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D 6.2 – CYCLE SAFETY EVALUATION RESULTS

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Work Package WP6 – Evaluation of the integrated system

Abstract

The XCYCLE project aspires to improve cycle safety and comfort. This has the potential in leading to increased cycling, which ultimately can contribute to increased sustainable mobility in general. The overall aim of WP6 was to provide an in-depth evaluation of the effects of the technological innovations developed in the XCYCLE project.

The willingness to pay studies focused on the XCYCLE on-bike system. A semi-controlled study showed that participants were willing to spend on average 63.00€ for the active system, and that prices should be kept relatively low to aid high market penetration. A cross sectional study showed that the passive system was most appealing for end users and that the worse the cycle conditions are, the more users are willing to spend on the systems.

The green wave studies evaluated the effects of the GLOSA (Green Light Optimal Speed Advisory) with adaptive control. A scale-up simulation showed a success of the green wave system in reducing number of stops for cyclists with a minimal impact on the overall traffic efficiency. Even though the system would need some future improvements, an observational and a semi-controlled study showed that the XCYCLE system improved cycling efficiency and quality, without negative effects on cyclist attention. Also, cyclists held positive attitudes towards the system, indicating that an improved version of the prototype in the project is likely to be accepted and used.

In the AIM research intersection in Braunschweig the amber light was installed and evaluated through a five-week observational study and a survey. The observational study revealed positive effects on traffic safety and behavioural adaptation. The criticality of encounters between right turning motorists and crossing cyclists decreased while

the approach speed increased without resulting in more safety-critical situations. The results of the survey study were in line with the observational study.

The on-bike system was evaluated through semi-controlled field study at the AIM intersection. Results showed that acceptance and trust ratings decreased with experience. Participants rated the idea of the on-bike system positive, but the ratings decreased after using and experiencing the system. Reasons for this are discussed. The on-bike system was also evaluated through focus group discussions. Results highlighted positive attitudes in terms of trust and usefulness when considering the system without actually using it, which was in line with the semi-controlled field study results.

The in-truck warning system was evaluated through a focus group study, aimed to assess truck drivers' and cyclists' perceived usefulness, trust, potential risks of the system, as well as collecting suggestions for further improvements. The results showed that truck drivers recognized the situation where a truck turns right to cross a cycle path as a dangerous situation. Truck drivers expressed positive attitudes to the warning system in general. The bicycle bell warning sound was perceived as very nice and intuitive. Some drivers expressed that due to the increasing number of driving assistance system installed in trucks they might be "overloaded" and discussed over-trust/over-reliance phenomena as possible as well. All drivers concluded that the pros of the system would overweigh the cons by far. Cyclists also expressed positive attitudes toward the system, maintaining concerns related to the system functioning and possible false positives or false negatives.

A Cost-benefit analysis (CBA) has been conducted to assess the socio-economic impact of the XCYCE system on a holistic perspective. A framework has been developed to identify the impact on specific incidence groups (i.e. road authority, cyclists, drivers, industry/OEM and the government) before accounting for it at a societal level. Analysis revealed that there is a good economic case for all the XCYCLE systems, even if some performed better (In-truck system) than others (On-bike system).

In the final section of the documents, results from each studies have been discussed and linked. The overall conclusion of WP6 is that the XCYCLE systems proved promising results towards increased cycle safety and comfort. Future work should focus on improving and refining the systems in some respects.

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1 Introduction

The overall aim of the XCYCLE WP6 is to evaluate the single technologies and the integrated system that have been developed during the course of project in terms of behavioural effects, safety outcomes and cost-benefits ratio. The vision of the XCYCLE project is to ultimately have a decisive impact on cycling safety and comfort, reducing the occurrence of dangerous interactions between cyclists and motorised vehicles and at the same time increasing cycling efficiency and making cycling more attractive. This encourage more European citizens to choose the bicycle as their primary mean of transport for urban trips. The vision of the XCYCLE project is to ultimately have an impact in increasing cycling safety and comfort.

In WP3, WP4 and WP5 each technology and the integrated XCYCLE system have been tested from a technical perspective, showing that the consortium has delivered new technological advancements that can actually increase cyclists' safety and have the potential to foster road users' safe behaviours in the traffic environment. Being the user-centred design one of the core approaches of the XCYCLE project, WP6 activities have been devoted to assessing how proposed solutions and innovations actually impact road users' behaviour and if they properly respond to road users' needs. Both young and elderly cyclists have been included in most of the study samples. The purpose of the current deliverable is to report an in-depth evaluation of the user acceptance of the XCYCLE innovations. The main variables observed in the different studies regards users' tactical behaviour, attitudes, willingness-to-pay and cost benefit ratios. Evaluation activities here reported have been conducted following the evaluation plan reported in D6.1.

The assessment of each solutions has been conducted with different methods and instruments due to the peculiarity of each system, but comparability and integration of results have been of great concern for the whole duration of the project, as D6.2 will show. For example, when assessing users' willingness to pay, infrastructure-based systems do not have to be directly payed by end users. In this case it is more relevant to investigate actual safety outcomes and changes in road users' behaviour to make the systems more appealing for municipalities and local institutions, who can decide to have them installed in certain locations and foresee method to sustain their implementation and maintenance. In the case of the XCYCLE truck-based system, which has been proven to be effective, it is eventually more likely to spread, either, because the system will become standard in new vehicles, or because it is attractive to the end users, or because of regulations. The successful and lasting introduction in the market of the on-bike system is instead much more dependent on being attractive enough to end users. Due to this reason we focused thoroughly on assessing cyclists' willingness to pay of such system.

In the present deliverable, the costs and benefits of the XCYCLE systems for the society at large are investigated as well. It is important to account for system effects on multiple perspective, especially because those effects can be beneficial, but might also include possible unwanted side effects. If the green wave for cyclists leads to increased waiting times for cars, pollution may increase, and efficient work time is lost, but it might also lead to some drivers shifting to cycle instead. A vehicle-based system may be an initial cost for the owner, but may save both lives, societal costs and insurance fees in the long run. An on-bike system may require some battery maintenance but may save lives. Considering both short-term and long-term effects, as well as direct and indirect effects will lead to a clearer picture about the impact of the system.

Before getting to the reported results of the two willingness to pay studies, the evaluation of the effect of each XCYCLE systems and the cost benefit analysis of the whole proposed solutions, we here give a brief overview of each system and their functioning.

1.1 Green wave system

The green wave system was installed at the Paterswoldseweg-Parkweg intersection in the city of Groningen, the Netherlands, with the aim to facilitate for cyclists so they should experience unimpeded, safe and comfortable riding. The green wave system consisted of a sensor 200 m before the intersection for detecting cyclists, as well as a variable message sign at the right-hand side of the cycle path in the intersection, counting the time down until the traffic light for cyclists would be green (Figure 1). This would let the cyclists adjust their speed according to the count down and create their own green wave. In the intersection buses have priority, and hence the sign showed an additional bus to the countdown digits when a bus was close by in order to inform users that the countdown may be less reliable due to the priority.

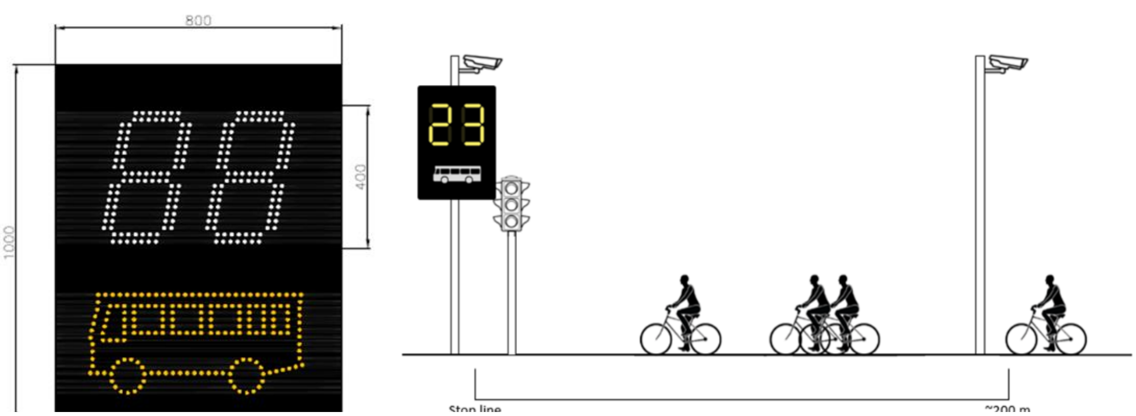


Figure 1: Green wave system installed in Groningen

1.2 Infrastructural detection system

An infrastructure-based vehicle and vulnerable road user (VRU) detection system was installed at the AIM Research Intersection in Braunschweig. The detection system consisted of two poles (TraffiTowers) with a base width of approximately 40 cm. Each pole was equipped with a vertically oriented stereo video camera and a computer for stereo video signal processing. The camera system consisted of two cameras providing images with high resolution. A Linux operational system was used for executing the algorithms for real time objection detection. The field of view as well as the images provided by the detection system is presented in Figure 2.

