafe”, “secure-unsecure”, “intrusive-unnoticeable”, “speed-decreasing - not affecting speed”, “demanding attention – making it possible to devote more attention to the traffic”.

If one or several of the nudges were not mentioned, the Ps were shown an image of the specific nudge and asked if they recognised it, and then asked the same questions. At the end of the test, they were asked to choose which nudge they preferred. Afterwards they were given compensation in the form of a cinema ticket and any questions they had regarding the study or the project were answered.

7.3.1.5 Analysis

The speed and location data from the Garmin cameras were extracted manually. All video recordings were analysed to find disturbances that could have influenced the behaviour of the cyclists. Reasons for removal of a case included vehicles approaching the intersection or waiting to cross, reduced field-of-vision for cyclists, pedestrians in the lane or the cyclist having just speeded up or slowed down before. If the DigiSigns showed speeds that clearly did not apply to the cyclists, this case was removed as well. Moreover, behaviours such as taking shortcuts, overtaking other road users and signalling with the cycle bell were noted.

Baseline results were compared to nudge results for each intersection. Significant differences were calculated by means of two-sample t-tests in MATLAB, assuming that one average value was lower than the other, and that the variances were not necessarily equal. P-values lower than 0.05 were considered statistically significant.

The results were normalised for each intersection; hence baseline values are set to '0'. The reported speed reductions are therefore the additional decrease accounted for by the respective nudges. The period during which the cyclists were affected by the nudge is called 'the period of influence' and it is defined as the period between the highest and the lowest speed.

Slowing down before an intersection. Average speed varies considerably between cyclists. In order to determine if the nudges had any effect on a Ps speed, the 'slowing pattern' had to be determined. The decrease in speed in percentages before the intersection was chosen as the main indicator, calculated as:

Total speed decrease = (Initial speed – Final speed)/Initial speed [%]

In case of the cyclist slowing down, the initial speed was set as the highest speed before slowing down, and the final speed as the lowest speed. In baseline scenarios, some cyclists increased their speeds, so the initial speed was set as a cruising speed and the final speed as the speed right before the intersection.

Braking distances. Braking distance was measured in several ways, two of which proved most important. One measure was for how long the nudges influenced the cyclists, that is the period of influence in metres. This was defined as the distance between the initial and the final speed. However, some cyclists accelerated slightly after the initial brake and then braked again. Therefore, as a second measure the distance of continuous braking before the intersection was determined. To counteract potentially erroneous data, small apparent deviations from braking were neglected, as long as the overall trend was clearly indicated reductions in speed.

The exact point where the lowest speed was reached in relation to the intersection proved impossible to measure with high accuracy due to the offset GPS data. The video recordings could show a speed-stamp, but this was updated only once per second. The specific location for the lowest speed was therefore difficult to pinpoint with camera images and it was not feasible to calculate a distance to the intersection by this assumed location and perspective image.

Looking left and right before an intersection. The Ps head movements before each intersection were noted. A method of expressing this behaviour in numbers was developed where '1' was awarded for looking in both directions, '0' if not looking at all, and in-between values if the Ps only looked in one direction (see Appendix 5 for more information).

Trajectory. A straight line was drawn between the position for the highest and lowest speeds respectively and average deviations from this line were calculated. If large deviations were found, coordinates were plotted and compared with the video recordings. If any disturbance was noted (such as the GPS data showing a rapidly changing offset without this actually occurring), the case was removed from analysis.

Cyclist ratings. Ratings of how participating cyclists experienced the nudges were deemed valid if the cyclists mentioned the nudge or had recognised it and had experienced it without disrupting factors (such as cars crossing the intersection of pedestrians standing in the way). As most tests included two nudges, pairwise comparisons were made by the Ps. Coherent results allowed establishment of a rank order, but as some tests included three nudges the order is not fully complete.

7.3.2 Results

The following section summarise the main results of concept test 1. Differences are regarded as statistically significant for $p \leq 0.05$, whereas $p < 0.15$ is described as a trend.

7.3.2.1 Slowing down before intersections

Initial speeds varied between 11.9 km/h and 37.7 km/h. The male Ps ($p=0.0140$), Ps who biked regularly ($p=0.0077$) and Ps who reported to be regular 'overtakers' ($p=0.035$) had higher speeds than other Ps.

Except for one case involving Narrow I and one case involving Transverse I, all cyclists slowed down when exposed to the nudges. A third of the cyclists increased their speed in the baseline scenarios. Table 7-4 presents average speed reductions compared to baseline.

	Average speed reduction in %	Baseline	Transverse I	Transverse II	Narrow I	Narrow II	DigiSign I
DigiSign II	19.83%	8.79E-10	2.33E-04	0.0018	0.0019	0.0048	0.1039
DigiSign I	16.06%	1.07E-09	0.0038	0.0284	0.0304	0.0581	
Narrow II	11.90%	6.87E-07	0.1465	0.4575	0.4905		
Narrow I	11.85%	1.29E-10	0.1029	0.4573			
Transverse II	11.66%	2.78E-09	0.1288				
Transverse I	9.35%	7.82E-06					
Baseline	0.00%						

Green = statistically significant difference (p≤0.05); yellow=statistical trend (0.05<p<0.15); red=no statistical significance (p≥0.15).

Table 7-4. Average speed reductions in percentages for each nudge compared to baseline.

DigiSigns were overall the more effective measure but dependent on being noted and associated with the P's own cycling. Noticing or recognising the nudge afterwards was correlated to larger speed reductions for DigiSign I (p=0.0029) and DigiSign II (p=0.0014). The Transverse II nudge resulted in similar speed-reducing effect to the narrowing lane nudges whereas Transverse I was less effective. For the stripe nudges, there seems to be no effect at all based on whether the Ps noticed them or recognised them (p≈0.5). Narrowing lane and transverse stripe nudges therefore seemed to have an effect even when not consciously noticed.

There was a strong correlation between Ps reporting that they often slow down in actual traffic and slowing down in baseline conditions (p=0.0022). However, there was no correlation between frequency of slowing down and the speed decrease for any of the nudges. This indicates that the nudges were acceptable to all cyclists, not only those regularly slowing down. In addition, even though the effect varied between cyclists, it was never zero, no matter their cycling behavioural profile. This indicate that the nudges have potential to affect all types of cyclists.

7.3.2.2 Head movement before an intersection

Several of the nudges seemed to attract the Ps visual attention. Transverse and DigiSign II were the only ones that did not significantly reduce the P's attention to surrounding traffic (Table 7-5).

All stations	Average difference to baseline (%)	DigiSign I	Narrow II	Narrow I	DigiSign II	Transverse II	Transverse I
Baseline	0.0%	0.0062	0.0169	0.0322	0.1004	0.1583	0.378
Transverse I	-3.5%	0.0582	0.0893	0.1375	0.2395	0.3307	
Transverse II	-8.8%	0.0822	0.1328	0.2105	0.3623		
DigiSign II	-12.6%	0.1752	0.2417	0.3453			
Narrow I	-17.1%	0.2866	0.3694				
Narrow II	-20.7%	0.419					
DigiSign I	-22.9%						

Green = statistically significant difference (p≤0.05); yellow=statistical trend (0.05<p<0.15); red=no statistical significance (p≥0.15).

Table 7-5. Average difference in head movement compared to baseline.

Narrow I was presented without dashes at Stations I and II, due to weather issues. This may have reduced the demand for visual attention by the Ps compared to when presented with dashes (p=0.0040). The effect on speed was similar, however. This implies that more complex nudges may demand more (visual) attention.

In general, the male Ps seemed to look more at intersections than did the female Ps (p=0.0242), despite indications that they may be less inclined to slow down in regular cycling.

7.3.2.3 Trajectory

The narrowing lane nudges lead to significantly more straight trajectories than was observed in baseline conditions. No nudge seemed to lead to less straight paths. Table 7-6 shows if average deviations are lower (minus) or higher (plus) than baseline.

	Average difference to baseline (%)	Transverse I	DigiSign II	Baseline	DigiSign I	Transverse II	Narrow II
Narrow I	-0.1260	0.01337	0.06398	0.01072	0.05998	0.41833	0.42183
Narrow II	-0.1155	0.0262	0.0839	0.0385	0.12556	0.46741	
Transverse II	-0.1077	0.0768	0.12737	0.13373	0.24437		
DigiSign I	-0.0412	0.13732	0.22269	0.26213			
Baseline	0.0000	0.27420	0.34087				
DigiSign II	0.0474	0.49330					
Transverse I	0.0495						

Green = statistically significant difference (p≤0.05); yellow=statistical trend (0.05<p<0.15); red=no statistical significance (p≥0.15).

Table 7-6. Average deviation from a straight line compared to baseline. A negative value indicates a straighter trajectory than baseline.

In baseline scenarios, trajectories were straighter the earlier the lowest speed was reached before the intersection (p=0.0241). Larger decreases in speed appeared to be related to a straighter path (p=0.0557).

7.3.2.4 Braking distance

The distance between highest and lowest speed was longer than baseline for all nudges and the longest for DigiSign II (Table 7-7).

	Average difference to baseline (%)	Baseline	Transverse I	Narrow II	DigiSign I	Transverse II	Narrow I
DigiSign II	19.981	1.67E-08	3.24E-04	1.49E-03	0.011	0.051	0.057
Narrow I	14.950	6.34E-06	0.024	0.053	0.171	0.383	
Transverse II	13.858	2.55E-04	0.083	0.127	0.285		
DigiSign I	11.550	1.22E-03	0.216	0.284			
Narrow II	9.364	4.65E-03	0.430				
Transverse I	8.777	3.61E-03					
Baseline	0.000						

Green = statistically significant difference (p≤0.05); yellow=statistical trend (0.05<p<0.15); red=no statistical significance (p≥0.15).

Table 7-7. Average braking distance in addition to braking distances in baseline, defined as the period between the highest and the lowest speed.

7.3.2.5 Cyclist ratings

The nudges were spontaneously mentioned (i.e. noticed) by between 14% and 67% of the Ps (Table 7-8). When combined with Ps who recognised it from an image shown to them, the percentage increased to between 52% and 90%.

	N	Noticed	Placed correctly on map	Noticed and recognised	Understood	Believed affected
Narrow I	36	13.9%	8.3%	52.0%	13.9%	19.4%
Narrow II	29	62.5%	55.2%	82.8%	41.4%	53.6%
Transverse I	23	36.4%	31.8%	59.1%	33.3%	28.6%
Transverse II	27	44.4%	38.5%	81.5%	74.1%	50.0%
DIgiSign I	27	66.7%	59.3%	88.9%	88.5%	50.0%
DigiSign II	28	53.6%	46.4%	89.3%	57.1%	59.3%

Table 7-8. Proportion of bicyclists noticing, recognising, understanding and believing that their cycling was affected by the respective nudge out of how many experienced the respective nudges as intended.

Overall the responses to the nudges were positive. On average, all nudges scored on the positive side for pleasantness (0.6 –1.1), safety (0.5 – 0.9), security (0.4 – 1.0) and attentiveness (0.1 – 0.4). Intrusiveness scores on average very close to zero (0.1 to -0.5). Those Ps who did not recognise the nudges have been excluded from the summary. Only two (n=2) of the in total 93 Ps expressed some negative thoughts on the nudges (one for Narrow I and one for DigiSign II). The majority of the Ps spontaneously mentioned how much they appreciated that the nudges were not haptic whereas three (n=3) would have preferred haptic measures.

The pairwise comparisons between the different nudges were very coherent but as two tests included three nudges, pairwise comparisons were not made between all nudges. If three nudges are encountered and one is preferred, it is not known which of the others is least preferred. The more apparent nudges (i.e. DigiSign II, Transverse II and Narrow II) were preferred over less apparent ones (i.e. DigiSign I, Transverse I, and Narrow I).

Regarding the P's ratings on how much they believed the nudges slowed them down, the impact of Transverse II was rated higher than that of Narrow I and Narrow II, despite their having had an equal actual effect on speed (Table 7-9).

	Impact rating	Narrow I	Transverse I	Narrow II	DigiSign I	Transverse II
DigiSign II	2.83	2.717E-05	0.00317	0.00304	0.0722	0.103
Transverse II	2.36	0.00103	0.0254	0.0447	0.367	
DIgiSign I	2.23	0.00686	0.0540	0.108		
Narrow II	1.7	0.107	0.268			
Transverse I	1.39	0.365				
Narrow I	1.23					

Green = statistically significant difference (p≤0.05); yellow=statistical trend (0.05<p<0.15); red=no statistical significance (p≥0.15).

Table 7-9. Average ratings of impact on speed on a scale from 1 to 5 where 1= not at all and 5= very much.

7.4 Summary and Implications

The results of the concept test imply that:

- Visual nudges can influence cyclist speed and trajectory.
- Visual nudges appear to affect different types of cyclists, no matter how much they usually slow down when approaching an intersection.
- The transverse stripe-based nudges were equally effective independent of whether the Ps noticed them or not, indicating that the stripes worked on a subconscious level. They exhibited the qualities of Type 1 nudges. The DigiSigns were highly dependent on being spotted and therefore exhibited type 2 nudge qualities.
- Several of the nudges appeared to draw the participants' visual attention away from the surrounding traffic.

- Less apparent nudges seemed to require less attention from the Ps and were less understood. More apparent nudges were preferred by the Ps and also reduced speed more than did the less apparent nudges.

In general, Ps appreciated and would accept visual nudges. Implementing them would probably not lead to undesirable effects, such as cyclists steering away into the road or feeling the necessity to take another route. Cyclists would therefore be subjected to the nudges, and they would slow down no matter how they cycle.

Transverse stripes and narrowing lane solutions are easy and cheap to implement. Long-term effects must be determined but may be higher for the subconscious stripe nudges as, for example, solutions such as DigiSigns are easier to ignore. This could make them lose at least part of their effect, if they are not constantly moved around to different potentially dangerous intersections. They can also cause some information overload and many of the Ps did not understand that the information was aimed at them.

8 Concept Development and Test 2: Haptic Nudging of Speed

This chapter describes the second concept development and test which focused on haptic nudges.

8.1 Aim

The aim of the development and test was to discern whether there is any potential in using haptic nudges to decrease cyclist speeds ahead of intersections, what type of haptic nudges could be implemented in a trial, and if these nudges are accepted by cyclists.

8.2 Development of concept nudges

Five different types of haptic nudges were identified in the ideation workshops (see Chapter 5):

- Modified surface structure such as shaggy surface, rugged surface or rubber ball surface
- Modified surface properties such as soft surface, or increasing friction with speed
- Road bumps and strips such as smaller and smoother bumps, made in soft material
- Cut-out grooves in asphalt
- Upward slope

To select the appropriate nudges for a more structured test involving cyclists (described in section 8.3), a series of prototypes were first built and tested in 'quick and dirty trials' performed in the earlier mentioned indoor test facility (Figure 8-1).

The main purpose was to determine if the nudges resulted in a haptic experience (at all) and if this experience was negative or not and this was accomplished by asking colleagues and students at Chalmers University cycle across the haptic nudges and then provide feedback on whether or not they perceived the nudge haptically and whether the sensation was comfortable or nor. The most promising alternatives were then moved outdoors and tested, one-by-one, by random passer-by. The same question regarding perception and comfort were asked.

Figure 8-1. Early tests in the indoor test facility where different haptic nudges were placed in a long line.

8.2.1 Modified surface structure

Two different types of surface structures were tested: a rugged surface (including a rubber ball surface) and a 'shaggy' surface.