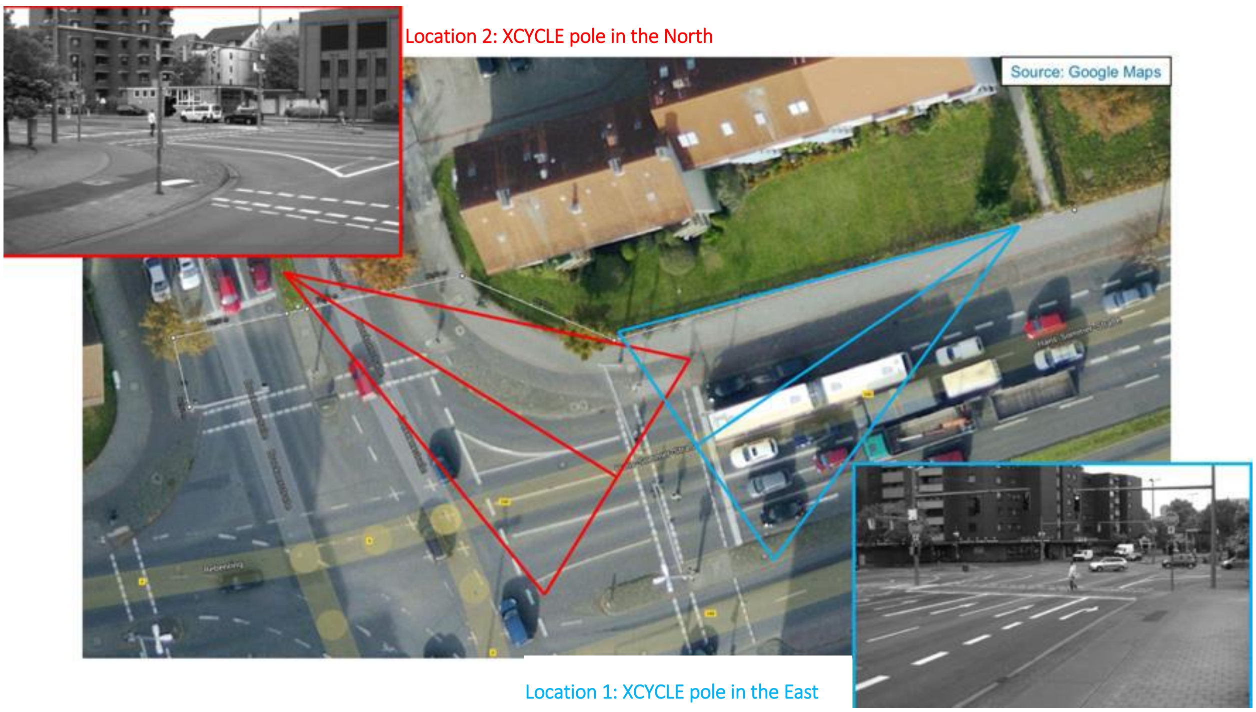


Figure 2: Position and field of view of the poles of the infrastructure-based detection system.

The infrastructure-based detection system was able to detect, categorize, and track road users travelling through the intersection. In this particular scenario, motorized traffic approaching the intersection in the right lane coming from the East and turning North was detected and tracked. In addition, cyclists were also detected and tracked travelling from East to West through the intersection. As a result, trajectory data of those road users were generated and recorded.

Those trajectories were the basis for the online situation and risk assessment predicting the risk of a collision between a right turning motorist and a crossing bicyclist. The assessment was based on the analysis of cycling and driving behaviour as well as interaction patterns between motorists and cyclists. When the algorithm predicted a conflict between a cyclist and a motorist, a message was generated. The degree of conflict was based on the estimated level of risk (see Table 1). For more information on the development of the online risk and situation assessment algorithm, please see D5.3.

Table 1: Overview of defined risk levels. Definitions of risk are based on the definition of encounters and conflict postulated by Erke & Gstalter (1985).

Risk level value	Risk level name	Definition
0	No risk	Road users are not on a collision course
1	Information	Non-critical interaction (spatial-temporal encounter situation of two road users anticipating their behaviour)
Critical interactions: Road users approach each other in a way that the probability/risk of a collision increases. In such a case only a risk mitigating manoeuvre can prevent the collision		
2	Warning	1st degree critical interaction (late but controlled evasive manoeuvre, such as braking or swerving)
3	Assistance	1st degree critical interaction (late but controlled evasive manoeuvre, such as braking or swerving), but more severe than risk level 2
4	Intervention	2nd degree critical interaction (last second evasive manoeuvre, such as braking or swerving)

This message could be transmitted wirelessly to the parties involved in the potential conflict. For example, the message might either be sent to the so-called amber light informing motorists or to a so-called on-bike system warning cyclists (for more technical information, please see D4.2 and D5.3).

1.3 Amber light

The amber light was installed at the AIM Research Intersection for the purpose of testing the effects of the warnings on road traffic safety. The amber light was a mobile and battery operated traffic light with an incorporated bicycle emblem. It consisted of four components: (1) a basis box, hosting the batteries, a junction box, a Raspberry-Pi and a Linkbird modem, (2) the mast, (3) an antenna, and (4) the signalling light (Figure 3). When activated, depending on the estimated level of risk, the amber light illuminated either amber-coloured (risk levels 2 & 3) or flashed (risk level 4) at a frequency of 6 Hz.

Figure 3: Installation of the amber Light at the AIM Research Intersection showing the warning for the motorist.

1.4 On-bike system

The on-bike system was based on an active tag cyclist detection developed by the University of Bologna. It was designed to locate different road users, especially bicyclists, and provide early warnings about dangerous interactions with other road users, particularly motorists. Being able to identify individual cyclists also means, being able to send targeted messages to only those involved in the situation. In order to do so, bicycles need to be equipped with an active tag. The position of the bicyclist can be determined based on data exchange with geo-referenced nodes, called anchors. For the user evaluation at the AIM Research Intersection in Braunschweig, those nodes were placed in the TraffiTowers. The tag ID was fused with the positioning information obtained through cameras detecting moving road users. When the online risk and situation assessment estimated a potential danger, a warning could be sent to the corresponding on-bike system. A sketch of the designed HMI as well as the result of the 3D printing is shown in Figure 4 (for more technical details. Please see D5.2).

Figure 4: Left: Sketch of the designed HMI. Right: Result of the 3D printing mounted to the handlebar.

1.5 Truck system

The truck system evaluated in this work package was developed in WP3 and consisted of an in-vehicle mounted HMI, placed in the middle of the console in front of the driver, and sensors on the side of the truck for cycle detection. The HMI comprised a number of LED-lights in a horizontal alignment, connected with an auditory directional warning in the form of a bicycle bell. The aim of the warning system is to inform and alert the truck driver of a potential collision with a cyclist, when executing a right turn (right hand traffic) and the cyclist is located in the "dead" viewing angle of the driver. The warning system consists of four different warning stages as shown in Figure 5: Left: HMI in truck. Right: Warning stages.

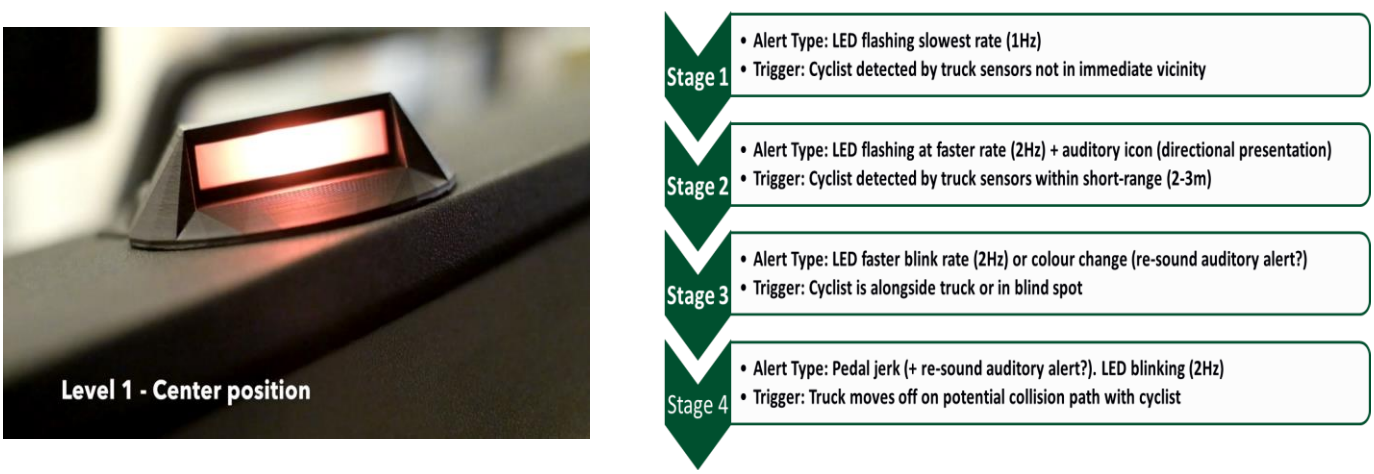


Figure 5: Left: HMI in truck. Right: Warning stages.

Willingness to pay study (T6.2)

This section reports the two willingness to pay (WTP) studies conducted to evaluate users' reactions and interactions with the XCYCLE on-bike systems. To this regard, two studies were conducted.

The specific aim of the first study was to investigate potential users' WTP and willingness to accept (WTA) of an on-bike system that warns about potential collisions with motorized vehicles. In this first study, participants had the opportunity to experience the on-bike systems in a controlled environment. WTP and WTA were investigated using Contingent Valuation (CV) methods which offer a more direct route to obtaining WTP or Willingness to Accept (WTA) values.

In the second study, two separate methodological approaches have been taken to obtain the WTP from potential users. The first approach uses a stated preference behavioural choice-based methodology, whilst the second relies on a Contingent Valuation methodology.