A first version of a rugged surface included gravel poured out onto and then glued to different types of roofing felt (Figure 8-2). The gravel had to be of larger than average size to provide any haptic experience.

A second type of rugged surface was achieved by click plates with protruding diagonal lines (Figure 8-3) and a third version by means of a rubber ball surface (Figure 8-4). Also in this case no effects on perception could be determined.

Figure 8-2. Gravel on roofing felt.

Figure 8-3. Protruding diagonal lines.

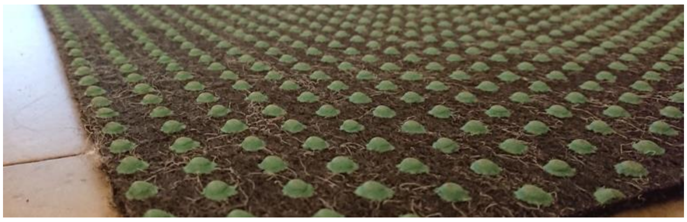

Figure 8-4. Rubber ball surface.

To determine the effect of a shaggy surface, a black mat of synthetic grass was tried but no haptic experience was reported.

8.2.2 Modified surface properties

One type of soft surface was simulated by a mat made of three-dimensional rubber threads. It deformed under pressure, and bike tires were perceived to sink down into the material. This was deemed not to be merely a 'soft' surface, but actually a 'spongy' surface (Figure 8-5).

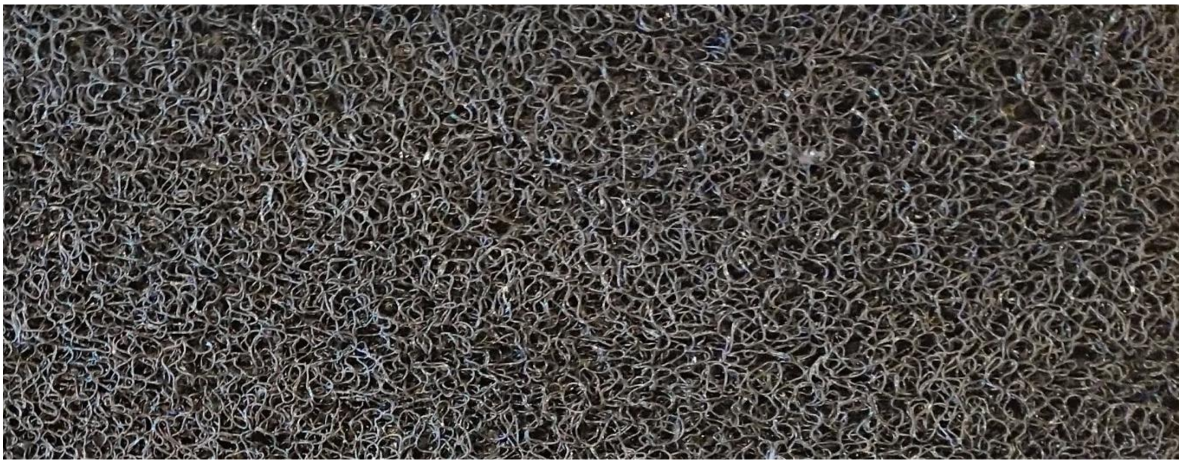

Figure 8-5. Detail of soft surface.

Figure 8-6. Hard rubber plates.

Another soft surface was simulated by using hard rubber plates of different thicknesses (Figure 8-6). In this case ramps had to be used. The small bump cycling up the ramp affected the haptic experience more than the actual material did.

All in all, the soft surfaces were found to result in an experience that was not perceived as directly uncomfortable.

8.2.3 Road bumps and strips

Road bumps and rumble strips have in earlier studies been found to be severely disliked by cyclists. As user acceptance is a cornerstone in the MeBeSafe project softer strips were researched. Small spongy rubber strips were tested as a first step. This first version was not discernible at all when people cycled over them, not even if two or three strips were placed on top of each other. Semi-soft rubber strips with a circular cross section provided a haptic experience but in a comfortable way (Figure 8-7).

Figure 8-7. Semi-soft rubber strips distributed at a distance of 25 cm.

Two rubber ramps were used to form a bump (Figure 8-8) that was found to be a bit more comfortable than regular bumps. The ramp had an effect on the haptic experience due to its shape. In the outdoor tests, the speed bump was reported to be the most uncomfortable but at the same time better than existing road bumps.

Figure 8-8. Two rubber bumps put together.

8.2.4 Cut-out grooves

Cut-out grooves are similar to strips but advantageous from a road maintenance point-of-view as they do not protrude upwards which could interfere with road machines. They were produced by pouring out cold asphalt in several layers on roofing felt (Figure 8-9) but they never dried, not even when mixed with gravel. Hence, this type of nudge had to be withdrawn from the list of feasible solutions.

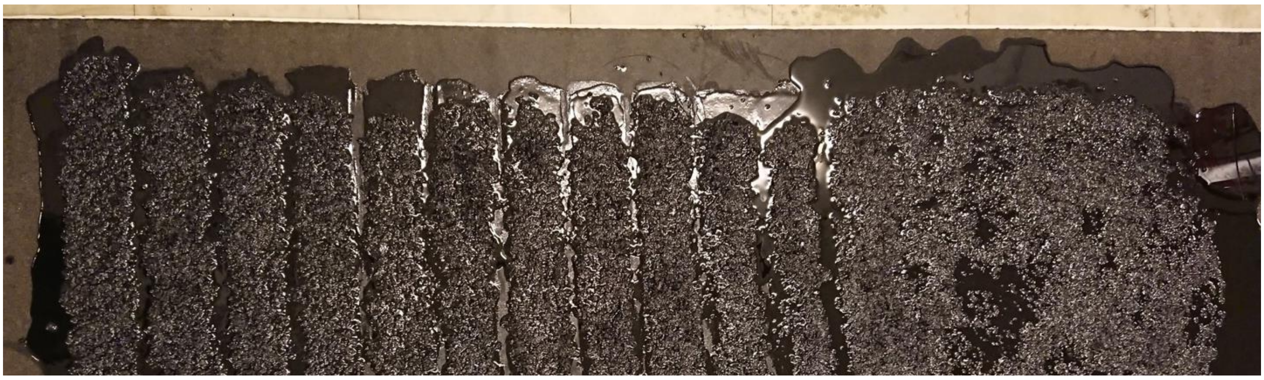

Figure 8-9. An attempt to create 'cut out groves' in asphalt.

8.2.5 Upward slope

An upwards slope was first simulated with a skateboard ramp which proved to be too narrow. A second solution slope was then constructed using plywood and wooden bars (Figure 8-10). As the cycle pedals could touch the ground if the angle was too acute, a safe angle had to be calculated. A series of equations were set up including different scenarios; front wheel on slope and rear behind, front wheel on top and rear behind, front wheel on top and rear on slope or both on slope (if the slope had to be that long) to ensure that the angle of the slope did not have any negative impact on pedalling. Simulations in MATLAB (https://se.mathworks.com) were done for traversing the entire slope (see Appendix 3) and angles below 20° were found feasible for implementation. This type of slope was found to be a feasible alternative for further tests.

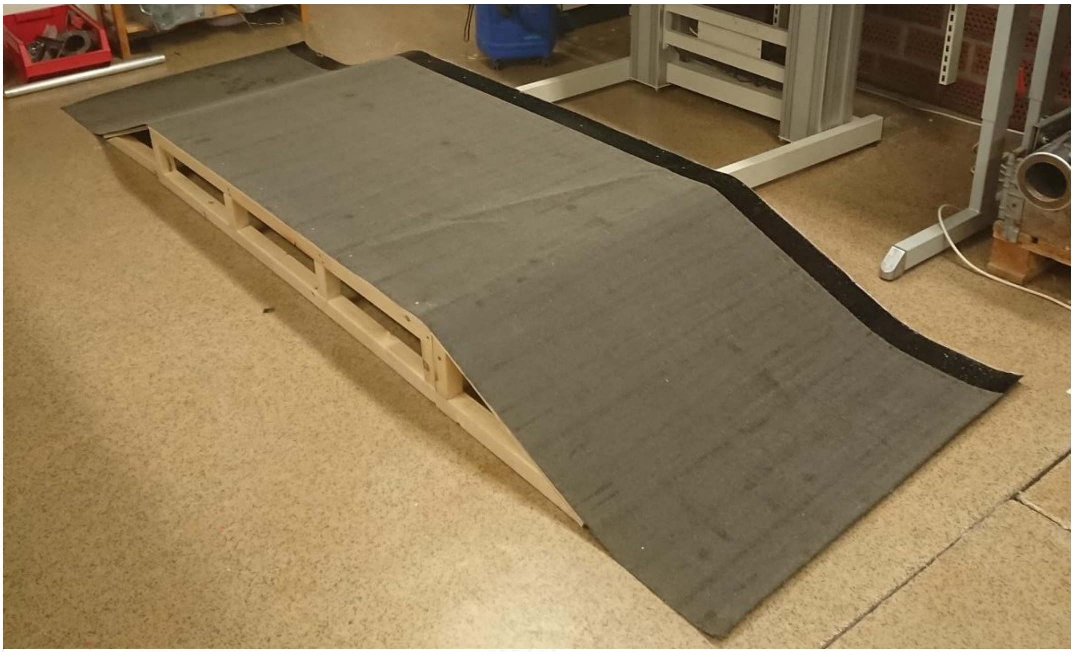

Figure 8-10. Upward slope.

8.3 Test of concept nudges

8.3.1 Method

8.3.1.1 Participants

The test consisted of 16 Ps between 19 and 75 years old (mean = 41). Seventy-five percent were male and 25% female. A majority, 94%, had a driving licence but none drove their car very frequently. Instead, 69% biked every day, hence the majority consisted of experienced cyclists who cycled also during the winter and in poorer weather conditions. One-third of the Ps had been involved in a bike accident during the previous three years.

Based on a screening questionnaire (see Appendix 1b) the cyclists involved in the concept test were more experienced cyclists and more likely than others to adopt a more unsafe cycling behaviour in that they reported to be more likely to speed, overtake other cyclists, and so on. They could therefore be considered to be a critical group of cyclists who are also the people who should be affected by the nudges.

8.3.1.2 Equipment

The Ps used their own bikes on which a Garmin Virb camera (https://www.garmin.com/en-GB) was mounted to provide video-recordings of the test and document speed and position of Ps. If the Ps could not bring their own bikes, they could borrow an electric bike with or without propulsion being turned on.

8.3.1.3 Test route

For different reasons, including the safety of the Ps, the decision was to carry out the trials in a defined area without additional traffic. The selected area was found in Frihamnen which is a isolated open area close to Gothenburg city centre. No intersections or other road users could disrupt the results. Therefore, the measured effects would solely arise from cyclists being subjected to different surfaces.

Three of six abandoned ferry queuing lanes were used as the test route. Two nudges were placed in each of the 3 metre wide lanes, and the cyclists were told to keep to the right at all times (Figure 8-11).

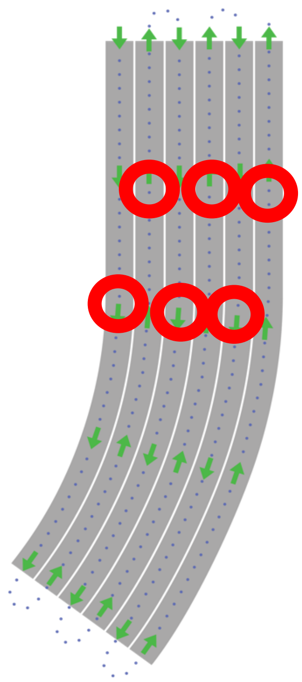

Figure 8-11. Queuing lanes with green arrows indicating how the cyclists were to travel, and nudge locations in red.

The nudges to be implemented were chosen based on the results of the indoor and outdoor tests described in the former sections:

- a spongy surface
- a rough surface (gravel on felt)
- a rubber surface
- soft bump
- upward slope.

Each of the lanes was 100 metres long, which was deemed long enough for the cyclists to reach cruising speed, be subjected to the nudge and then slow down smoothly before turning.

8.3.1.4 Procedure

All tests were held on days with no rain or snow, in daylight, and took approximately 30 minutes for each P. The Garmin action camera was mounted on the bicycle and the participants were instructed to bike along the lanes in the pattern shown in Figure 9-11. They were told to behave as much as possible as they would in a normal situation and bike over all elements that they encountered on the route .

After the test, the Ps were asked to answer a questionnaire. Mainly open questions were asked, which focused on the experience of navigating the nudges, if the Ps thought they were affected in any way, what was the reason (observing the nudge, a vibration, sound etc.), and how they would react if encountering the nudge in a real traffic environment. In addition to open questions, the questionnaire included a semantic differential scale. The Ps were asked to rate their experience according to six different items: "positive-negative", "comfortable-uncomfortable", "safe-unsafe", "secure-unsecure", "intrusive-unnoticeable" and "speed-decreasing - not affecting speed".

8.3.1.5 Measurements

Several measures were introduced to capture any effect of the haptic nudges. Speed reductions were calculated as the decrease in percentage between the highest speed and the speed at certain predetermined positions. The nudges were placed where there was no intrinsic reason to slow down and therefore no baseline was introduced. If the cyclists had not reached cruising speed when reaching the nudge, it is possible that they could have kept accelerating had the nudge not been there. Whether or not cruising speed was reached when reaching the nudge was determined by the speed /distance graphs.

The nudges were not placed at real intersections. It is possible that the effect might have been different if they were. However, if the nudges work on a subconscious level, location should have less of an effect. The aim of the concept test was not to gain a perfect measurement of the potential effects, but to see if there is any effect at all and if the cyclists accept and appreciate the haptic nudges.

Unobstructed sky view is a prerequisite for accurate GPS data. Speed can therefore be measured exactly before reaching and exiting the nudge surface, as well as where the lowest speed is reached. Several measurements of speed decrease will therefore be used. Total maximum speed decrease, speed decrease before reaching the nudge (i.e. the solely visual part), maximum speed decrease on nudge surface and speed reduction over the nudge length. This makes it possible to break down the total maximum decrease into solely visual and mainly haptic parts.

Compared to the trials described in the former chapter (Chapter 8), braking distance was not measured, as the nudges had different lengths and any braking before the nudge would be based solely on visual (not haptic) input. In addition, it was not meaningful to measure trajectory in this artificial situation where cyclists were told to bike over all nudges and as no real traffic existed, it was not meaningful to determine how much the cyclists looked to the left and right.

8.3.2 Results

8.3.2.1 Speed decrease

Several measurements of speed decrease were taken to convey different aspects of the decrease in speed with the overall purpose of separating the visual and haptic elements influencing the decrease.

Analyses of the effect of the visual input revealed a speed decrease of 8-10% for the bumps and slopes. For the rubber strips, soft surface and rough surface the effect was 2-3% and for the spongy surface 1%. Thus, the order is equal to that of the total decrease in speed, but it seems that half the speed decrease for the bump was due solely to visual input (i.e. seeing the contours of the nudge from a distance), with only 15-20% for soft and spongy surfaces.

However, the most relevant measurement for all nudges apart from the slope was how much speed was decreased over the nudge length; in other words how much lower the speed was when exiting the nudge compared when entering it. This is the haptic effect that is persistent over the nudge period. The slope was the only nudge not captured correctly with this measurement, as the slope downwards is supposed to be after the intersection in a real implementation. The analysis showed that the effect of the nudge on reductions in speed was approximately 5% (Table 8-1).