With WTP experiments, better results are usually attained through the use of Stated Preference (SP) approaches where valuations of attributes are derived through a process of trading off between different levels of attributes over a number of hypothetical scenarios. In this way, more information is elicited from each person than just a simple reported WTP and we can get robust valuations from fewer responses. In making trade-offs the participant is made to think more carefully about their implicit valuation of attributes.

Resultant WTP valuations from such choice experiments can be derived through discrete choice modelling such as multinomial, nested or mixed logit. Results could additionally be segmented by various dimensions to look at variation in valuations by dimensions such as traveller type, sociodemographic characteristics, whether they have had actual experience of such devices, and location.

Both approaches were administered through an online panel survey which presented a set of SP questions to the participants first, followed by the more direct WTP and WTA questions. Further detail of how the survey was conducted can be found in Section 3 but in summary, the survey was undertaken across six countries – Spain, the Netherlands, Hungary, Italy, Sweden and the UK – by respondents who had cycled at least, on average, once a month during a sustained period, e.g. the summer. These countries were chosen to reflect a range of existing cycle levels (see D2.1) as well as covering different geographical areas, economic situations, and cultural regions of Europe.

2.1 Objectives

The foundations for a business case assessment will be laid by investigating the cyclists' WTP for either passive or active safety devices. User willingness to pay will have a significant impact on system adoption and overall effectiveness. There may be large differences between countries in WTP for devices and also differences between different groups of cyclists. Such differences can be clearly seen in current attitudes towards and use of protective devices, such as helmets. The WTP research contained in this report provides an opportunity to investigate these issues by ascertaining willingness to pay for and use of both passive (tags) and active (two-way communication) devices.

2.2 Scope

The scope of this report is to investigate WTP values in a field study as well as in a panel study at a European level by focussing on a sub-section of 6 European countries, namely – Spain, the Netherlands, Hungary, Italy, Sweden and the UK.

2.3 Structure of this section

First, we report the field study and then the panel study. This report first outlines the methodological approaches taken for this part of the XCYCLE project (Sections 2.4 and 2.6). In Sections 2.5 and 2.7 a series of key analyses are outlined and discussed, with conclusions drawn together in Section 2.8.

2.4 Study 1: Methodological Approach

2.4.1 Contingent Valuation (CV) methodology

This study relies on a Contingent Valuation methodology. CV represent a more direct way to obtain WTP and WTA values. Specifically, we asked respondents, either: (1) What is the maximum price at or below which as a consumer they will definitely buy a unit of the product (WTP)?; or (2) What is the minimum amount for which a person is willing to accept to sell the product (WTP)? The WTP measures the benefit received by individuals, and the WTA represents the expected selling price for individuals. Under normal conditions the WTP is higher than WTA when the estimated value of the developed technology is low.

2.4.2 Ethical Considerations

The data collection procedure complied with the Research Ethical Code of the Italian Association of Psychology. All participants were asked to provide written informed consent prior to their inclusion in the study. Specifically, we informed participants about (1) the purpose of the study and its characteristics (e.g., duration and procedures); (2) their right to decline to participate, and to withdraw participation at any time without penalty; (3) potential risks, discomfort or adverse effects associated with the study (e.g., the risks associated with this research are the same as what they face every day while riding a bicycle); (4) any potential research benefits; (5) any data collected during the study that personally identifies them would have been treated with confidentiality; (6) incentives for participation; and (7) an explanation of the proper person to contact for questions about the research, its findings, and research participants' rights.

2.4.3 Participants

Thirty-one participants (27 female, 87%) aged between 19 and 57 years ($M = 23.80$, $SD = 9.22$) took part in the study. The median family monthly income of participants was between 2,000.00 and 3,000.00€ (range = 1,000.00-4,500.00€). Twelve participants (39%) do not usually cycle, while ten (32%) cycle once a week, six (19%) twice a week, one (3%) three times a week, and two (7%) four or more times a week. The mean percentage of use of bicycle on the basis of various travel purposes was 9.17% ($SD = 15.15$) with a range between 0 and 80%, while mean percentage of use of motorized vehicles was 39.00% ($SD = 25.68$) with a range between 0 and 80%.

2.4.4 Measures

First, we asked participants if they were willing to buy the on-bike system if available on the market (response options were yes or no). Then, we measured WTP by asking them to indicate the maximum amount of money they would be willing to pay for it (Simonson & Drolet, 2004). To measure the WTA, we asked the amount of money for which they would sell the system if they had it in their possession (Simonson & Drolet, 2004).

2.4.5 Procedure

Participants were contacted during the lessons of the course in Social Psychology hosted by the Faculty of Political Sciences of the University of Bologna, in Forlì, Italy. A researcher explained the study during the lessons and students were invited to contact the researcher by email showing their interest in participating and stating their preferred date to take part in the study. The course allowed students the possibility of obtaining course credits by participating in the field test or by performing another type of assignment. Participation in the study involved one day and lasted around 45 minutes. The study consisted in three phases: (1) pre-experiment survey; (2) experiment tasks; and (3) post-experiment survey. Next, we explain each one of the phases.

Pre-experiment survey. In this phase, participants were welcomed in a facility nearby the experiment circuit and were asked to complete the informed consent form. After having signed the written informed consent, each participant was asked to fill out a brief questionnaire containing questions about bicycle use and socio-demographic data (e.g., family income, gender). Once the survey was completed and the previous participant had finished, they were accompanied to the circuit.

Experiment tasks. The main task undertaken by the participants consisted in riding the bicycle throughout the circuit and interacting with a car at an intersection. The circuit was oval and contained an intersection equipped with the reference nodes to estimate the position of the bicycle (Figure 6).

Figure 6. Intersection with cones to restrict the zone where participants could cycle. The upper image shows the scenario in which the car comes from the opposite direction and turns left, whereas the lower picture shows the location of the cones for the scenario in which the car approaches from the left.

The car that interacted with participants was always driven by the same researcher to minimize differences in trajectories and speed. To keep a safe distance between the car and the participants, in each scenario we established a landmark that the car could not surpass. Moreover, we demarcated a part of the road which participants could use based on the side from which the car approached the intersection. For this, we placed conspicuous and colourful cones on the road surface to ensure that the participants would not cycle too close to the car landmark. Figure 6 shows how the cones were placed in each situation.

There were two different conflicts between car and bicycle at intersection, involving distinct car manoeuvres. All the participants had to go through each one of them. In one conflict, the car appeared from behind a small truck conveniently parked on the left side of the intersection when the participant was approaching (Figure 7).

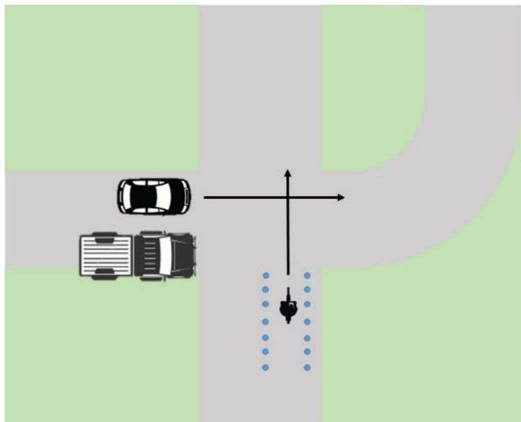


Figure 7. "Right-angle" type of conflict between car and bicycle.

The other conflict involved the car coming from the opposite direction, turning left, and eventually stopping to yield to the participant (Figure 8).

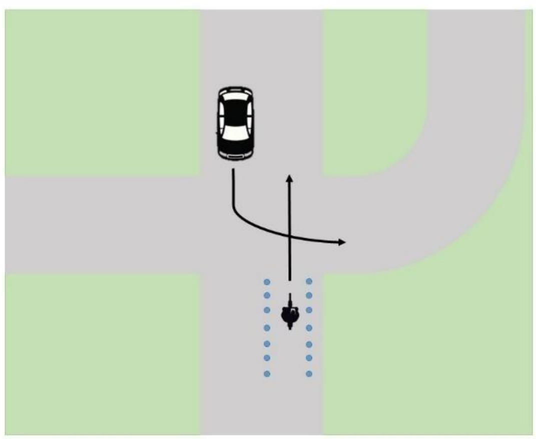


Figure 8. "Left-turn" type of conflict between car and bicycle

Moreover, there were two conditions that regarded the use of the system: the first one without the system, and the second one, in which the system was switched on and the participants were warned of the incoming hazard. The conditions always followed the same order, whereas the two conflicts were randomly counter balanced in ordering across participants to eliminate the order and sequence effects of passing through one conflict with the car before the other.

Before taking part in the different conditions, participants were provided with a helmet and were instructed to ride the bicycle through the circuit. They were told that they would share the road with a vehicle, and that all the situations were controlled so that the vehicle would not surpass a minimum distance threshold from them to avoid any contact. Moreover, they were asked to respect the road rules and to behave as they would do outside of the experiment. Then they were instructed to stop when they were requested to and were told that they would be shortly interviewed about the latest laps then. Once the experimenter had ensured that the instructions were well-understood and effectively addressed any doubts and uncertainties about the study, participants were asked to start cycling.

Participants completed three laps of the circuit. The first lap involved no interaction with the car and served for habituation of the participants to the bicycle and for verification of the correct understanding of the path that they were required to follow. The second and third laps involved the participants interacting with the car, keeping the scenarios in the order previously assigned to each one of them. In the second lap, the on-bike device was not activated, while in the third lap, participants received a warning message signalling impending conflict with the car. Such a message was delivered by a simple HMI composed of an audio alert (a buzzer beeping) and a visual alert (a LED blinking). The HMI was activated manually by a researcher only in the last lap, a few meters before the bike was approaching the intersection where the conflict with the car took place.