Decrease in speed over nudge length (in %)		Spongy	Soft	Rough	Bump	Rubber strips
Slope	6.3%	0.011	0.142	0.144	0.336	0.394
Rubber strips	5.5%	0.025	0.220	0.223	0.461	
Bump	5.3%	0.004	0.191	0.195		
Rough surface	3.6%	0.075	0.497			
Soft surface	3.6%	0.074				
Spongy surface	1.0%					

Green = statistically significant difference ($p \leq 0.05$); yellow=statistical trend ($0.05 < p < 0.15$); red=no statistical significance ($p \geq 0.15$).

Table 8-1. Decrease in speed over the entire length of the haptic nudge.

The analysis also shows that lowest speed was not always reached at the end of the nudges. For the soft bumps the lowest speed was reached 'on' the bump and for the slope, the lowest speed was reached before going downwards.

Most Ps stated that they only slowed down because they wanted to experience the nudge first, and believed they would not slow down when subjected to it a second time. The speed curve data support this. By extrapolating results from the speed curve to what would happen if the same behaviour was maintained over 20 metres, a potential maximum effect can be found. This takes no account of starting to speed up again, and the results would most likely be much lower in real life. Potential speed reductions are therefore 15% for the slope, for rough, <7% for soft and spongy surface and 4-5% for bumps and rubber strips respectively.

8.3.2.2 Cyclist ratings

The surface and rubber strips received an overall positive rating, the spongy and rough surfaces a neutral rating (i.e. neither positive or negative), while the slopes and bumps received an overall negative rating. The differences are statistically significant (p<0.05). The ratings for comfort, safety and non-intrusiveness were similar.

According to ratings for how much Ps believed the nudges to actually result in a decreased speed, the bumps appeared intrinsically linked to speed reduction (and slopes, due to the slope being presented as an elongated bump) whereas the other nudges were not (Table 8-2).

Average rating of speed decrease potential		Spongy	Soft	Rubber Strips	Rough	Slope
Bump	3.2	1.2E-7	2.6E-6	1.6E-4	2.1E-4	0.16
Slope	2.8	1.3E-5	1.8E-4	0.0030	0.0050	
Rough surface	1.6	0.032	0.14	0.36		
Rubber strips	1.4	0.081	0.26			
Soft surface	1.1	0.20				
Spongy surface	0.69					

Green = statistically significant difference (p≤0.05); yellow=statistical trend (0.05<p<0.15); red=no statistical significance (p≥0.15).

Table 8-2. Cyclists rating of the respective nudges assumed potential to decrease speed on a scale from 1 to 5 (where 1= not at all and 5=to a large extent).

Regarding Ps' acceptance of the respective haptic nudges, 25% of the Ps could accept the bump whereas more than 80% could accept the rubber strips and soft surface (Table 8-3).

Type of nudge	Acceptance	Comment
Soft surface	81%	The main reasons for not accepting the soft surface were that it was found to be confusing and did not fit into traffic. It was accepted because it was found to decrease the risk of injury from falls, because it is more predictable than asphalt.
Rubber strips	81%	Rubber strips were not accepted because they were regarded as intrusive, not soft enough or because they were considered to distract attention. They were accepted because they were softer than ordinary rumble strips and were not perceived as decreasing speed.
Spongy surface	69%	The spongy surface was not accepted because it was believed to remove kinetic energy or to provide poor grip. It was accepted because it was believed to decrease the risk of injury in falls or because it could help in braking or by draining water.
Rough surface	63%	The rough surface was not accepted because it was regarded as "evil" based on its look. It was accepted mainly because it was believed to give a better grip than some of the other solutions.
Slope	44%	The slope was not accepted because it was believed to distract attention or not be suitable in traffic. It was accepted as a means to use when absolutely necessary.
Bump	25%	The bump was not accepted because it was believed to be uncomfortable or dangerous or to result in queues if novice bikers slowed down. It was accepted by those believing it was softer than ordinary bumps.

Table 8-3. Overview of acceptance and motives.

Ps were also asked to rank nudges from their most favoured option (rank 1) to their least favourite least favoured one (rank 6). Each of the nudges was the favourite of someone, and all (apart from the soft surface and rubber strip) were also the least favoured one by somebody (Table 8-4). The soft surface was preferred by many of the Ps because it was found to be soft and harmless and the rubber strips were preferred for the same reasons. The spongy surface was either liked or disliked because it was perceived as harmless but at the same time "unnecessary". The rough surface was either appreciated or loathed, depending on whether it was assessed as "evil" or a way to provide better grip. The slope and the bump were either accepted or found too hard.

	Soft surface	Rubber strips	Spongy surface	Rough surface	Slope	Bump
No 1 (most preferred)	19%	**25%**	19%	19%	13%	6%
No 2	13%	33%	27%	0%	7%	20%
No 3	**33%**	13%	7%	20%	20%	6%
No 4	27%	20%	20%	0%	20%	13%
No 5	7%	7%	20%	7%	33%	13%
No 6 (least preferred)	0%	0%	6%	**44%**	13%	**38%**

Table 8-4. Participants' ranking of haptic nudges.

8.4 Summary and Implications

The haptic solutions that were tested were all basic prototypes and would therefore require significant further work before implementation. For example, a soft surface could be implemented by submerging plates in the ground, but a more realistic alternative would be to mix asphalt and rubber as done on running tracks. In a similar way, a rough surface could be constructed using coarser gravel in the actual asphalt. In order to implement a spongy surface, one would need a much more thorough investigation into what properties are most important for the desired effect. A slope could be made of asphalt without steep sides. However this requires all bike lanes to be submerged or all intersections to be raised, which makes large-scale implementation an improbable solution. The solution that is most easily implemented is the bump since it could be installed as-is if the material is durable enough.

Nevertheless, while at least some of the haptic nudging solutions may be possible to build, the study indicates that haptic nudges could be difficult to implement. None of the haptic measures were fully accepted for different reasons. Even though soft surfaces and rubber strips were accepted by a majority of the Ps, a significant minority did not accept them. However, these more accepted nudges were also the ones that resulted in less of a speed decrease than the non-accepted ones (or any of the visual nudges tested). It is also possible that the observed speed reduction was mainly due to the visual stimulus and not to haptic nudging.

9 Concept Test 3: Visual Nudging of Trajectory 1

This chapter summarises a study performed by TNO to investigate if trajectories could be nudged in a similar way as speed. The project was undertaken in collaboration with Erasmus University Urban, Port and Transport Economics and further described by Vermeulen (2018).

The study tested the influence of presence and absence of centre lane markers in a two-directional bike lane in Amsterdam. Cyclist density at the specific site is up to 2000 cyclists per hour. Separated and wide bike lanes are provided that should accommodate these high cyclist flows. Wider lanes provide a greater margin of manoeuvrability for cyclists, especially when the lane is two-directional. It is important that cyclists feel safe and comfortable while still keeping the lane as narrow as possible. Wide lanes are costly to build and maintain and occupy a large amount of space.

Two-directional cyclist paths come with and without centre lane markers, depending on cyclist flow in the two directions over the day and depending on the width of the cycle path. Centre lane markers are sometimes absent, for example in cases where the cyclist flow in the morning is much larger in one direction than in the other, and in the evening the flow is the reversed. Still it is allowed for cyclists to follow the path in both directions. This leads to interactions between cyclists in both directions.

9.1 Aim

The aim of the study was to investigate whether or not a centre lane marker influences the cyclist's spatial behaviour, more specifically to determine changes in cyclist spatial behaviour when applying a dashed lane divider.

The question was raised by the municipality of Amsterdam, with the objective of finding the ideal width of cycling lanes based on cyclist flow.

9.2 Method

Based on discussions with the Amsterdam municipality, a two-way bike lane separated by a hedge from the main roadway was chosen; Fred Roekestraat (Figure 9-1).

Figure 9-1. The cycle lane used in the test seen from the camera mount.

The two-way cyclist lane has a width of 4 metres and no centre lane marker. The lane has a low hedge with lampposts at one side on a level difference with trees on the other side. This is to prevent cyclists from entering the road or the sidewalk.

Two cameras were mounted, facing in different directions. The TNO Intelligent Imaging department trained a neural network to detect cyclists from the camera images. The tracks were merged over time and image coordinates were converted into real-world coordinates to provide real-life positions of cyclists.

Cyclist intensity, defined as cyclists/hour, was measured over the width of the cycling lane, divided into sections of 50 cm each. This was measured at two locations 40 metres apart, called W and E (Figure 9-2; Figure 9-3).

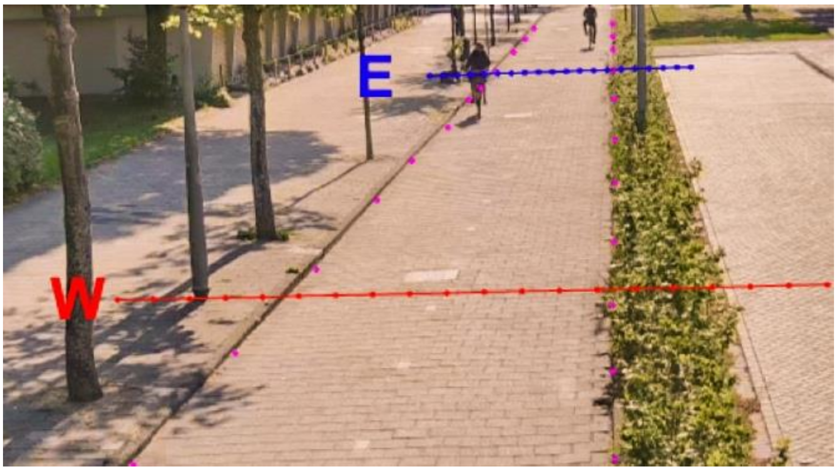

Figure 9-2.The applied centreline was not present at position E.

Measurements were made for cyclists using the bike lane in real life. Camera measurements were taken on two separate Thursdays in May 2018 with similar sunny weather. The days were assumed equal. On the first day no centrelines were applied and on the second day, they were applied over a distance of 40 metres. The centrelines were applied using crayons.

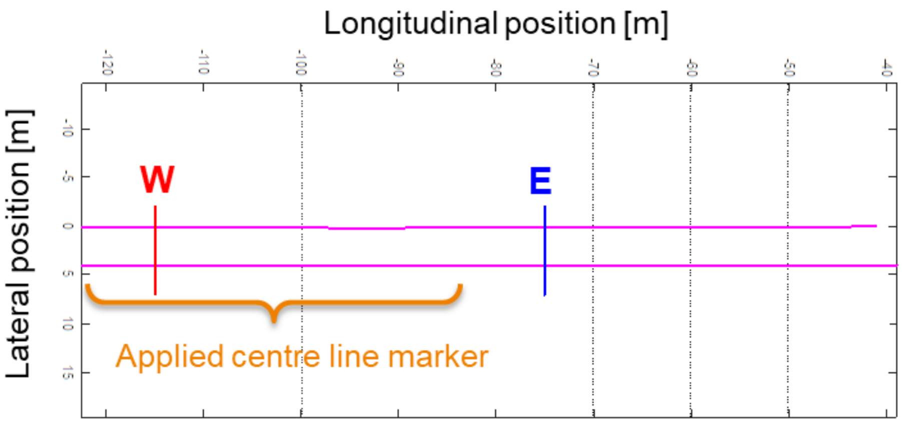

Figure 9-3. Locations where cyclist intensity was measured for each 50 cm of width. The applied centre line is visible in the photo.

9.3 Results

The influence of the centreline marker was measured by comparing the day without a centreline and with a centre line. Figure 9-4 shows the cyclist intensity along the width of the road for positions E and W. Cyclists going in different directions were not taken into account.

No statistically significant differences were found in the position of cyclists with or without the centreline nudge and not for either of the locations.

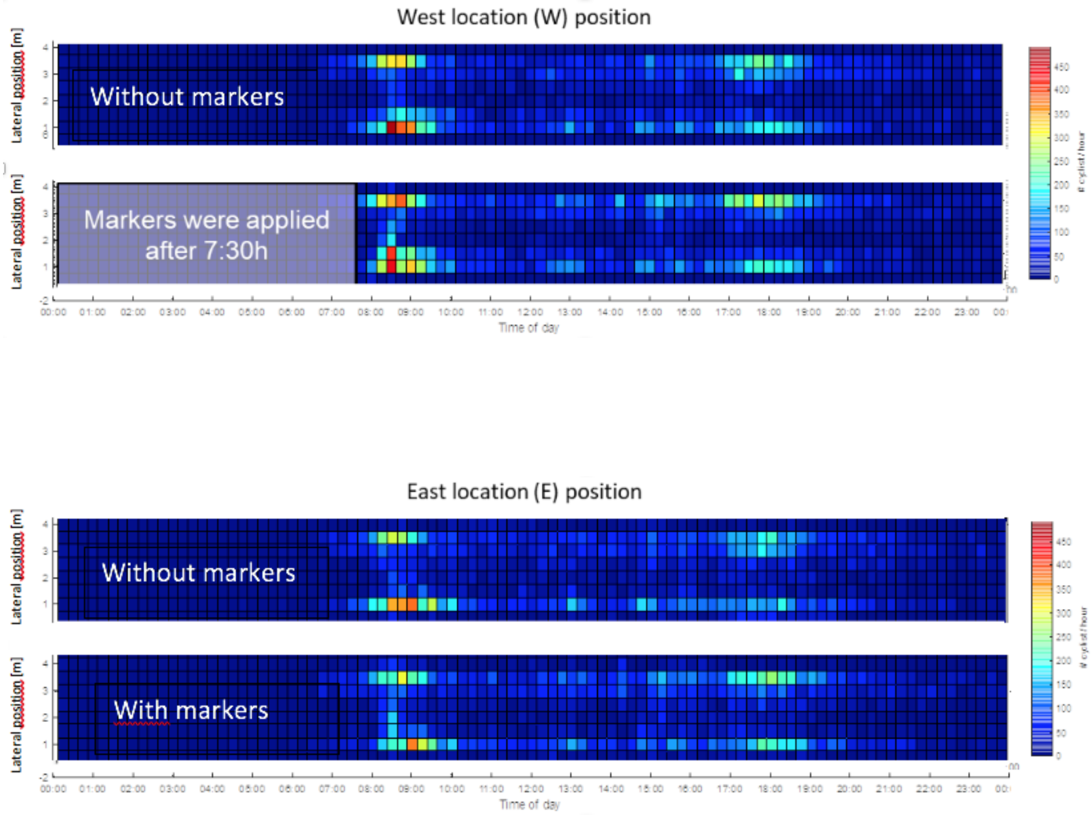

Figure 9-4. Cyclist intensity at different widths along the lane over time, at position W and E.

9.4 Summary and Implications

The study found no difference in the position of cyclists with or without the centreline nudge and not for either of the locations. It is possible that one reason is that the centre lane markers were been poorly visible as the markers were applied with crayon, as an easily applicable non-permanent solution. It may not have been seen as sufficiently demanding. In several cases, multiple cyclists or mopeds were still driving alongside each other. Another possibility is that the cyclists' anticipation behaviour does not need any centreline markers to keep the opposite cyclist flow separated in a safe way.

The absence of an effect on behaviour may therefore be because the layout is already safe or because the centreline was not seen. It is therefore recommended to use more visible markers or even a solid line in future research.

10 Concept Test 4: Visual Nudging of Trajectory 2

This chapter describes an experimental study performed to nudge cyclist's trajectory and speed using lane markings, with the aim of improving cyclist interactions and safety.

10.1 Aim

The aim of this study was to influence cyclists to adjust their trajectory and speed in traffic situations that likely have a higher risk of cyclist conflicts and accidents.

For this purpose, two scenarios were selected for analysis. The first scenario was a lane narrowing situation and the second was a cycling intersection with a sharp turn. A review of relevant literature indicated that these locations, where a bike lane narrows, and a sharp turning exists at an intersection, have a higher risk of cyclist accidents and traffic conflicts (Dozza, & Werneke, 2014; Petzoldt, Schleinitz, Heilmann, & Gehlert, 2016; Wijlhuizen et al., 2016).

Wijlhuizen et al. (2016) analysed the cycling infrastructure of 50 km/h roads in Amsterdam, the Netherlands. The study showed that the number of cycling accidents per metre are related to the uneven profile of the cycling infrastructure including: the presence of sharp turns, missing road markings, missing lighting, sudden narrowing of the path and the presence of a slope. Furthermore, several studies using naturalistic cycling data have shown that cycling near an intersection increases the risk of traffic conflicts for cyclists (Dozza, & Werneke, 2014; Petzoldt, Schleinitz, Heilmann, & Gehlert, 2016). Additionally, a study by Imbert and te Brömmelstroet (2014), also performed in Amsterdam, shows that when intersections get crowded with a lot of cyclists, cyclists tend to adhere less to the traffic rules due to high and uncomfortable levels of stress. Traffic flow might not be ideal in these situations, which could result in a higher risk of traffic conflicts. Nudging could be a way to improve traffic flow if cyclists reduce their speed and adjust their trajectory in time.

In this study lane markings are adopted as a nudge to guide cyclists' trajectories and speed to improve cyclist interactions and safety. The aim is to adopt lane marking nudges for each of the mentioned scenarios in such a way that a cyclist automatically gives way to another cyclist and is able to better anticipate the oncoming situation, possibly reducing the number of conflicts and improving traffic flow.

10.2 Method

The experimental study is part of a research collaboration set up by researchers from the Technical University of Delft (TUDelft). This chapter presents the experimental design and the participants, the data collection process, and the performed analysis.

10.2.1 Experimental Setup

The experimental study was performed in a large indoor hall, where a cycling track was outlined with white tape on the floor of the hall. As shown in Figure 10-1 the cycle track was an oval loop with a width of 2 metres throughout the track. In addition to the loop, there was an additional segment connecting two parts of the loop to create the cycling intersection. Cyclists were allowed to travel in one direction indicated by the red arrow in Figure 10-1.

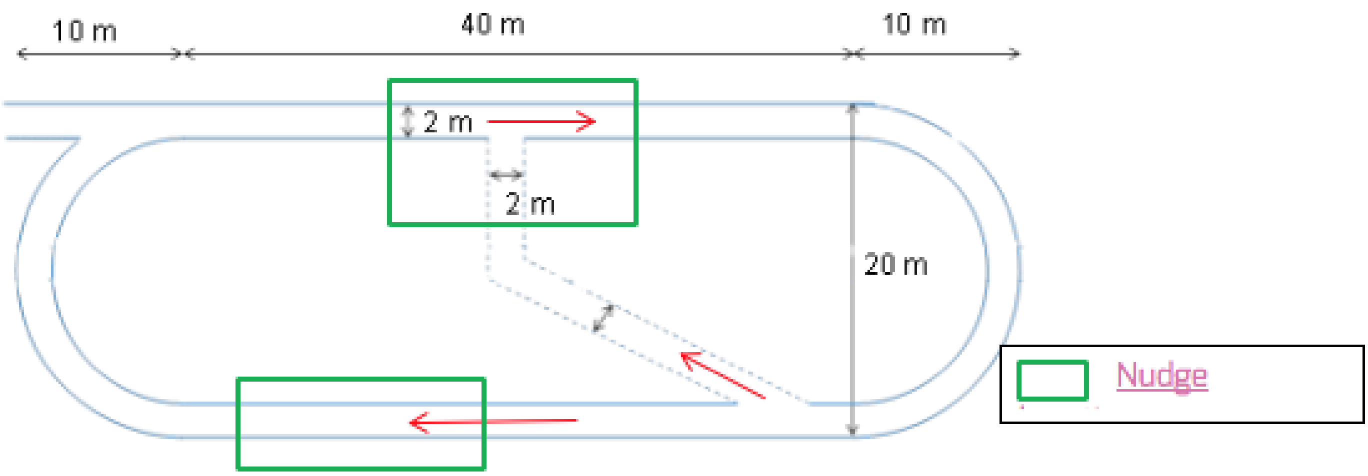

Figure 10-1. The entire cycling track schematically shown

The location of the nudges was then selected at the T-intersection and the long track section for the narrowing lane. These two scenarios were created by adding lane marking nudges with white tape on the floor. In total there were four scenarios:

- Intersection without a nudge (1a)
- Intersection with a nudge (1b)
- A narrowing lane without a nudge (2a)
- A narrowing lane with a nudge (2b)

Figure 10-2 shows the first scenario at the cycling intersection without the nudge where cyclists travel in the direction indicated in red.

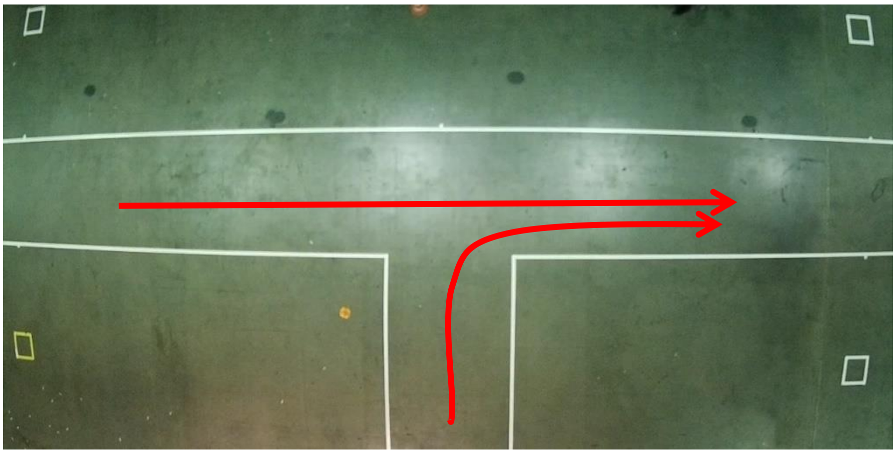

Figure 10-2. Video screenshot from Scenario 1a: intersection without a nudge

Video cameras were installed to record an overhead view of each section of the cycle track. The participants first cycled the track without the nudge and later on in the day with the nudge. After cyclists travelled through the first scenario, a dashed line was added with white tape to the centre of the lane as the nudge. The purpose of adding the centreline is to guide cyclists travelling straight ahead to the left and allow the right turning cyclists to turn into the right side of the lane reducing the number of interactions between the cyclists. The schematics of the nudge design are shown in Figure 10-3 and the implemented nudge is shown in Figure 10-4.

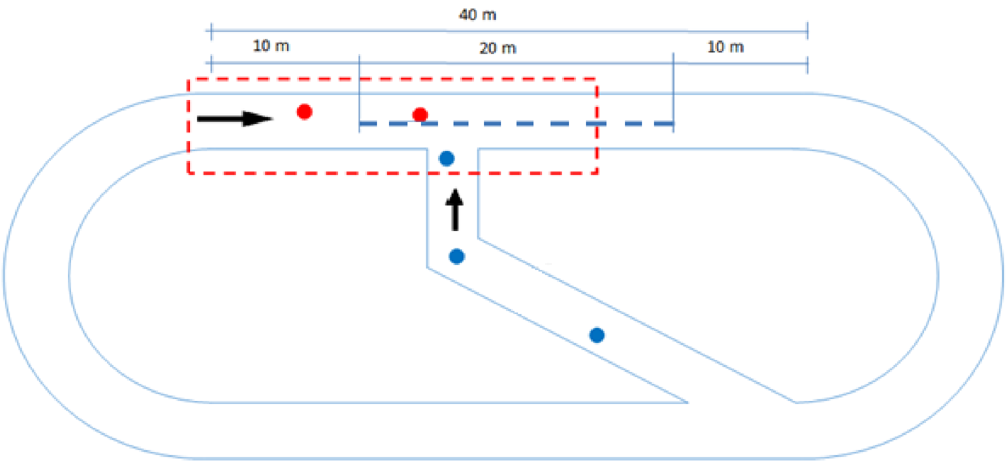

Figure 10-3. Scenario 1b - Intersection with a centreline as nudge. Cyclists are directed two different ways (blue and red), merging at the red lined area. Scenario 1a is the same but without the nudge.

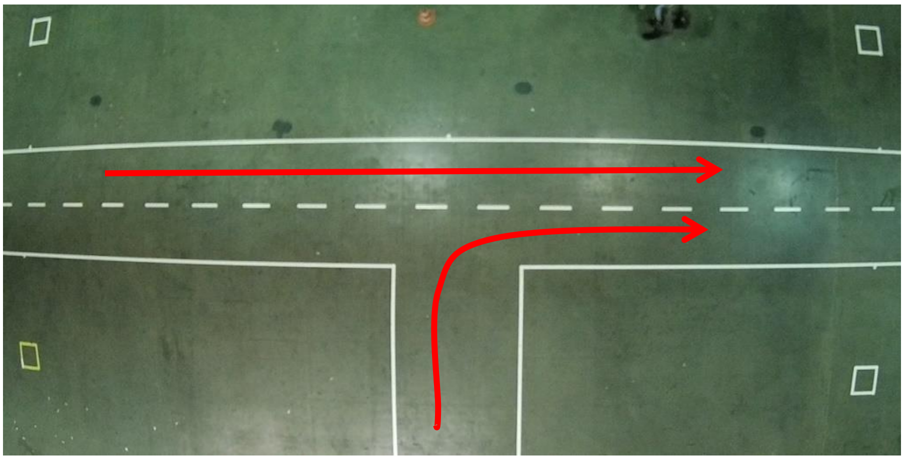

Figure 10-4. Video screenshot from Scenario 1b: Intersection with the implemented centreline nudge

The second scenario is the lane narrowing. Figure 10-5 shows the scenario without the nudge where cyclists travel in the direction indicated in red.

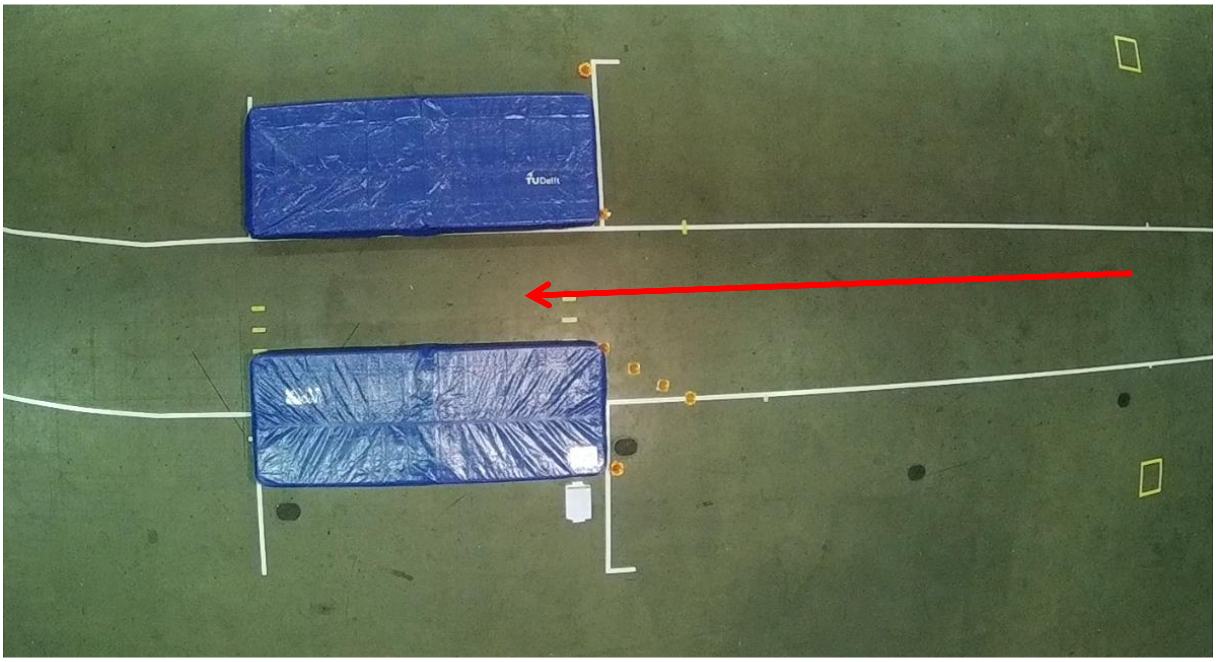

Figure 10-5. Video screenshot from Scenario 2a: Narrowing lane without a nudge

Scenario 2b incorporates a narrowing line starting 10m before the point of narrowing. This nudge aims to slowly guide cyclists to keep to their right and not create a bottleneck situation at the point of the narrowing. Schematics of the design are shown in Figure 10-6 and the implemented design is shown in Figure 10-7.

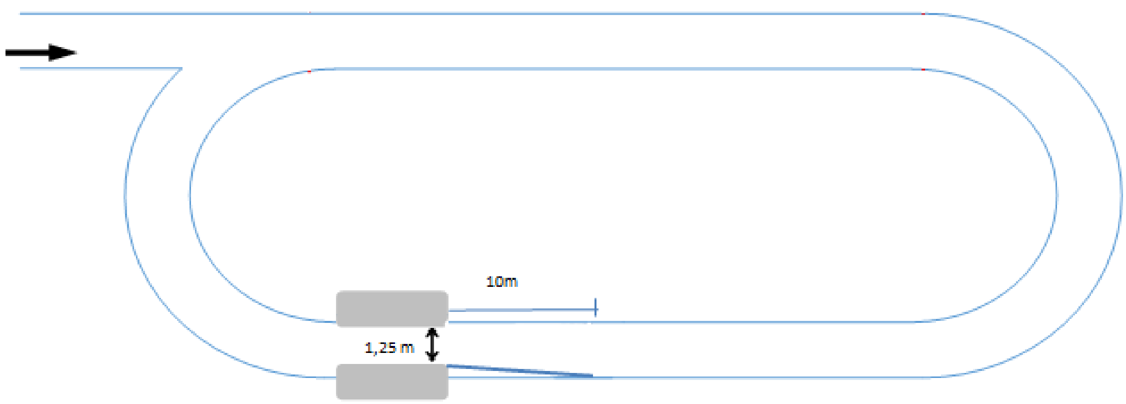

Figure 10-6. Narrowing scenario 2b - A narrowing lane with a nudge on the left hand side to direct cyclists inwards. Scenario 2a is the same but without the nudge.