Post-experiment survey. The questionnaire was completed in the same nearby facilities in which the pre-experiment survey was conducted, and participants were accompanied there by a researcher once the experiment tasks were completed. The questionnaire included the measures of WTP and WTA described above.

2.5 Study 1: Results and Discussion

Twenty-six participants (84%) reported that they are willing to buy the on-bike system if available on the market, while five participants (16%) were not willing to buy it. Participants were willing to spend on average 63.00€, SD = 50.72€, min = 10.00 max = 200.00. In terms of willingness to accept, the mean lowest price for which participants were willing to sell the on-bike system was 46.25€, SD = 31.73€, min = 0.00€ max = 150.00€. The average WTP and WTA values were calculated using the responses of those participants who reported they were willing to buy the on-bike system. WTP was statistically higher than WTA; W_s = 168.00, $z = -2.37$, $p = .018$, $r = -.45$. The present findings suggest that the price of the on-bike system should be kept relatively low. Otherwise, incentives should be considered to ensure large scale deployment of this on-bike system. The non-significant correlations of the WTA and WTP with the behavioural intention to use the on-bike system suggest that there might be other factors which can hinder or facilitate the usage of the systems. In other words, participants may value the on-bike system but the intention to use does not increase as the value increases.

The relationship between bicycle use and willingness to buy the on-bike system (see Figure 9) was not significant, $F(4, 24) = 0.24$, $p = .912$. Also, the relationship between bicycle use and willingness to accept the on-bike system was not significant, $F(3, 23) = 1.22$, $p = .323$.

To put our findings in context of existing findings, a comparison to what people are willing to pay for support systems in cars was made. Specifically, we compared our results to those obtained in the acceptance analysis (Jamson & Hibberd, 2016) of the system developed in ecoDriver (a project co-funded by the European Commission 7th Framework Programme for Research and Development). In that study, drivers were asked to think about how much they would be willing to pay for the ecoDriver system either as an optional feature on a new car or as a retrofit on an existing car. At the end of the trial, drivers were willing to pay approximately 137 euros for the full ecoDriver system as an optional feature on a new car and 106 euros as a retrofit on an existing car. Thus, participants were willing to pay approximately double for the ecoDriver system when compared to the on-bike system in the XCYCLE project. We note that this comparison should be interpreted with caution because the systems have different uses and road users.

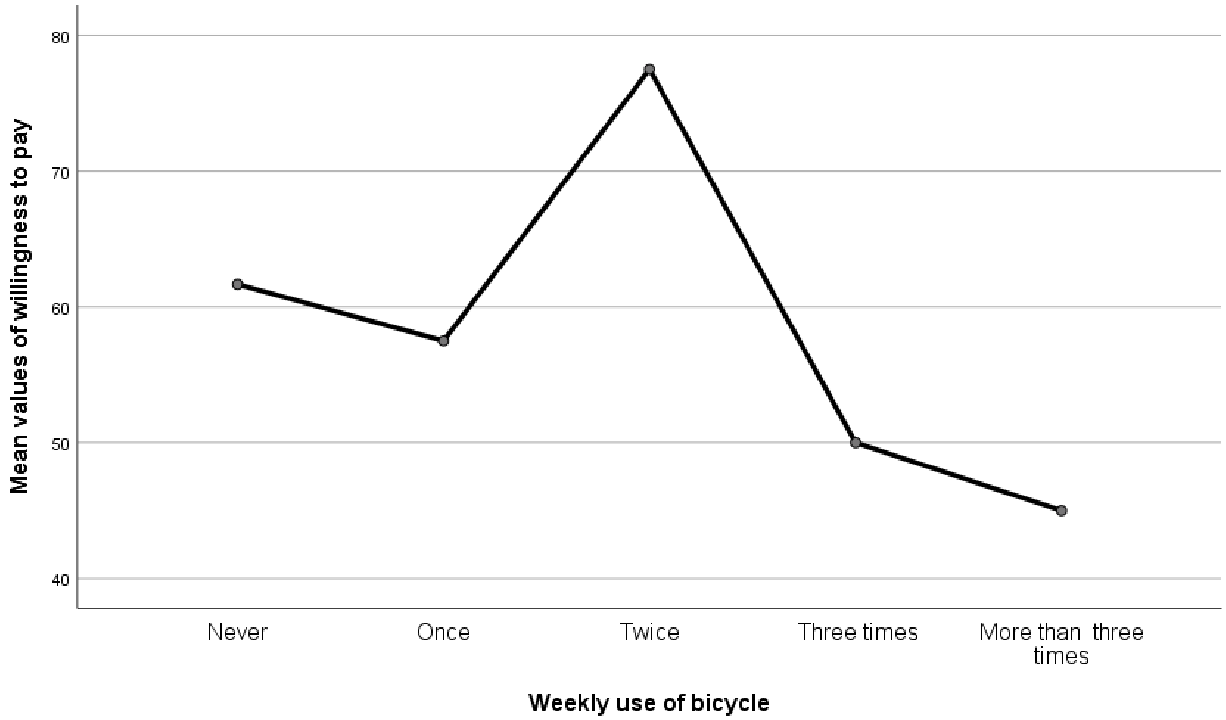


Figure 9. Relationship between bicycle use and willingness to buy the on-bike system.

2.6 Study 2: Methodological Approach

2.6.1 Stated Preference Analysis

The objective of the stated preference exercise aspect of the survey was to elicit users' willingness to pay for on-bike safety technology.

Stated preference choice-based experiments establish willingness to pay (WTP) values through respondents' responses to a set of hypothetical choice-based tasks. This implicitly involves respondents making trade-offs between different options with corresponding different attribute levels. Survey respondents' choices are then used to estimate utility functions from which Willingness to Pay values can be elicited.

In our application, a Stated Choice survey was designed in which respondents were faced with 8 hypothetical choice scenarios regarding potential purchase (or not) of on-bike safety technology. In each choice scenario the respondent had to select between two on-bike technology options and a 'no purchase' option.

The choices were described using the following attributes:

- **Detection rate (%)**
  The % of imminent collisions which are detected correctly

- **False Alarm rate (%)**
  The % of times an imminent collision is signalled but falsely detected, i.e. when there was no danger of an imminent collision

- ***Purchase Cost (Euros)***
  The cost to purchase the system

- **Warning system type** on bike: no warning (RFID tag), indicator light nor vibrating handlebars

The design of the survey was undertaken in NGene, which is a software used to allocate efficiently values of attributes in different scenarios. An efficient design approach was used to minimise the total number of scenarios and survey responses required to yield robust parameter estimates.

Given the different capabilities of the passive and active technologies, we structured the design so that higher rates of detection and lower rates of false alarms were available for the active technology. The active technology also had higher levels of cost on average than the passive technology.

An example in which users were asked to select one of the three options on the bottom of the screen is shown below in Table 2. Choice exercise example

Table 2. Choice exercise example

	ALTERNATIVE 1	ALTERNATIVE 2	ALTERNATIVE 3
Type of technology	Active: Audio and Visual	Active: Handlebar Vibration	No purchase
Detection rate (%) The % of imminent collisions which are detected correctly. *E.g. a rate of 100% means all imminent collisions are detected.*	85	100	
False Alarm rate (%) The % of times an imminent collision is signalled but falsely detected, i.e. when there was no danger of an imminent collision. *E.g. a rate of 10% means that 1 in 10 of the alerts from the system were incorrect in suggesting an imminent collision.*	0	10	
Purchase Cost (Euros) The cost to purchase the system *For the active technology, this does **not** include the cost of charging the batteries*	15	110	
Choice			

2.6.2 Model Specification

The key objectives of the exercise were to estimate willingness to pay values associated with the on-bike safety technology. Because of the exploratory nature of the technology we cannot identify a WTP for the technology independent of an accompanying specification of the capability of the technology in terms of false positives and detection rates; i.e. our WTP values are linked to the system capability and to the type of the system itself. Although we specified two types of active technology, preliminary investigation revealed no statistically significant difference between the valuations associated with the handlebar vibration or illumination, so we have bundled both these options together as the 'active' technology option for purposes of simplifying the analysis.

The model is specified as follows for the technology-based choices:

$U(i,j) = \beta cost * Cost_j + \beta pas * pas\_dum_j + \beta act * act\_dum_j + \beta detection * detection\_rate_j + \beta false * false\_rate_j$

Where:

U(i,j) is the utility of respondent i from choice alternative j;

Cost is the specified purchase price of the technology;

pas_dum is a dummy to indicate whether the choice involves a passive tag;

act_dum is a dummy to indicate whether the choice involves active technology;

detection_rate is the detection rate (%) ;

false_rate is the false alarm rate (%);

with the associated β parameters capturing sensitivity of respondents to differences in each of these attributes.

The model principally measures the difference in utility between choices involving the technology and the no purchase option. The no purchase option has the attributed utility of zero.

From the resultant coefficient estimates, WTP values for changes in specific attributes can be derived by calculating ratios of the coefficient of these attributes and the cost coefficient. Accordingly, in order to estimate the WTP for the passive technology we use the following calculation:

$WTPpas = (\beta pas + \beta detection * detection\_rate_{pas} + \beta false * false\_rate_{pas}) / \beta cost$

where detection_rate pas and false_rate pas are the average detection and false alarm rates used in the SP design.

Similarly, for the WTP for active technology WTPact we use βact in association with the average detection and false alarm rates used in the SP design.