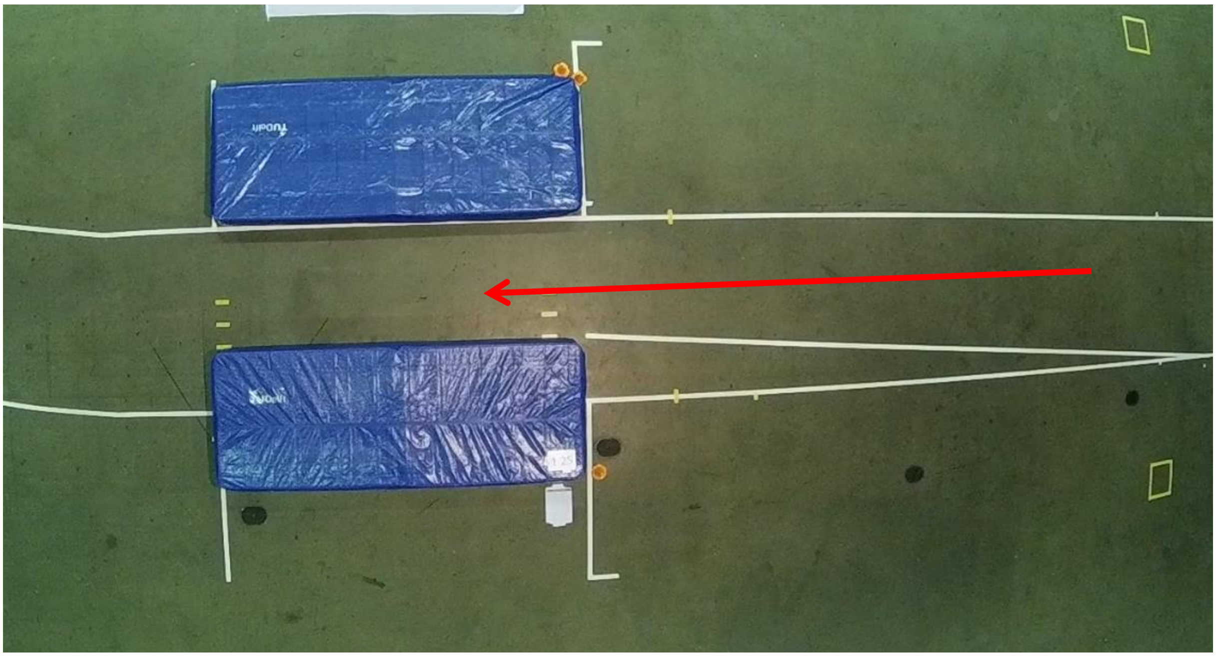

Figure 10-7. Video screenshot from Scenario 2b: Narrowing lane with implemented narrowing line nudge

10.2.2 Participants

Participants were recruited through flyers and by e-mailing cyclists who had participated in previous studies at SWOV. They had to bring their own bicycle to the study location, a regular bicycle, a cargo bike, a racing bicycle or an e-bike. Altogether 40 participants (Ps) participated in the study. The average age of the Ps was 51 (SD=19), ranging from 17 to 89. The Ps were asked to be available for the study for four hours. In those four hours they had to cycle between 1 and 1.5 hours. The cyclists cycled on one track at 10-minute intervals. The Ps received a voucher for 35 euros.

10.2.3 Analysis

Video cameras were placed above the points of interest (shown in Figures 10. 4, 10.5 and 10.7), making it possible to evaluate cyclist trajectories, speed, and safety information. For each scenario, ten minutes of video data were recorded. The two dimensional images were converted into real world coordinates and the cyclist trajectories were extracted using an open-source automated tool called "Traffic

Intelligence" (Jackson, Miranda-Moreno, St-Aubin, & Saunier, 2013). The accuracy of the video analysis algorithms integrated in "Traffic Intelligence" has been validated in previous studies with regard to its tracking accuracy (St-Aubin et al. 2015), accuracy in counting cyclists in various conditions (Zangenehpour, Romancyshyn, et al. 2015), and accuracy in measuring speed (Anderson-Trocmé et al. 2015).

Once cyclist trajectories were extracted, the similar trajectories were clustered together to represent the general cyclist motion patterns for each scenario. The automated clustering algorithm computes the similarity between two trajectories based on their distance and manoeuvre. The outcome is a set of trajectories representing the cyclist motion patterns at these locations. If a trajectory is not similar to a motion pattern, it becomes a motion pattern itself where other trajectories that are similar can be assigned to it. The motion patterns give a clearer picture of the cyclist trajectories, location in the lane and movement compared to the plot of all trajectories.

Furthermore, interactions between cyclists are selected for conflicts between cyclists travelling straight ahead and cyclists turning right. The Post-Encroachment Time (PET) surrogate safety measure is used to represent the time it takes for the first cyclist to leave the conflict point and the second cyclist to arrive. The closer the PET value is to zero the higher the probability of a collision. If the PET = 0 it means both cyclists are at the conflict point at the same time resulting in a collision. Literature indicates that an interaction with a PET value below 1.5 s is a severe conflict, between 3 and 1.5 s has moderate severity, between 3 s and 5 s is an interesting interaction to study, and values above 5 s are safe interactions (Laureshyn et al., 2016).

To evaluate whether or not the nudge affected cyclists' trajectories, speeds, and safety, the motion patterns, speeds, and number of severe interactions of the before-after nudge scenarios are compared.

10.3 Results

10.3.1 Nudge for intersection

Figure 10-8 shows the trajectories extracted from the intersection scenario before the nudge was implemented, and Figure 10-9 shows the plot of trajectories after the nudge. In the before-nudge scenario 719 cyclists were detected and in the after-nudge scenario, 729 cyclists were tracked. The red circles indicate the location from which the tracking originates. In some locations, the origin of the trajectory is located halfway through the lane which indicates the origin of cyclists who have stopped, yielding to the cyclists turning right. Not a lot can be stated from these figures since the manoeuvres are hard to distinguish, except for a few trajectories that travel outside the lane boundary on their left in the after-nudge scenario. To make an easier assessment of the effects of the centre-lane nudge on cyclist trajectories, motion patterns are identified and compared.

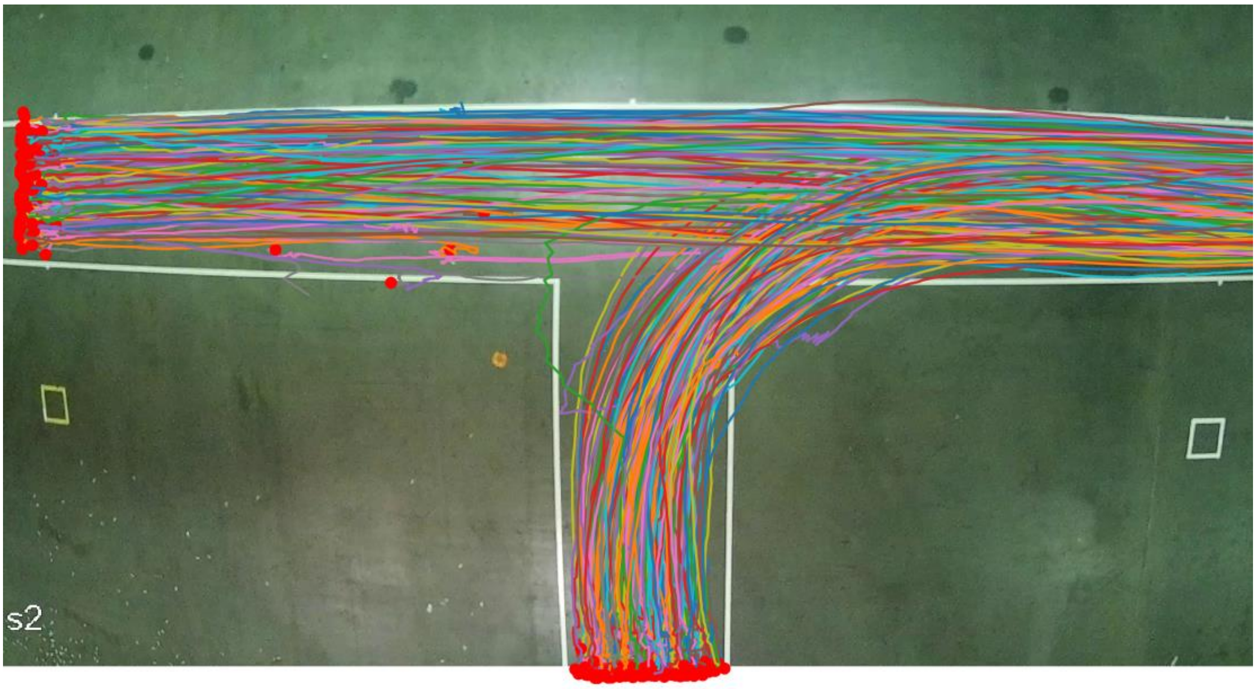

Figure 10-8. Intersection scenario - trajectories before nudge

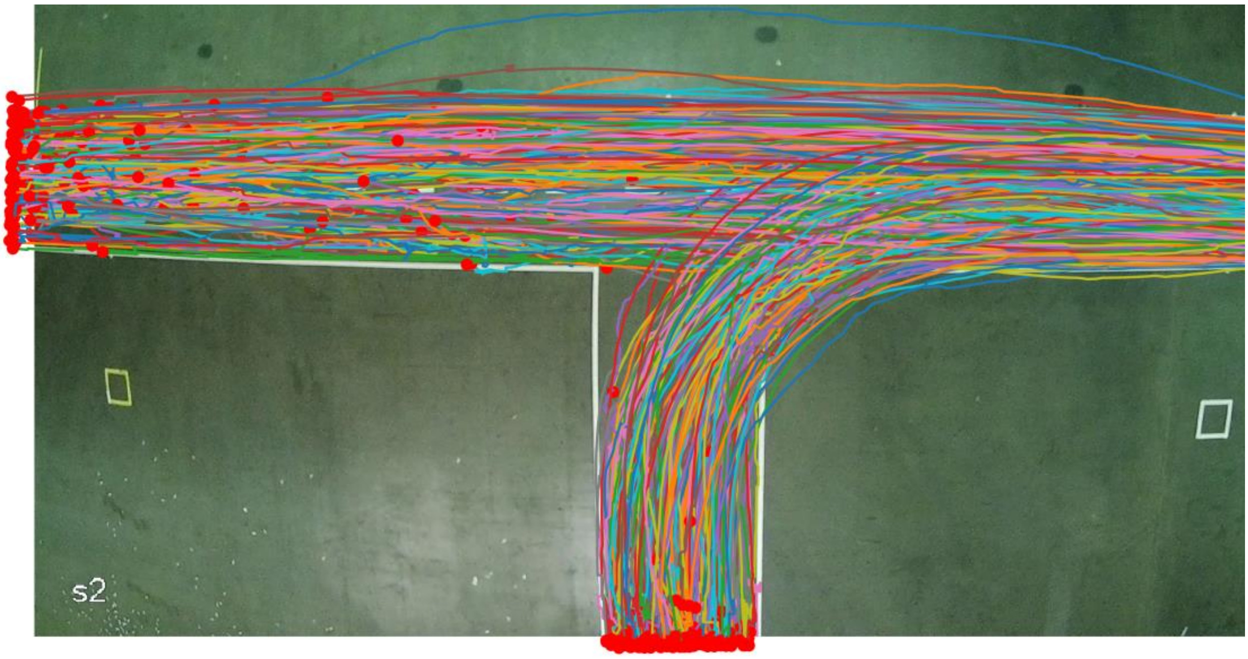

Figure 10-9. Intersection scenario - trajectories after nudge

All trajectories with similar manoeuvre within a 0.5 metre distance were combined to produce the general motion patterns shown in Figure 10-10. Motion patterns are given random unique IDs to eliminate confusion between scenarios. The mean speeds of the cyclists within each motion pattern are represented as boxplots for both before and after scenarios in Figure 10-11.

Looking at the before-nudge scenario, there are 11 general motion patterns and the after-nudge has 10 cyclist motion patterns. In the before scenario focusing on the cyclists travelling straight ahead, around 31% of all cyclists ride the centre of the lane (Figure 10-10Figure 10-10 a. motion patterns 3 and 4), around 20% keep to the left (Figure 10-10 a. motion patterns 1 and 2), 4% stop to give way to the cyclists turning right (a. motion pattern 6), and 0.3% change lanes before the intersection point (a. motion pattern 5). In the after-nudge scenario, the centre-line nudge stratified cyclists into two lanes where roughly 34% of cyclists travel in the left lane (Figure 10-10 motion patterns 432, 70, and 214), 12% ride in the right lane

(Figure 10-10Figure 10-10 b. motion pattern 203), 1% change lanes (Figure 10-10b. motion pattern 90), and only 1% to give way to cyclists turning right (Figure 10-10 b. motion pattern 146). There are fewer cyclists stopping in the after-nudge scenario, and the position of cyclists stopping to give way is also different from the before and after scenario; in the before scenario, 4% of cyclists stop in the centre of the lane whereas 1% of cyclists stop at the right side in the after-nudge scenario. These indicate that the centre lane nudge is able to guide cyclist trajectories into two lanes to allow for easier merging of right turning cyclists. In the before-nudge scenario (Figure 10-10 a), cyclists turning right who stay to the far right make up 27% of all cyclists whereas in the after-nudge scenario cyclists are more evenly distributed in right-turning motion patterns (Figure 10-10 b). Looking at Figure 10-11, the mean speeds of cyclists in the before- and after-nudge scenarios are also different. In the after-nudge scenario cyclists have generally higher speeds: 10.1 km/h compared to a mean speed of 9.2 km/h in the before-nudge scenario. The speed of cyclists turning right, however, is higher in the before-scenario possibly due to the fact that cyclists travelling in the centre must slow down to give way to those turning cyclists. The information is summarised in Table 10-1 and Table 10-2.

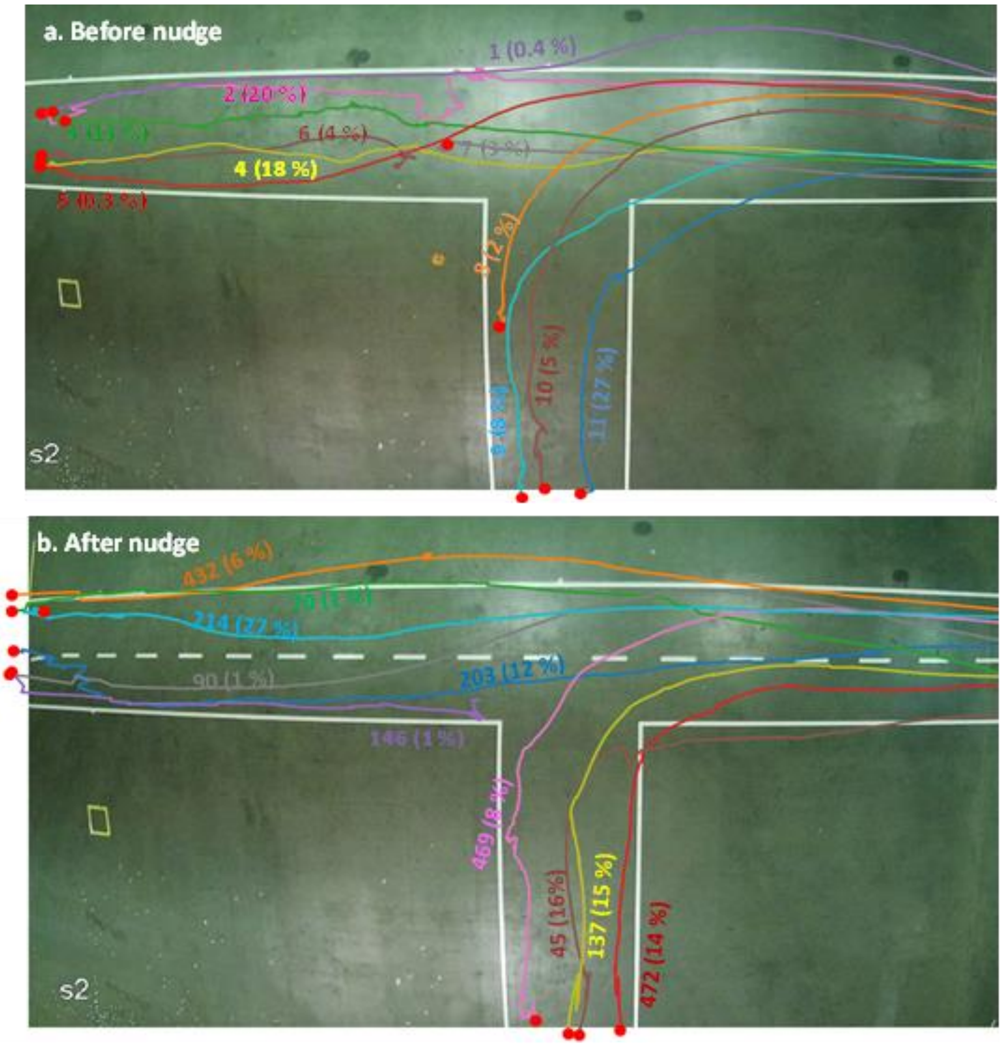

Figure 10-10. Intersection scenario - motion patterns and cyclist proportions a. before nudge, and b. after the nudge.

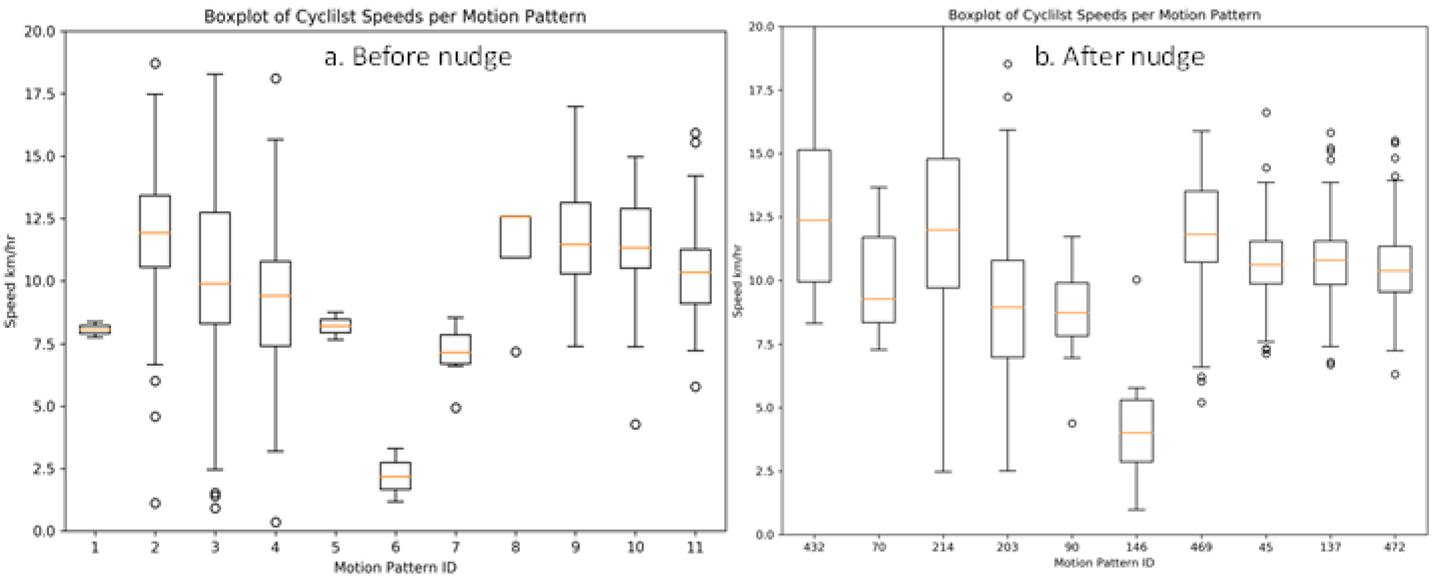

Figure 10-11. Intersection scenario - boxplot of mean speeds per motion pattern a. before nudge, and b. after the nudge

Motion pattern ID (M.P.)	% and (#) of cyclists in M.P.	Mean speed in M.P.	Standard deviation of mean speeds in M.P.	Min mean speed in M.P.	Max mean speed in M.P.
1	0.4% (3)	8.1	0.3	7.8	8.4
2	20% (142)	12.0	2.9	1.1	18.7
3	13% (92)	10.1	3.7	0.9	18.3
4	18% (129)	9.3	3.0	0.4	18.1
5	0.3% (2)	8.2	0.5	7.7	8.8
6	4% (29)	2.2	0.9	1.2	3.3
7	3% (20)	7.1	1.1	4.9	8.6
8	2% (17)	11.2	2.1	7.2	12.6
9	8% (57)	11.7	2.1	7.4	17.0
10	5% (38)	11.4	2.1	4.3	15.0
11	27% (190)	10.3	1.6	5.8	15.9

Table 10-1. Summary table of the intersection scenario before the nudge

Motion pattern ID (M.P.)	% and (#) of cyclists in M.P.	Mean speed in M.P.	Standard deviation of mean speeds in M.P.	Min mean speed in M.P.	Max mean speed in M.P.
432	6% (48)	12.9	3.6	8.3	21.6
70	1% (6)	10.0	2.3	7.3	13.7
214	27% (206)	12.2	3.5	2.5	20.2
203	12% (101)	9.0	3.0	2.5	18.5
90	1% (8)	8.7	2.2	4.4	11.7
146	1% (14)	4.4	2.6	1.0	10.0
469	8% (55)	11.7	2.5	5.2	15.9
45	16% (119)	10.7	1.5	7.1	16.6
137	15% (113)	10.7	1.6	6.7	15.8
472	14% (104)	10.6	1.8	6.3	15.5

Table 10-2. Summary table of the intersection scenario after the nudge

10.3.2 Nudge for narrowing lane

The before- and after-nudge trajectories from the lane narrowing scenario are presented in Figure 10-12 and Figure 10-13. In the before-nudge scenario 737 cyclists are detected and in the after-nudge scenario, 580 cyclists are tracked. The red circles indicate the location where the tracking originates. When looking at the trajectories, they seem to follow a similar movement in both before- and after-nudge scenarios. To better identify the differences, motion patterns are extracted and compared.

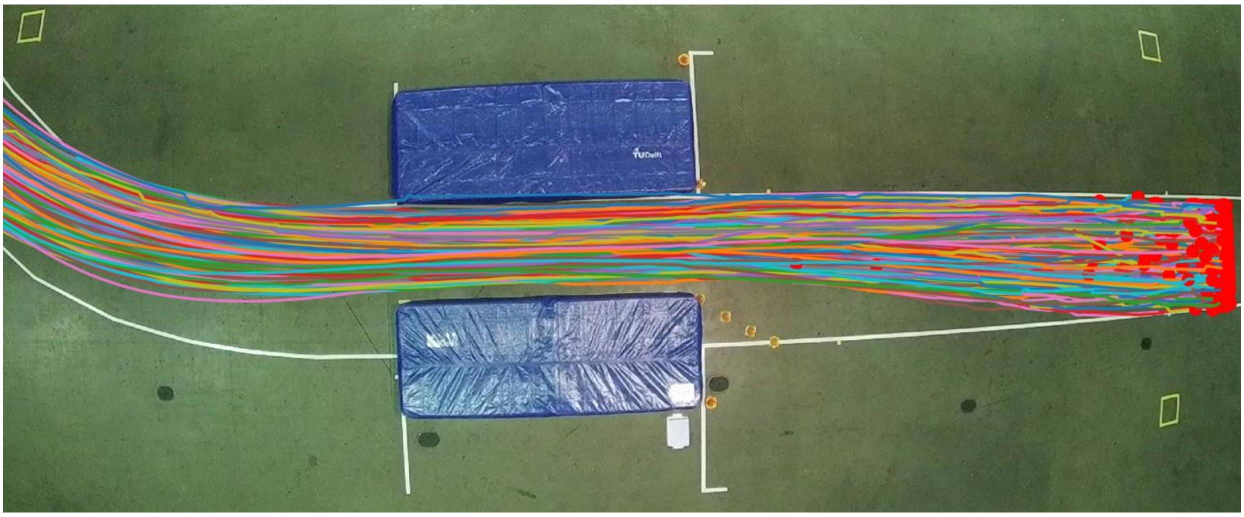

Figure 10-12. Narrowing scenario - trajectories before nudge

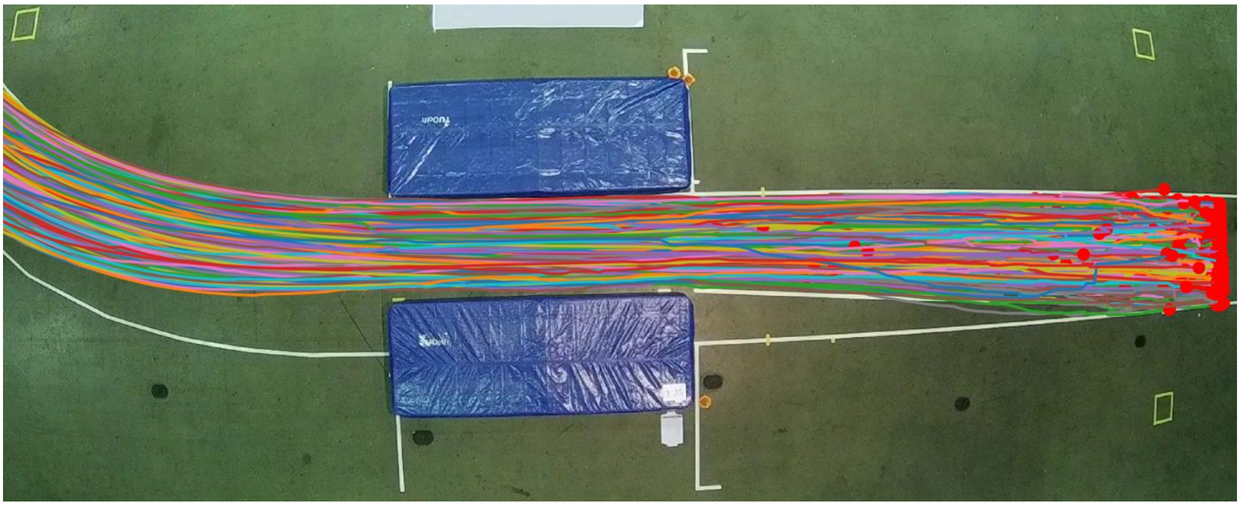

Figure 10-13. Narrowing scenario - trajectories after nudge

Figure 10-14 shows the motion patterns from before and after the nudge (motion patterns are given random unique IDs to eliminate confusion between scenarios), and Figure 10-15 shows the boxplot of the cyclist mean speeds per motion pattern. The information in these figures is summarised in Table 10-3 and Table 10-4.

Comparing the motion patterns, the before-nudge scenario has five general movements compared to four in the after-nudge scenario. Looking at the motion patterns, they both follow the same pattern for cyclists traveling on the far right, in the centre and to the left (Figure 10-14 a. motion pattern number 75 and b. motion pattern number 395). However, the compositions are different; in the before-nudge scenario, the majority of the cyclists (69%), travel closer to the right (Figure 10-14 a. 42% of cyclists follow a motion pattern similar to 551, and 27% follow a similar motion pattern to 75), while in the after-nudge scenario, cyclists travel both in the right and left sides of the lane (Figure 10-14 b. 46% have trajectories similar to 305 to the right of the lane, and 36% have trajectories similar to 495 towards the left of the lane). There is also variation in speeds, where higher speeds are observed in the after scenario compared to before the nudge. The mean speed of the detected cyclists in the before-nudge scenario is 10.0 km/h compared to 11.1 km/h in the after scenario (Figure 10-15; Table 10-3; Table 10-4).

Focusing on the effect of the nudge on manoeuvres, there is no significant change since in the before-nudge scenario cyclists slowly swerve to the right before the narrowing point, following a similar pattern as if the nudge lane marking is already implemented. However, the higher speeds and the more even distribution of cyclists can indicate a higher confidence in cycling when there is a nudge, whereas in the before scenario cyclists slow down and keep more to the right.

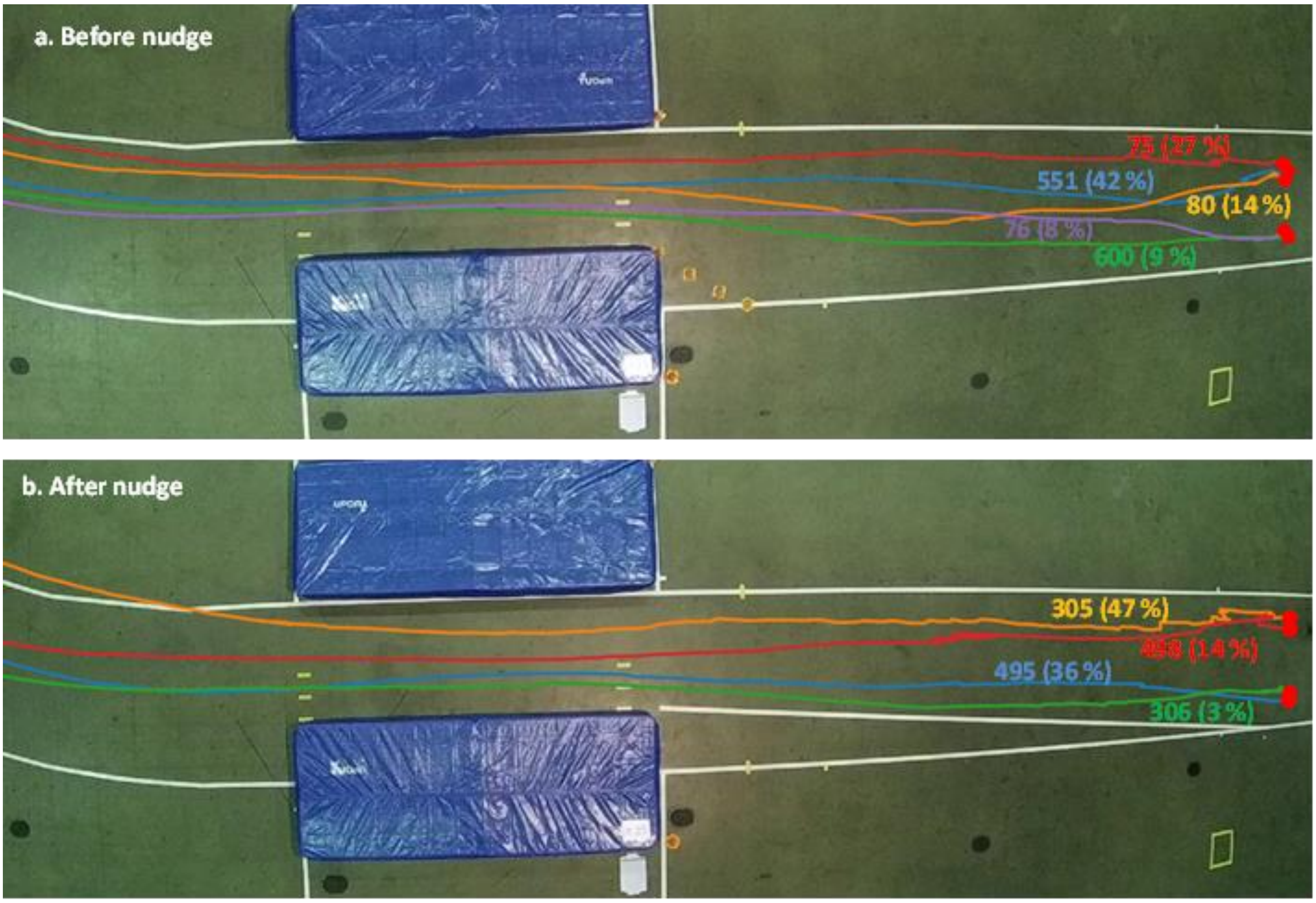

Figure 10-14 Narrowing scenario - motion patterns and cyclist proportions a. before nudge, and b. after the nudge