$WTPact = (\beta act + \beta detection * detection\_rate_{act} + \beta false * false\_rate_{act}) / \beta cost$

2.6.3 Online Panel Survey

Market research was undertaken in the form of an online panel survey. This was considered to be the best approach to target cyclists who are usually a difficult group to survey. An online panel also reduces the need for local staff. Given that six countries to be covered, this was a strong advantage.

An initial draft of the questionnaire was circulated to the consortium members for comments. Following this, further iterations took place internally between UOL and UNIBO. The final questionnaire had several sections, the first of which asked a number of scoping questions to check the eligibility of respondents to take part in the survey, e.g. age and frequency of cycling.

The next section asked questions around respondents' current cycling behaviour, including how many trips they currently made, why they made them and the type of cycling environment the majority of those trips were made within. A further set of questions examined attitudes to cycling and risk.

Respondents were then introduced to the XCYCLE technologies with detailed descriptions of the active and passive system options. They were then presented with eight stated preference scenarios and asked to choose their preferred options for each scenario, including the "no purchase" option. Respondents were then asked to rate how realistic they found the SP's scenarios. Then they answered a series of questions about how the new technology might impact their cycling behaviour (e.g. change of the number of trips they make per week).

The final section asked a series of questions regarding socio-economic variables. This allows segmentation by age, gender, and others. The questionnaire was designed to last around 15 minutes. This clearly impacted the number of questions that could be asked.

2.6.4 Data Collection & Cleaning

Data collection for this research was carried out by Qa Research, a social and market research company based in York, UK. The survey was administered to an 'online panel' of respondents. These are individuals that have agreed to take part in surveys regularly and are registered to a 'panel' in order to do so. Panellists receive compensation for completing surveys from the company that manages the panel, typically in the form of 'points' or vouchers that can be exchanged for goods.

Online panels hold a significant amount of demographic data on their panellists and keep them up to date. This allows targeting of surveys at specific groups to obtain a certain sample, such as a nationally representative sample or a female only sample.

For this project, the sample within each county was required to meet the following criteria:

- All respondents must make at least 1 cycle trip per months (on average)
- At least 50% of respondents must be regular cyclists (i.e. make on average >2 cycle trips per week)
- At least 30% of the sample must be female
- At least 10% of the sample must be aged 50 years or more

The inclusion of participants aged 50 or more years old was particularly relevant in order to assess whether there were significant differences between young and elderly cyclists.

The survey was administered to panellists in each of the following countries;

- Hungary
- Italy

- Spain
- Sweden
- The Netherlands
- United Kingdom

An initial draft of the survey was piloted amongst the British and Netherlands samples, comprising of 30 completed surveys in each country. The initial data was examined and some changes to the questionnaire were made following the pilot feedback. After this, the finalised questionnaires were translated, set up in Qa's online survey platform, and the survey administered to each of the six countries. Pilot survey data was not included in the final dataset due to changes in the post-pilot questionnaire.

In order to ensure data quality, a minimum survey completion time (8 minutes) was set whereby any questionnaire completed in under that time was rejected as invalid. This was to exclude responses from those deemed not to have properly considered the information presented in the survey, i.e. they had just clicked through.

Fieldwork was conducted between 27th January and 5th February 2018. The final sample collected was as follows (Table 3):

	Min. Target (per country)	UK	NLD	ESP	HUN	ITA	SWE	TOTAL
Total	**400**	**401**	**407**	**403**	**401**	**406**	**399**	**2417**
Female	**120**	202	205	205	200	188	223	**1223**
Male and Other		199	202	198	201	218	176	**1194**
Aged under 50		274	291	292	296	306	273	**1732**
Aged 50+	**40**	127	116	111	105	100	126	**685**
Regular cyclists (3 times per week or more)	**200**	210	258	201	211	237	210	**1327**
Not regular (less than 3 times per week)		191	149	202	190	169	189	**1090**

Table 3. Outline of data collected

The raw data was checked and cleaned by Qa and then passed to the University of Leeds for analysis. During these checks the data revealed anomalous responses from two Swedish panellists and these surveys were removed, leaving a total of 399 rather than 401 originally collected for Sweden; and a total of 2,417 respondents.

Following the handover of the data from Qa, diagnostics checks were run on the data to identify any potential concerns around either the respondent or individual responses to questions. Qa had already identified 27 cases where they suspected evidence of 'flatlining' whereby respondents provide repetitious answers (press the same keys) to complete the survey in the fastest possible time. After examining the data, the researchers agreed with Qa and discarded them from the sample to be analysed. A further participant was discarded as she or he was not within the age scope (18+ years), leaving a sample of 2,389.

For several questions, respondents appeared to have mistyped their answers, for example, I own 50 bicycles for personal use whereas they probably meant to enter 5. With such cases a decision was made to record the answers 'as missing', as such this did not reduce the number of respondents in the sample. This involved the following questions and number of participants:

a) 2 participants stated that 15 or more people living in their household are children under 12 years of age;
b) 1 participant declared to own 50 bicycles for personal use;
c) 2 participants declared to own 50 bicycles in their household.

A number of questions asked people to estimate costs, for example the cost of annual bike maintenance, with answers provided in their own currencies except Sweden and Hungary, who were asked to provide answers in Euros. Despite this an examination of the responses for Sweden and Hungary identified a strong suspicion that a small number of respondents were answering these questions in Swedish Krona or Hungarian Forints. A decision was made to use the median values from these questions in any calculation in order to minimise the impact. In addition, Power Purchasing Parity (PPPs) were applied to the responses to these questions in order to facilitate like for like comparisons. Please note that PPPs were not applied to the SP scenario values.

2.6.5 Characteristics of the Data

After the data was cleaned, responses from 2,389 participants were used for further analyses. These cases were distributed homogeneously among different countries. 8 participants identified themselves as transgender, for further gender-based analyses these participants were excluded as this number is too small in relation to the rest of the sample to allow comparisons or statistical tests (Figure 10).

2.6.5.1 Key Characteristics

For Hungary, the Netherlands, Spain and the UK the gender split tends to slightly favour females, reflecting the gender mix in these countries. This is not the case for Italy or Sweden, where the sample favours males with a split of around 54% vs 46% (Figure 10. Number of participants by gender and country of residence

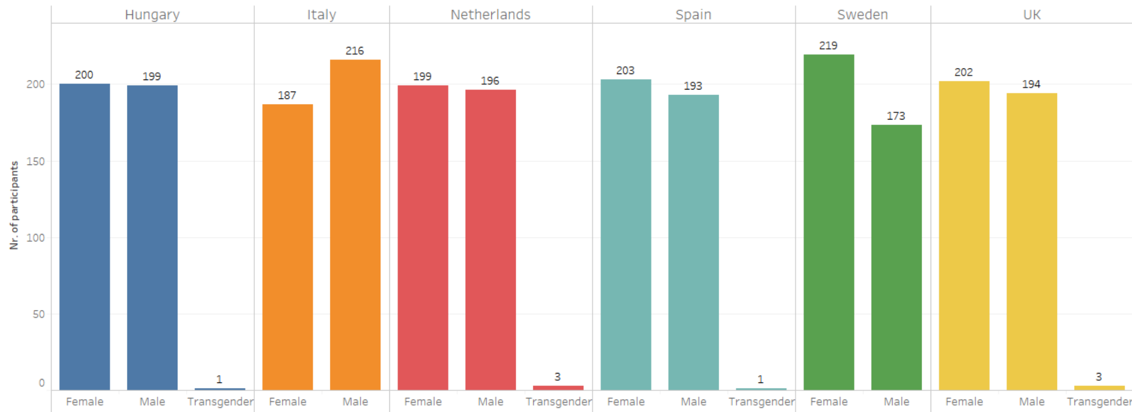


Figure 10. Number of participants by gender and country of residence

The participants for the whole sample are aged between 18 and 86 years with the average of 42.73 (SD=14.341). As it is possible to observe in

Figure 11 both young and elderly cyclists have been included in the sample.

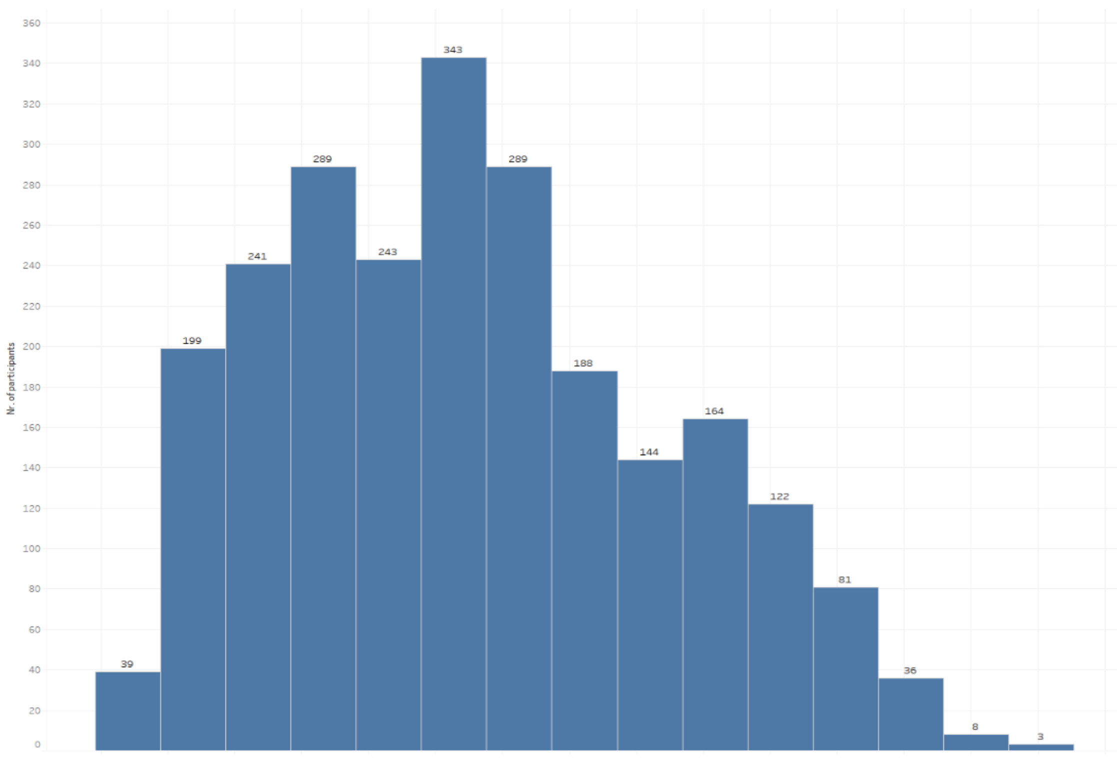


Figure 11. Age distribution - Full sample

The age distribution by each country is depicted in Figure 12. Most participants residing in Spain and Italy are aged between 36 and 45 years old, as well as in The Netherlands but for a lesser extent. In Hungary and Sweden, the higher percentage of participants are aged between 26 and 45 years old while the U.K. has the largest share of participants aged between 26-35 years old. Sweden and The Netherlands has instead the largest share of participants aged over 56 years old.

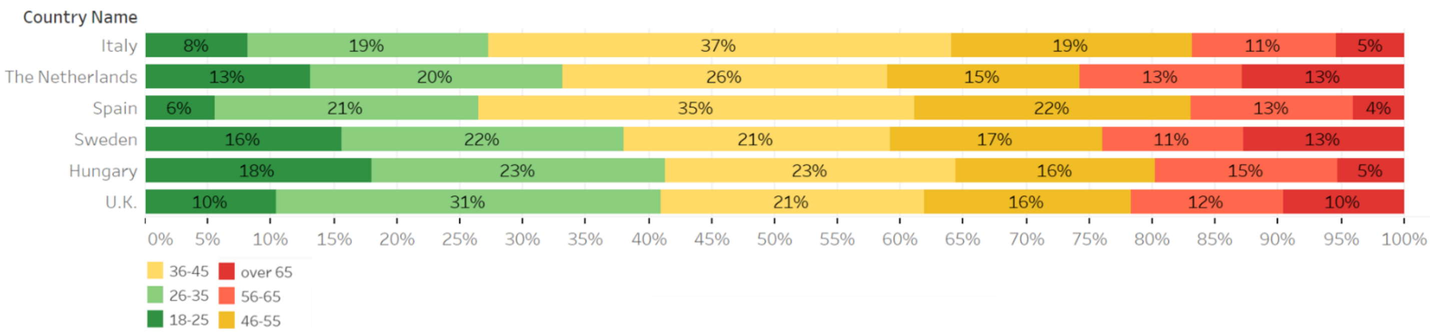


Figure 12. Age distribution of the sample by country

In the months during which the weather permits cycling, 441 participants (18.5% of total sample) reported cycling daily, while 874 participants (36.6%) cycle 3 or more days per week, 708 participants (29.6%) cycle at least one time per week and 366 participants (15.3%) cycle at least once per month.

Differences between countries are outlined in Figure 13 and reflect the relative propensity to cycle across those countries, with the Netherlands having the highest propensity and Spain having the lowest.

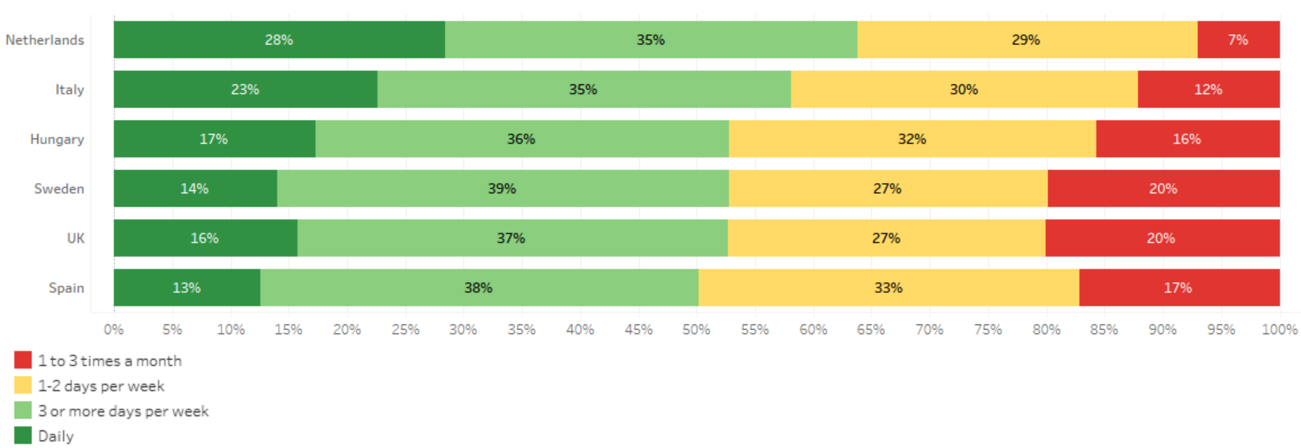


Figure 13: Cycling frequency by country

The participants cycled on average 189.48 km per year (SD=824.25 km). For comparison by gender and country, see Figure 13. There appear to be some major disparaties between countries and across genders. This may reflect different types of cycling (e.g. short commutes vs longer leisure/training rides) and/or different levels of access to a car ot to public transport in certain countries.

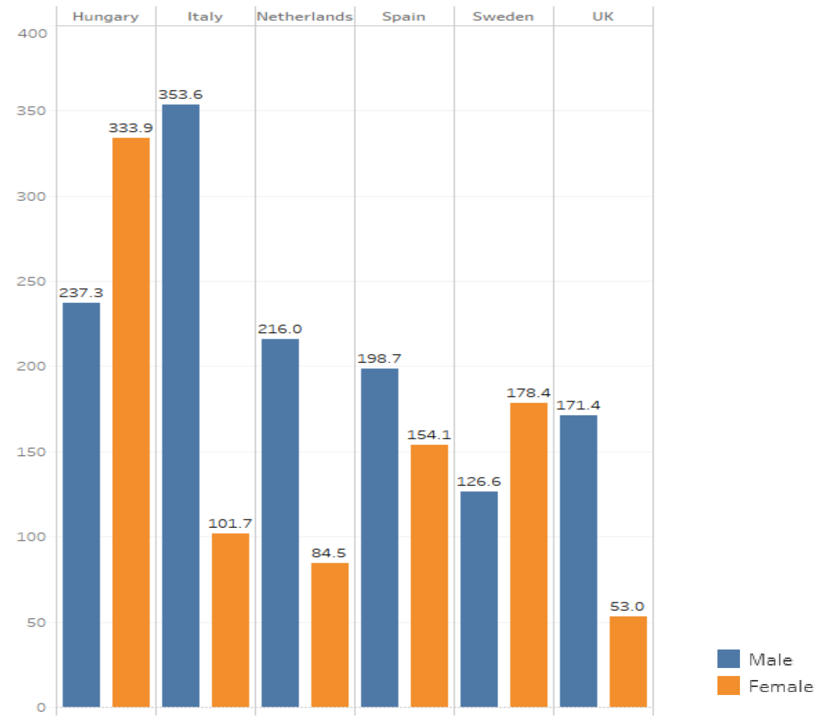


Figure 14. Average cycling distance by country and by gender

The participants were asked (Figure 15) how often do they use a car during the months in which they cycle. The portion of people who use a car 3 or more days per week or more is the highest for Italy (67%) and lowest for Hungary (44%).

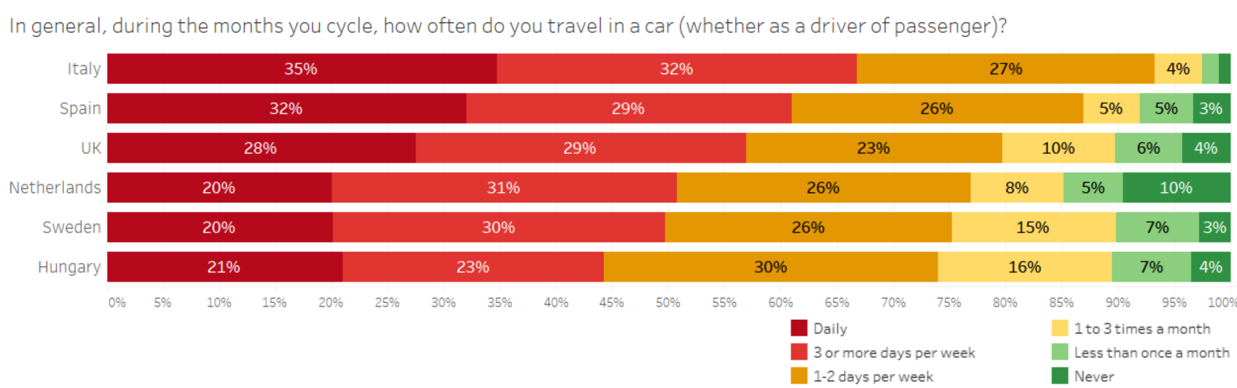


Figure 15: Car usage during months in which cycling is possible. Note: Percentage values rounded. Values lower than 3% are not shown.