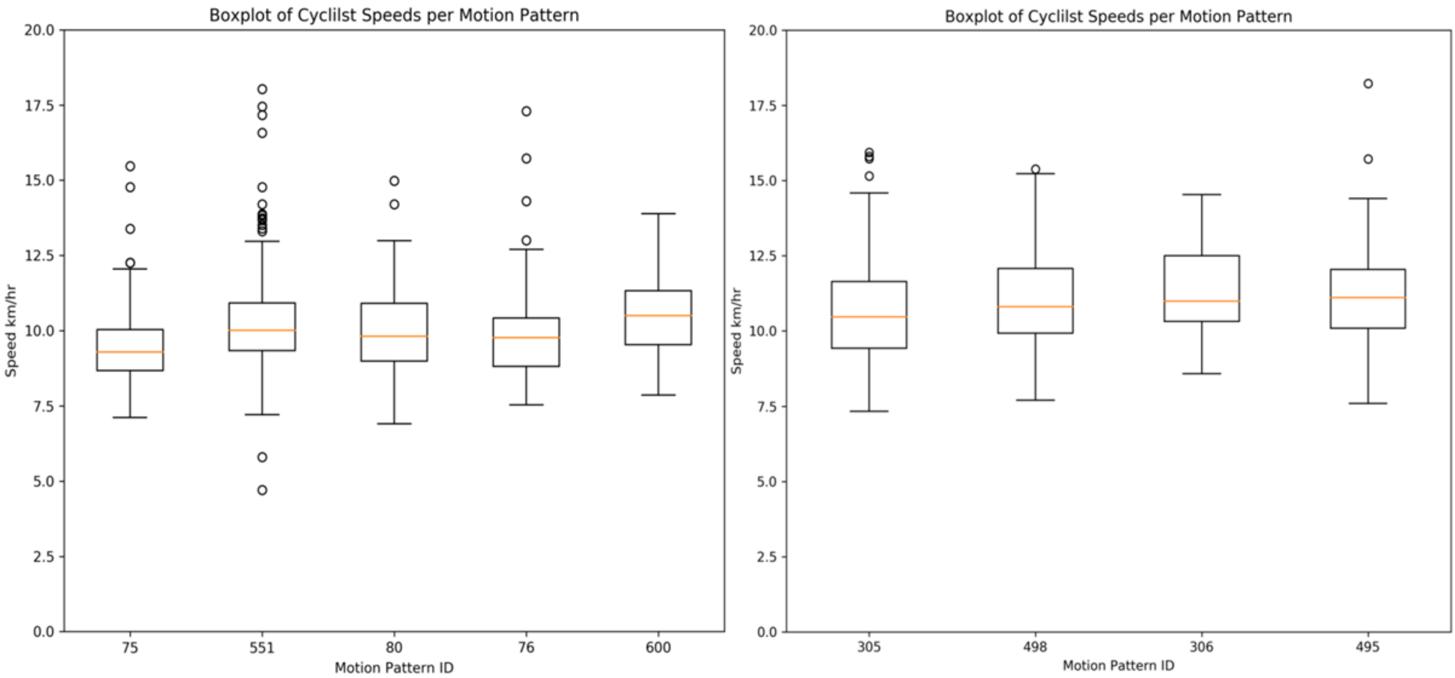

Figure 10-15 Narrowing scenario - boxplot of mean speeds per motion pattern a. before nudge, and b. after the nudge

Motion pattern ID (M.P.)	% and (#) of cyclists in M.P.	Mean speed in M.P. (km/h)	Standard deviation of mean speeds in M.P.	Min mean speed in M.P. (km/h)	Max mean speed in M.P. (km/h)
75	27% (196)	9.4	1.3	7.1	15.5
551	42% (309)	10.3	1.6	4.7	18.0
80	14% (103)	10.0	1.5	6.9	15.0
76	8% (59)	9.9	1.8	7.5	17.3
600	9% (70)	10.5	1.1	7.9	13.9

Table 10-3. Summary table of narrowing scenario before the nudge

Motion pattern ID (M.P.)	% and (#) of cyclists in M.P.	Mean speed in M.P. (km/h)	Standard deviation of mean speeds in M.P.	Min mean speed in M.P. (km/h)	Max mean speed in M.P. (km/h)
305	47% (272)	10.8	1.8	7.3	15.9
498	14% (84)	11.2	2.0	7.7	18.2
306	3% (18)	11.3	1.6	8.6	14.5
495	36% (206)	11.2	1.6	7.6	18.2

Table 10-4. Summary table of narrowing scenario after the nudge

10.4 Summary and implications

The visual nudges were successful in guiding cyclist manoeuvres and speeds especially in the intersection scenario. Generally higher speeds were observed after implementing a nudge in both scenarios. The intersection scenario motion patterns were more affected by the nudge compared to the lane-narrowing scenario. In the intersection scenario, cyclists were mostly divided into the two lanes after implementing the centreline compared to traveling in the centre of the lane in the before scenario. The results indicate that incorporating a lane marking nudge can improve cyclist movements and speeds. Given the low cost and easy implementation of these lane marking nudges, the effects can be considered as significant on cyclist behaviour.

11 Selection of Nudge(s) for Field Trial

This chapter describes the process and result of the selection of which nudges to implement in the field trial.

11.1 Aim

Based on the outcome of the design and evaluation process described in Chapters 6 – 11, the aim was to select which nudge (or nudges) that was (were) to be implemented in the MeBeSafe field trials that are to be run in Autumn 2019/Spring 2020.

11.2 Method

For this purpose, a workshop was arranged with representatives of the project partners, i.e. Safer/Chalmers, TNO, SWOV and the Swedish Transport Administration. All in all, the workshop included eight participants with different areas of experience and expertise.

As a first step, the participants were asked in groups formulate relevant evaluation criteria for the selection of the nudge(s) and to do this from different stakeholders' perspectives. The stakeholders to consider were

- Society in general
- Local authorities/municipalities
- Road maintenance organisations/staff
- Bicyclists and other road users

Altogether 26 criteria were formulated, based on the recommendations presented in D.1.1 and discussions with different stakeholders. Important examples of criteria are that "The nudge should not draw cyclists' attention away from other traffic" and "The nudge should comply with legal regulations".

As a second step, criteria were selected by the participants and weights from 1 to 3 (1= low importance, 2=moderate importance, 3=high importance) were added depending on how important they were considered to be.

In a final step, each type of visual and haptic nudge was assessed by using these criteria. The basis for this assessment was the experiences and results from the trials described in Chapters 6 to 11. In consensus decisions, a plus (+) was used to indicate that the criterion was judged to be met by the type of nudge, a minus (-) that the criterion was not believed to be met, and a zero (0) that the criterion was believed to be possible to meet under certain circumstances. A total score was calculated per type of nudge where a plus was counted as '1', a minus as ' -1' and a zero as '0'.

11.3 Results

11.3.1 Nudging speed

Table 11-1 to Table 11-4 present the results of the evaluation of visual and haptic nudges per stakeholder category.

Criterion (society)	Weight	Visual nudges			Haptic nudges		
		Transverse	Narrow	DigiSign	Soft surface	Rough surface	Dimensional
The nudge should reduce cyclist speed ahead of an intersection	3	+	+	+	-	-	+
The nudge should not decrease cyclists' attention to other traffic	3	+	-	-	-	-	-
The nudge should be possible to install in a variety of bike lanes	2	+	-	+	+	+	0
TOTAL SCORE		8	-1	5	-1	-1	3

Table 11-1. The result of the evaluation. General society's perspective.

Criterion (authorities and municipalities)	Weight	Visual nudges			Haptic nudges		
		Transverse	Narrow	DigiSign	Soft surface	Rough surface	Dimensional
The nudge should have a low installation cost	3	+	+	0	-	0	-
The nudge should have a low maintenance cost	3	+	+	0	-	-	+
The nudge should comply with legal regulations	3	?	?	?	?	?	?
The nudge should reduce the number of accidents on the road	3	+	+	+	+	+	+
The nudge should not cause any personal injuries	3	+	+	+	+	-	-
The nudge should not significantly reduce the efficiency of the biking network	3	+	0	+	0	+	-
The nudge should not be contradictory to the political agenda	2	+	+	0	0	-	-
The nudge should not cause pubic annoyance	2	+	+	0	-	-	-
The nudge should not cause major disturbances for other road users	2	+	+	0	+	-	-

The nudge should not demand closing of the road during installation	1	0	0	+	-	-	-
TOTAL SCORE*)		21	18	10	-1	-7	-10

**) Not considering the question marks in the table.*

Table 11-2. The result of the evaluation. Authorities' and municipalities' perspectives.

Criterion (infrastructure and maintenance)	Weight	Visual			Haptic		
		Transverse	Narrow	DigiSign	Soft surface	Rough surface	Dimensional
The nudge should not contradict laws and regulations	3	?	?	?	?	?	?
The nudge should not negatively affect the working environment	1	+	+	+	0	+	+
The nudge should be cost-efficient to maintain	3	+	+	0	-	-	+
The nudge should be cheap to implement	1	+	+	0	-	0	0
The nudge should not negatively affect accessibility for maintenance vehicles	2	+	+	+	-	-	-
The nudge should provide an attractive business opportunity for infrastructure	3	0	0	+	+	0	+
TOTAL SCORE		7	7	6	-3	-4	5

**) Not considering the question marks in the table.*

Table 11-3. The result of the evaluation. Authorities' and municipalities' perspectives.

Criterion (bicyclists and other road users)	Weight	Visual			Haptic		
		Transverse	Narrow	DigiSign	Soft surface	Rough surface	Dimensional
The nudging solution should not be confusing for cyclists	3	+	0	0	-	-	+
The nudging solution should not be confusing for other road users	3	0	+	0	-	+	+
The nudging solution should not create unsafe situations	3	0	0	0	-	-	-
The nudging solution should not compromise willingness to cycle	3	+	+	+	0	-	-
The nudging solution should be easy to accept and possible to ignore	3	+	+	+	0	-	-
The installation of the nudge should be completed within one day	1	+	+	+	-	-	-
The nudge should be accessible for all users of the cycling facility	3	+	+	+	0	0	-
TOTAL SCORE		13	13	10	-10	-10	-7

Table 11-4. The result of the evaluation. Authorities' and municipalities' perspective.

11.3.2 Nudging trajectories

The requirements put upon trajectory-altering nudges were found to be similar but not equal to those for speed-altering nudges. As they address other problems than the speed-altering nudges (i.e. making cyclists merge easier or dividing traffic from opposite directions), the nudges addressing cyclist trajectory were evaluated separately. Tables 11-5 to 11-8 present the evaluation of the centre line nudge aiming to divide traffic approaching from different directions.

Criterion (society)	Weight	Centre line
The nudge should help dividing traffic coming from opposite directions	3	0
The nudge should not decrease cyclists' attention to other traffic	3	0
The nudge should be possible to install at a variety of biking lanes	2	+
TOTAL SCORE		2

Table 11-5. The result of the evaluation of centre line. General society's perspective.

Criterion (authorities and municipalities)	Weight	Centre line
The nudge should have a low installation cost	3	+
The nudge should have a low maintenance cost	3	+
The nudge should comply with legal regulations	3	?
The nudge should reduce the number of accidents on the road	3	0
The nudge should not cause any injuries to persons	3	+
The nudge should not significantly reduce the efficiency of the biking network	3	+
The nudge should not be contradictory to the political agenda	2	+
The nudge should not cause pubic annoyance	2	+
The nudge should not cause major disturbances for other road users	2	+
The nudge should not demand closing of the road when putting it up	1	0
TOTAL SCORE		19

) Not considering the question marks in the table.

Table 11-6. The result of the evaluation of centre line. Authorities' and municipalities' perspectives.

Criterion (infrastructure and maintenance)	Weight	Center line
The nudge should not contradict laws and regulations	3	?
The nudge should not affect the working environment negatively	1	+
The nudge should be cost-efficient to maintain	3	+
The nudge should be cheap to implement	1	+
The nudge should not affect accessibility for maintenance vehicles negatively	2	+
The nudge should provide an attractive business opportunity for infrastructure	3	0
TOTAL SCORE		7

) Not considering the question marks in the table.

Table 11-7. The result of the evaluation of centre line. Infrastructure and maintenance perspectives.

Criterion (bicyclists and other road users)	Weight	Center line
The nudging solution should not be confusing for cyclists	3	-
The nudging solution should not be confusing for other road users	3	+
The nudging solution should not create unsafe situations	3	+
The nudging solution should not compromise willingness to cycle	3	+
The nudging solution should be easy to accept and possible to ignore	3	+
The implementation of the nudge should be realised within one day	1	+
The nudge should be accessible for all users of the cycling facility*)	3	+
TOTAL SCORE		16

Table 11-8. The result of the evaluation of centre line. Cyclists and other road users' perspectives.

Tables 11-9 to 11-12 summarise the evaluation of the merging line nudge which aim to make the transition smoother when cyclists are turning right into another bike lane.

Criterion (society)	Weight	Merging line
The nudge should help turning cyclists to merge into a biking lane	3	+
The nudge should not decrease cyclists' attention to other traffic	3	0
The nudge should be possible to install at a variety of biking lanes	2	0
TOTAL SCORE		3

Table 11-9. The result of the evaluation of merging line. General society's perspective.

Criterion (authorities and municipalities)	Weight	Merging line
The nudge should have a low installation cost	3	+
The nudge should have a low maintenance cost	3	+
The nudge should comply with legal regulations	3	?
The nudge should reduce the number of accidents on the road	3	+
The nudge should not cause any injuries to persons	3	0
The nudge should not significantly reduce the efficiency of the biking network	3	+
The nudge should not be contradictory to the political agenda	2	+
The nudge should not cause pubic annoyance	2	+
The nudge should not cause major disturbances for other road users	2	+
The nudge should not demand closing of the road when putting it up	1	0
TOTAL SCORE		18

) Not considering the question marks in the table.

Table 11-10. The result of the evaluation of merging line. Authorities' and municipalities' perspectives.

Criterion (infrastructure and maintenance)	Weight	Merging line
The nudge should not contradict laws and regulations	3	?
The nudge should not affect the working environment negatively	1	+
The nudge should be cost-efficient to maintain	3	+
The nudge should be cheap to implement	1	+
The nudge should not affect accessibility for maintenance vehicles negatively	2	+
The nudge should provide an attractive business opportunity for infrastructure	3	0
TOTAL SCORE		7

Table 11-11. The result of the evaluation of merging line. Infrastructure and maintenance perspectives.