Participants were also asked in which environment (Figure 16) they make majority of their trips. 29% of cyclists make cycle mostly in a city, 34% in a town, 18% in a village and 19% in rural environments (between villages).

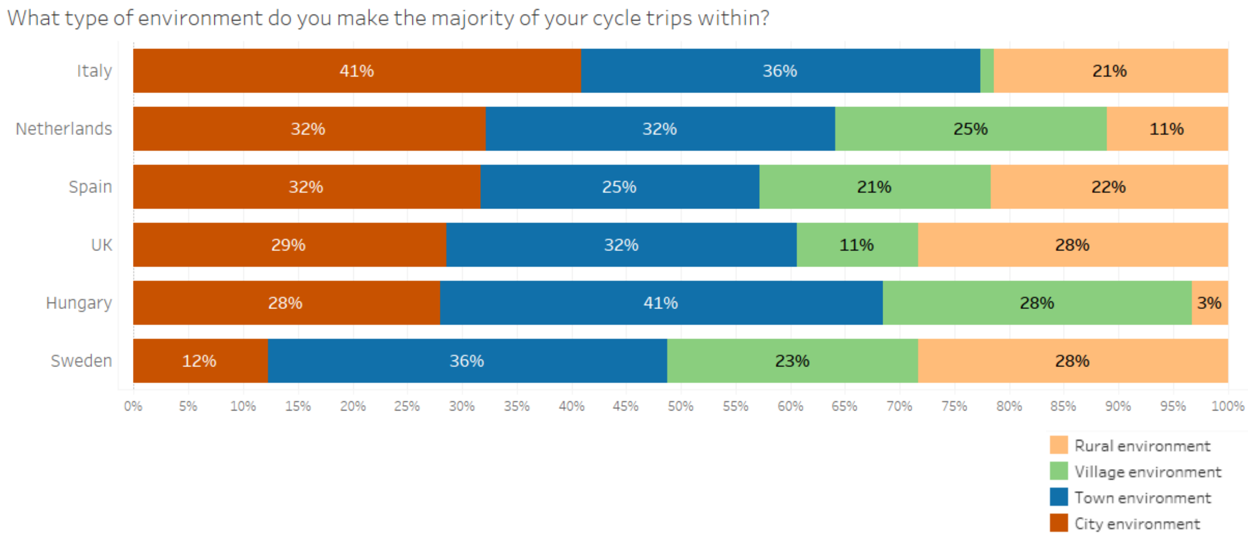


Figure 16: Cycling environment by country. Note: Percentage values rounded. Values lower than 3% are not shown.

According to the obtained data, participants have on average 2.71 bicycles in their household. Most bicycles per household were reported by Dutch cyclists (M=3.13), while in United Kingdom the average was lowest (M=2.37). Values for all countries are shown below in Figure 17.

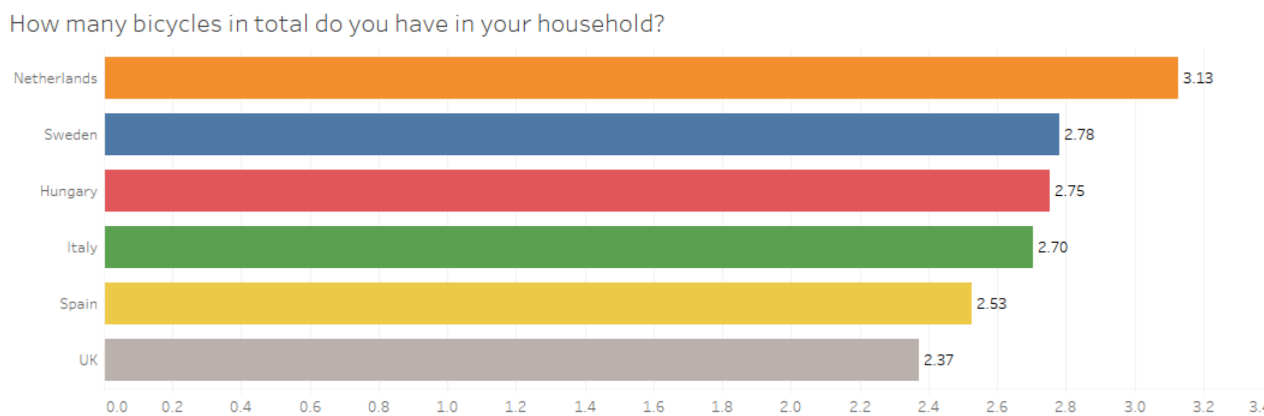


Figure 17: Average number of bicycles in household

When it comes to number of bicycles for personal use, the responses were more homogeneous. Hungary had the least average (M=1.15), while in Netherlands the average number of bicycles for personal use was the highest (M=1.37). Furthermore, 8.5% of all respondents answered that the bicycle they ride the most is an electric one.

2.7 Study 2: Analysis of the Data & Key Findings

2.7.1 Non-WTP Analysis

2.7.1.1 Reasons for Cycling

We asked participants to report why they make the cycle journeys (Figure 18). Almost seven out of ten participants reported they cycle for leisure or training. 42% of cyclists stated they use the bicycle for shopping or entertainment. About one third of cyclists revealed using the bicycle for personal business (e.g. health appointment), visiting family or friends, and commuting.

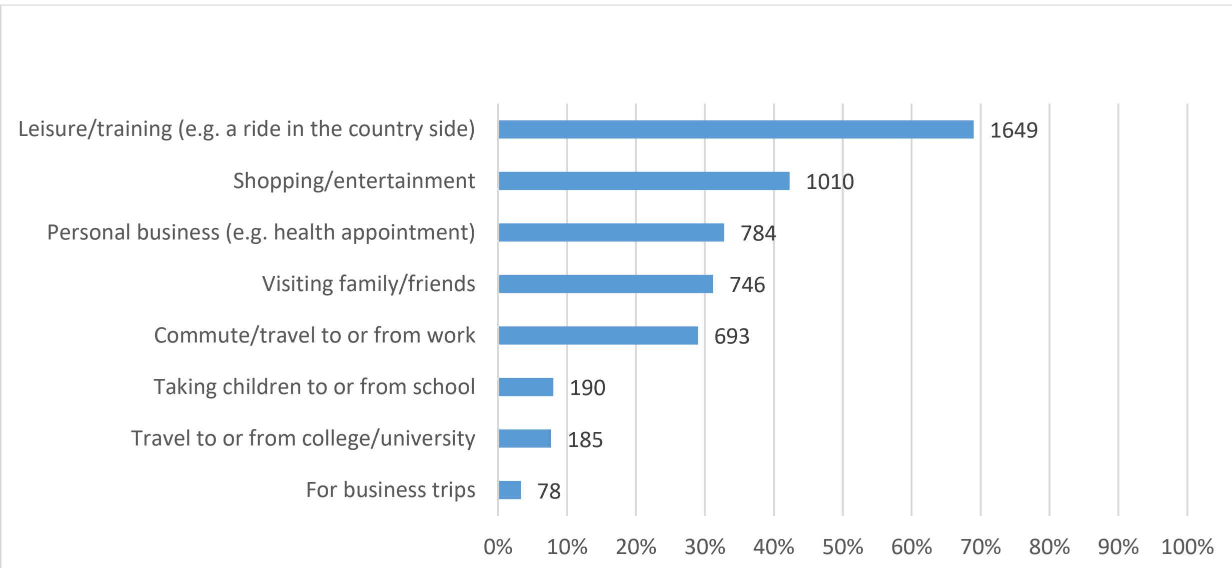


Figure 18: Frequencies of positive responses to the question "Why do you make these cycle journeys?". Participants could choose more than one option.

As shown in Figure 19, the trend regarding the reason why participants make the cycle journeys is similar across all age bands. It is possible to observe that younger cyclists, aged between 18 and 25 years old report using the bicycle to travel to or from college/university considerably more than other age bands, while cyclists aged more than 56 years old report using the bicycle for commuting considerably less than other age bands. This probably reflects the higher percentage of university students among the youngest and the higher percentage of retired workers among the elderly.