Criterion (bicyclists and other road users)	Weight	Merging line
The nudging solution should not be confusing for cyclists	3	+
The nudging solution should not be confusing for other road users	3	+
The nudging solution should not create unsafe situations	3	+
The nudging solution should not compromise willingness to cycle	3	+
The nudging solution should be easy to accept and possible to ignore	3	+
The implementation of the nudge should be realised within one day	1	+
The nudge should be accessible for all users of the cycling facility*)	3	+
TOTAL SCORE		19

**) Not considering the question marks in the table.*

Table 11-12. The result of the evaluation of merging line. Cyclists and other road users' perspectives.

11.4 Summary and implications

The visual transverse nudges received the highest score (Table 11-3). According to the assessments, transverse nudges are thus best at fulfilling the requirements for a cyclist speed-reducing nudge.

	Visual			Haptic		
Criterion fulfilment	Transverse	Narrow	DigiSign	Soft surface	Rough surface	Dimensional

Table 11-13. The result of the evaluation

Transverse nudges are considered to demand less visual attention than narrowing nudges and digital speed signs and, in addition, less attention than haptic measures. They are possible to implement on all types of roads, no matter the width. Narrowing nudges are more difficult to implement on narrow streets and cycle lanes.

Transverse nudges were also rated as the most comfortable by cyclists. A large proportion of the cyclists participating in the different tests seemed to understand that transverse nudges serve to decrease speed. This could mean that it is easier to avoid them, but as they are shown to work subconsciously this will most likely not be an issue. Instead, it is likely that there is a subconscious connection telling the cyclists to slow down, which is advantageous.

The only advantage of narrowing nudges is that they seem to help cyclists maintain straighter trajectories. However, there seems to be no connection between straight trajectories and safer cycling. Instead, the narrowing only seems to draw the cyclist's attention away from other traffic.

The two trajectory nudges provide solutions for two specific scenarios. Both score positive in their respective evaluations (Table 11-14; Table 11-15).

Criterion fulfilment	**Centre Line**
TOTAL SCORE	44
	Merging line
TOTAL SCORE	47

Table 11-14. The result of the evaluation of centre line and mergin line.

However, the centre line nudge was not found to have any effect on dividing traffic from opposite directions although it satisfies other requirements.

12 Summary, Discussion and Conclusions

Task 3.2. has followed an iterative design process of gathering knowledge, identifying problems, generating ideas, testing and evaluating. There is therefore considerable confidence that the implementation of the nudges in WP5 will be successful.

The main objective from MeBeSafe's perspective is that 20% of the cyclists should reduce their speed at intersections. A large number of potential nudges, both haptic and visual, have been developed and evaluated throughout the project. Some of the nudges have previously been used successfully on car drivers, while others were completely novel. The haptic nudges developed were found to have little effect on speed (Chapter 8). Furthermore, they were not appreciated by the participating cyclists. In addition to the perceived lack of comfort with the solutions, there were concerns regarding safety, environmental issues, and the possibility of keeping the bike lanes free of snow during wintertime if haptic nudges were to be implemented. These findings are in line with previous research on haptic measures to affect bicyclists.

On the other hand, the developed visual nudges were highly appreciated by cyclists and were found to reduce speed for all types of cyclists, on average between 12-20 % (Chapter 7). The stripe-based nudges were effective even if the cyclists did not actively notice them, thus affecting them on a subconscious level. This is a clear indication that they were true nudges, and not symbols that were interpreted as a sign to slow down.

The visual nudges were tested on 93 test persons in real traffic . In baseline conditions more than 50% were found to reduce their speed ahead of an intersection. However, the figures were much higher for the nudges. Narrow I and Transverse I both found only one (n=1) P not slowing down, whereas the other nudges found 100% of the cyclists reducing their speed (Chapter 7). Although one can argue that the significant effect of the nudge could to some extent be attributed to the participants in the test seeing the nudge for the first time, the fact that all participants reacted to it makes it plausible that we will meet or exceed the promise of 20% of cyclists reducing their speed in the long term tests.

The nudge chosen for WP5 in order to nudge cyclists' speed is the one with most promising results. It consists of a series of perpendicular transverse stripes over one direction in the bike lane, with the gap distance is decreasing by 7.25%. The stripes run over 20 metres, and the initial gap size is 2 metres. This solution was found to decrease speed by 12% on average and no observed distraction effects. It allows bicyclists to scan the traffic environment normally, without having to focus on the nudge.

The plan was to find one nudge with most potential and implement this in Swedish and the Dutch field trials. This would allow measuring the effect at various locations and in two different countries, to see if there are contextual factors affecting any effect of the nudges. The workplan also states that it is a speed-altering nudge that should be implemented and tried.

However, cycling is argued to differ considerably in Sweden and the Netherlands, in terms of volume of cyclists and bikes, types of bikes, and types of bike lanes, and so on. It makes sense to implement the speed-altering nudge make sense ahead of intersections in Sweden, where both bikes and cars arrive at a speed that is inappropriate for the specific intersection. The high bike-flow in the Netherlands has been claimed to affect the speed in such a way that elevated speeds are not really possible. Moreover, the illusions of a speed-reducing nudge could be obstructed by a large number of cyclists occupying the lane. Therefore, the speed-altering nudges do not make sense to be implemented in the Netherlands. The field trial in the Netherlands will instead focus on visually nudging cyclists' trajectory.

The merging line nudge is the only trajectory-modifying nudge which makes sense to implement in a field trial as it was the only one to have a demonstrated effect. This nudge requires a scenario where two bike lanes intersect, or at least a 3-way intersection. Such intersections are common in the Netherlands, but not in Sweden. Swedish bike lanes are normally built along roads, and will normally not intersect with another bike lane but with a road. Moreover, the traffic flows on Swedish bike lanes are low enough not to present any major merge-related problems. In the Netherlands, a much larger bike flow makes this a real problem.

This results in that the 'Merging Line' nudge will be implemented in the Netherlands, and the 'Transverse Stripe' nudge in Sweden. The field trials in Sweden and Netherlands will therefore collect different data to evaluate the effects of different KPIs. However, both nudges will be implemented at several locations to ensure feasibility at several locations.

13 Deviations from Work Plan

According to the Description of Work (DoW), Task 3.2 was to involve a series of smaller experiments in a controlled environment. The development of nudges has involved a series of experiments – in a controlled indoor environment, in a controlled outdoor environment, and in real traffic – in order to fine-tune and evaluate the respective nudges and consequently increase the likelihood that the nudges tested in the field trials, in WP5, will be successful.

According to the DoW, the work was to address speed reductions at intersections without traffic lights. The experiments have targeted speed reductions and also trajectories as both have potential to decrease accidents involving cyclists.

According to the DoW, the field trial was to involve a test of a visual nudge and a haptic nudge. However, as the results of the work performed in WP3.2 have so clearly shown that the implementation of a haptic nudge for speed reduction is unfeasible to implement from the perspectives of acceptance, safety, as well as bike lane maintenance, the decision was taken not to implement a haptic nudge in the field trial. Furthermore, the studies in WP3.2. have shown that the design of the intersection in itself and the surrounding traffic situation have an impact on the effectiveness of the nudge. Consequently, the decision was taken to implement the same visual nudge at least three different locations.

Furthermore, the plan was to find one nudge with most potential and implement this in Swedish and the Dutch field trials. However, cycling is argued to differ considerably in Sweden and the Netherlands, in terms of volume of cyclists and bikes, types of bikes, and types of bike lanes, and so on. Hence, speed when approaching intersections between bike lane and car route is not considered a main safety issue, instead problems are related to trajectory and flow in bike lane intersections. The field trial in the Netherlands will instead focus on visually nudging cyclists' trajectory.

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Annexes

13.1 Appendix 1a – Survey answered by participants in visual nudge test (translation from Swedish to English)

Responses of N=93

	1- Never	2 - Rarely	3 - Sometimes	4 – Somewhat often	5 – Often
Increasing speed to hit a green light	11.8%	28.0%	39.8%	15.1%	5.4%
Running red lights	32.3%	41.9%	17.2%	6.5%	2.2%
Cars run red lights when you have green	32.3%	38.7%	23.7%	3.2%	2.2%
Getting angry at other road users	10.8%	38.7%	40.9%	4.3%	5.4%
Other road users get angry with you	17.2%	64.5%	16.1%	1.1%	0%
Using mobile phone when biking	46.2%	30.1%	15.1%	6.5%	2.2%
Stopping to let pedestrians pass	1.1%	8.6%	35.5%	30.1%	24.7%
Cars stopping to let you pass	0%	5.4%	30.1%	52.4%	11.8%
Slowing down before an intersection	2.2%	3.2%	14.0%	39.8%	40.9%
Biking on the road instead of the bike lane	9.7%	32.3%	41.9%	15.1%	1.1%

13.2 Appendix 1b – Survey answered by the participants in haptic nudge test (translation from Swedish to English)

Responses of N=16

	1- Never	2 – Rarely	3 - Sometimes	4 – Somewhat often	5 – Often
Increasing speed to hit a green light	13%	25%	38%	19%	6%
Running red lights	31%	38%	19%	13%	0%
Cars run red lights when you have green	31%	44%	25%	0%	0%
Getting angry at other road users	6%	38%	38%	6%	13%
Other road users get angry with you	27%	40%	27%	7%	0%
Using mobile phone when biking	56%	31%	13%	0%	0%
Stopping to let pedestrians pass	0%	6%	44%	38%	13%
Cars stopping to let you pass	0%	13%	25%	56%	6%
Slowing down before an intersection	6%	6%	13%	38%	38%
Biking on the road instead of the bike lane	6%	31%	38%	25%	0%

13.3 Appendix 2 - Looking left and right

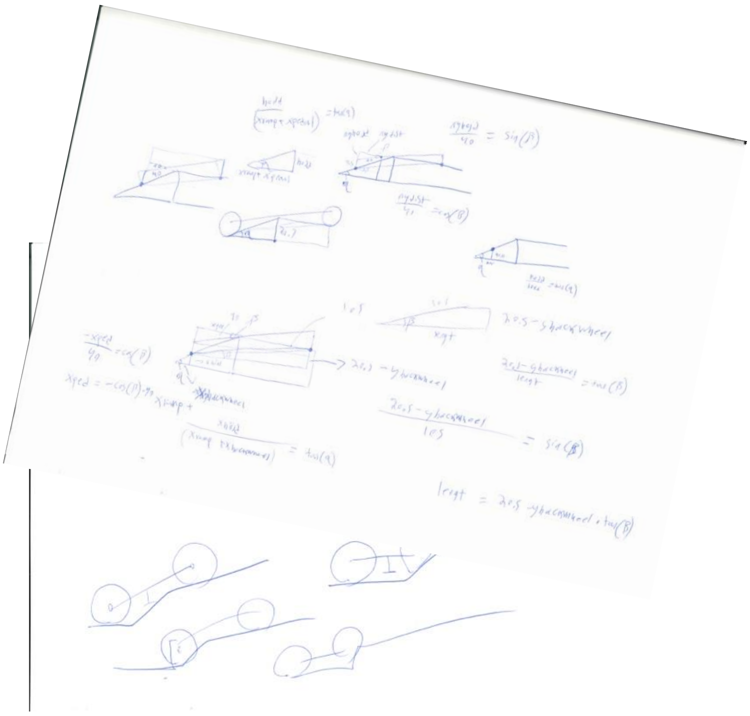
To assess how much the cyclists look to the left and right at intersections, the following classification was developed. It is based on the assumption that safe cycling requires the bicyclists to look to the left (if right hand traffic) on unidirectional roads, but safer to look both left and right.

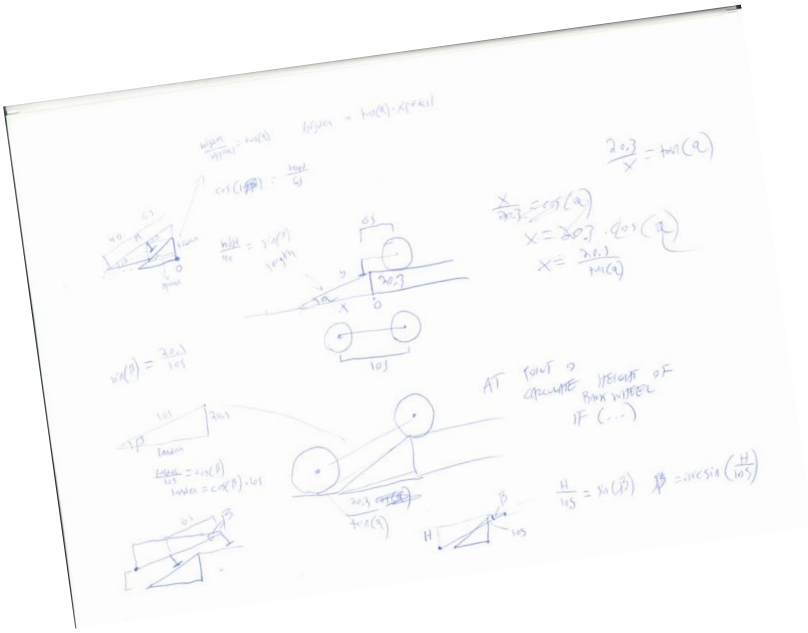
Looking in both directions	1
Looking slightly in both directions	0.8
Looking in the 'correct' direction	0.75
Looking slightly to the 'correct' direction and more in the "incorrect"	0.75
Looking slightly in the 'correct' direction	0.6
Looking in the 'incorrect' direction	0.5
Looking slightly in the 'incorrect' direction	0.3

13.4 Appendix 3 - Slope calculations

This is the MATLAB function used to calculate the possible angles for the slope.

```
function out=doesitwork(alfa)

xramp=-20.3/tan(alfa);

slopelength=sqrt(xramp^2+20.3^2);

if (slopelength<105)

    beta=asin(20.3/105);

    xpedal=-cos(beta)*65;
ypedal=sin(beta)*40+7.5;

    if (xpedal<xramp)

        yramp=0;

    else

      yramp=20.5-tan(alfa)*-xpedal;

    end


    if(ypedal<yramp)

        out=0;

        return

    end

    while (xpedal<(cos(beta)*40+xramp))
```





```
    ypedal=sin(beta)*40+7.5;

    xpedal=xpedal+0.1;

if (xpedal<xramp)

  yramp=0;

else

yramp=20.5-tan(alfa)*-xpedal;

end

if(ypedal<yramp)

    out=0;

    return

end

end




i=0;

while(i<-xramp)

yfrontwheel=20.5;

xbackwheel=xramp+i;

ybackwheel=(-xramp+xbackwheel)*tan(alfa);

beta=asin((20.5-ybackwheel)/105);
```

```
    xfrontwheel=(20.5-ybackwheel)*tan(beta)-xbackwheel;

    ypedal=40*sin(beta)+7.5;

    xpedal=cos(beta)*40+xbackwheel;

    yramp=(xramp+xpedal)*tan(alfa);

    if (xpedal>0)

        out=1;

        return

    end

    if(ypedal<yramp)

        out=0;

        return

    i=i+0.1;

    end

    out=1;

    return

    end

out=0;


end
```

```
function matris=to(matris)

dist=matris(:,1)

enddist=dist(end)

for i=1:size(dist)

    dist(i)=dist(i)-enddist

end

matris(:,1)=dist

end



for i=15:45

    use=i*pi/180

    out=doesitwork(use)

    working(i-14)=out

end

a=[15:45]'

formula=[a working']
```