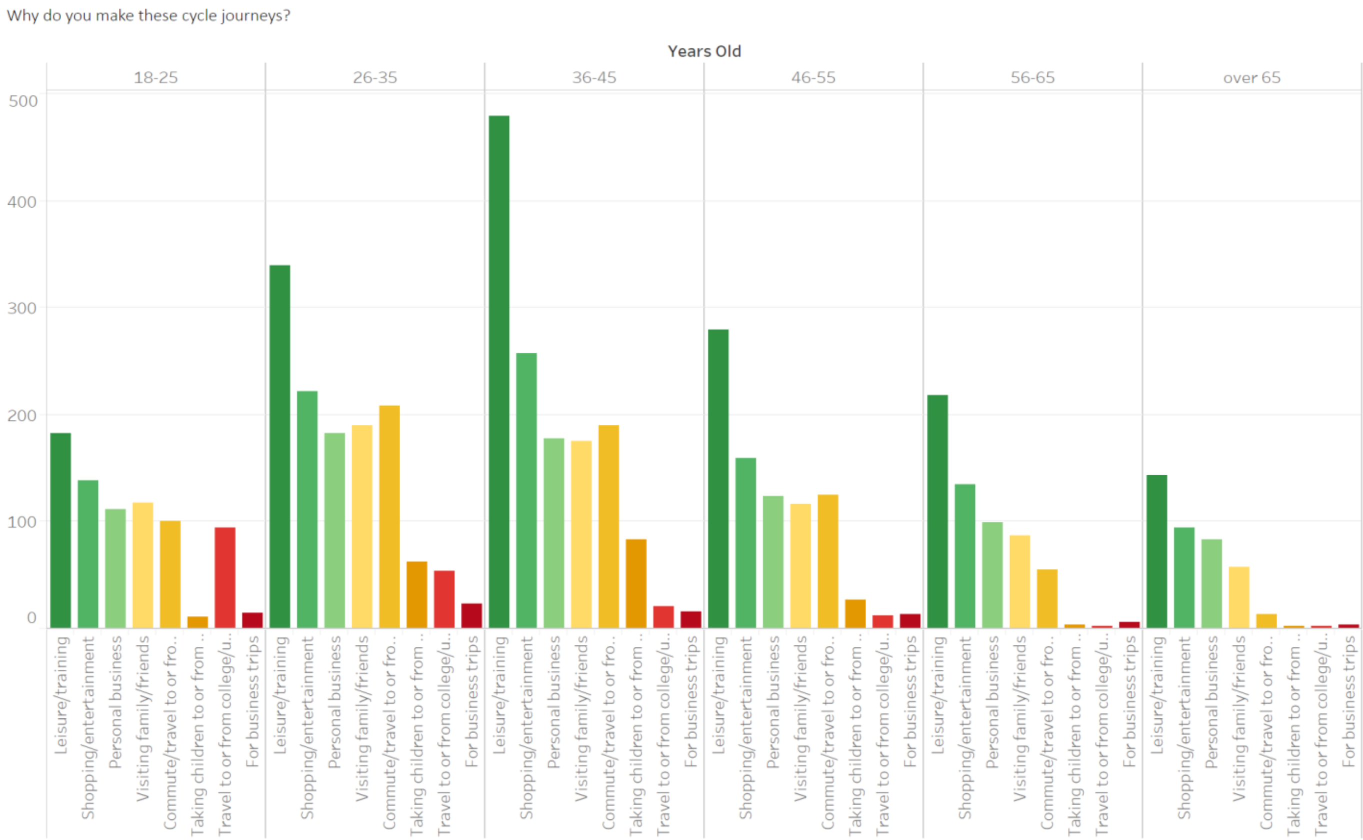


Figure 19. Frequencies of positive responses to the question "Why do you make these cycle journeys?" by age

2.7.1.2 Attitudes towards cycling

The participants were asked to indicate a degree of agreement with questions regarding attitudes towards different benefits of cycling. 86% of participants expressed strong agreement or agreement with question asking whether they cycle because it is pleasant. Other most positive attitudes were followed by mental relaxation (81% of responses *strongly agree* or *agree*), saving money (81%), health benefits (74%), and environmental benefits (74%). The benefits least appreciated were social status (21%), personal security (29%), and traffic safety (30%). For summary on responses regarding all attitudes and detailed data regarding different responses by age band see Annex 2.

2.7.1.3 Factor Analysis

To investigate the factor structure of the 14 items that investigate attitudes to cycling, we did a factor analysis of the items using principal axis factoring followed by quartimin rotation. Parallel analysis indicated a two-factor solution. A total of 51.7% variance was explained by exploratory factor analysis. The variance explained by each factor of the rotated six-factor solutions was, respectively, 41.6% and 10.1%. Table 5 shows the full factor pattern matrix. Absolute factor loadings greater than 0.40 were considered salient. Item 4 (i.e., How far do you agree that you cycle because it offers privacy?), was dropped because of its low factor loadings on the two factors. The first factor was about the benefits of cycling for the person and his or her environment. We labelled this factor as "Personal benefits". We labelled the second factor "Benefits of cycling as a mean of transport" because the items refer to the positive aspects of using cycling as a mean of transport in everyday life.

Table 4. Table 5: Attitudes to Cycling: Factor Pattern Matrix Using Principal Axis Factor and Quartimin Rotations. Note: Coefficients in bold face are retained for that factor

ITEMS	F1	F2
1. How far do you agree that you cycle because of the environmental benefits?	**.546**	.127
2. How far do you agree that you cycle because it is pleasant?	**.901**	-.109
3. How far do you agree that you cycle because it is mentally relaxing?	**.826**	-.039
4. How far do you agree that you cycle because it offers privacy?	.303	.396
5. How far do you agree that you cycle because it is physically relaxing?	**.649**	.125
6. How far do you agree that you cycle because it has health benefits?	**.863**	-.161
7. How far do you agree that you cycle because it is comfortable?	.381	**.458**
8. How far do you agree that you cycle because of the traffic safety?	.002	**.772**
9. How far do you agree that you cycle because of the time savings?	-.009	**.695**
10. How far do you agree that you cycle because it improves personal security?	-.101	**.901**
11. How far do you agree that you cycle because it is flexible?	.301	**.471**
12. How far do you agree that you cycle because it suits your lifestyle?	**.466**	.378
13. How far do you agree that you cycle because it is cheap?	**.440**	.153
14. How far do you agree that you cycle because it provides social status?	-.029	**.599**

2.7.1.4 Perception of cycling infrastructure

Respondents were asked to rate the level of provision and the quality of the cycling infrastructure in their cycling environment on a scale from *1-Excellent* to *5-Very Poor*. Dutch cyclists expressed highest ratings, with 74% of responses being either *Excellent* or *Good* regarding provision levels and 65% in regard to quality. Hungarian participants responded *Excellent* or *Good* in 26% of cases when rating level of provision and 22% when rating the quality (Figure 20).

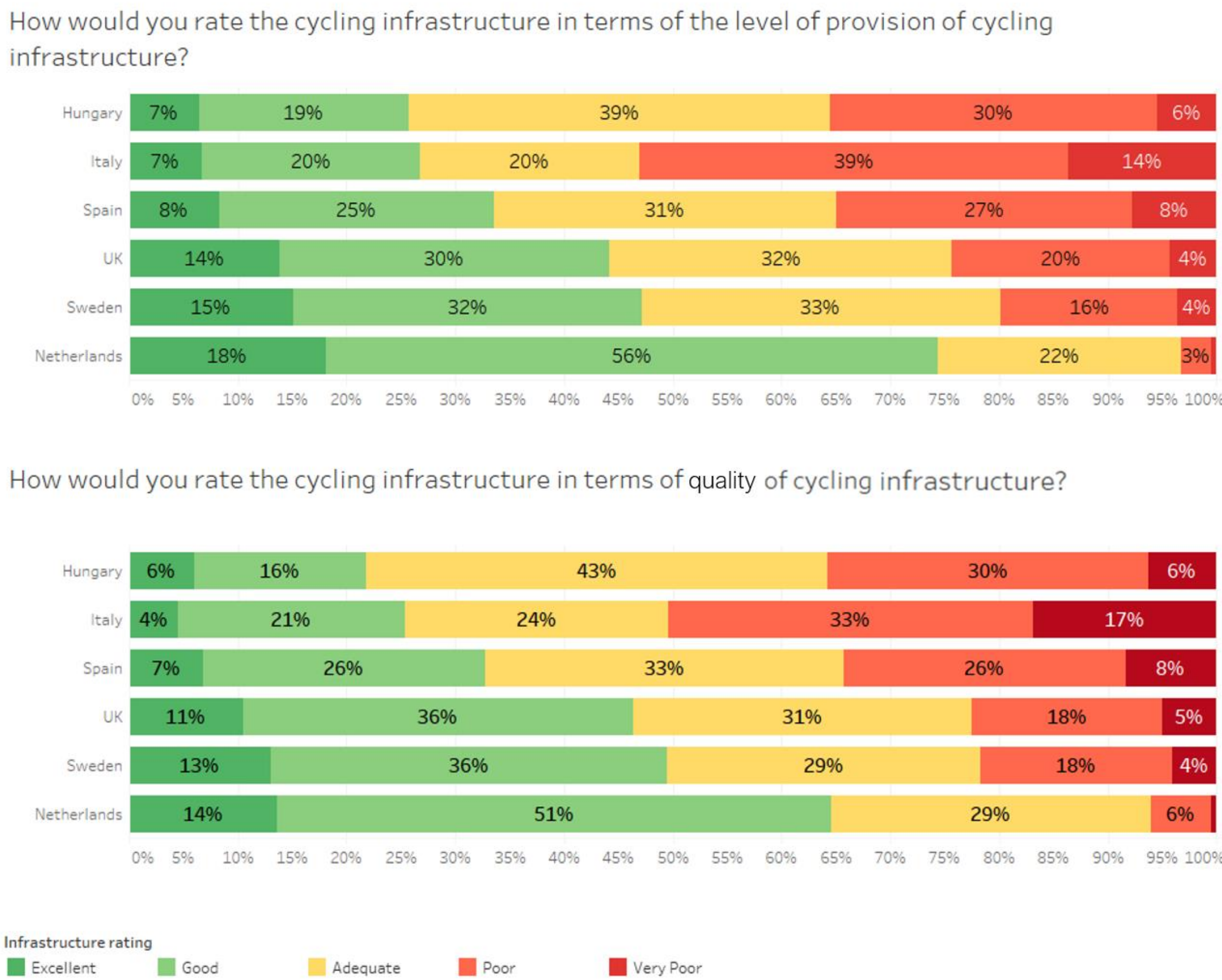


Figure 20: Cycling infrastructure rating. Note: Percentage values rounded. Values lower than 3% not shown.

Figure 21 presents an overview of cycling infrastructure ratings (provision and quality) by age band. It is possible to note that younger cyclists expressed highest ratings, with 51% of responses being either *Excellent* or *Good* regarding provision levels and 49% in regard to quality. Participants aged between 56 and 65 years old responded *Excellent* or *Good* in 31% of cases when rating level of provision and 27% when rating the quality.

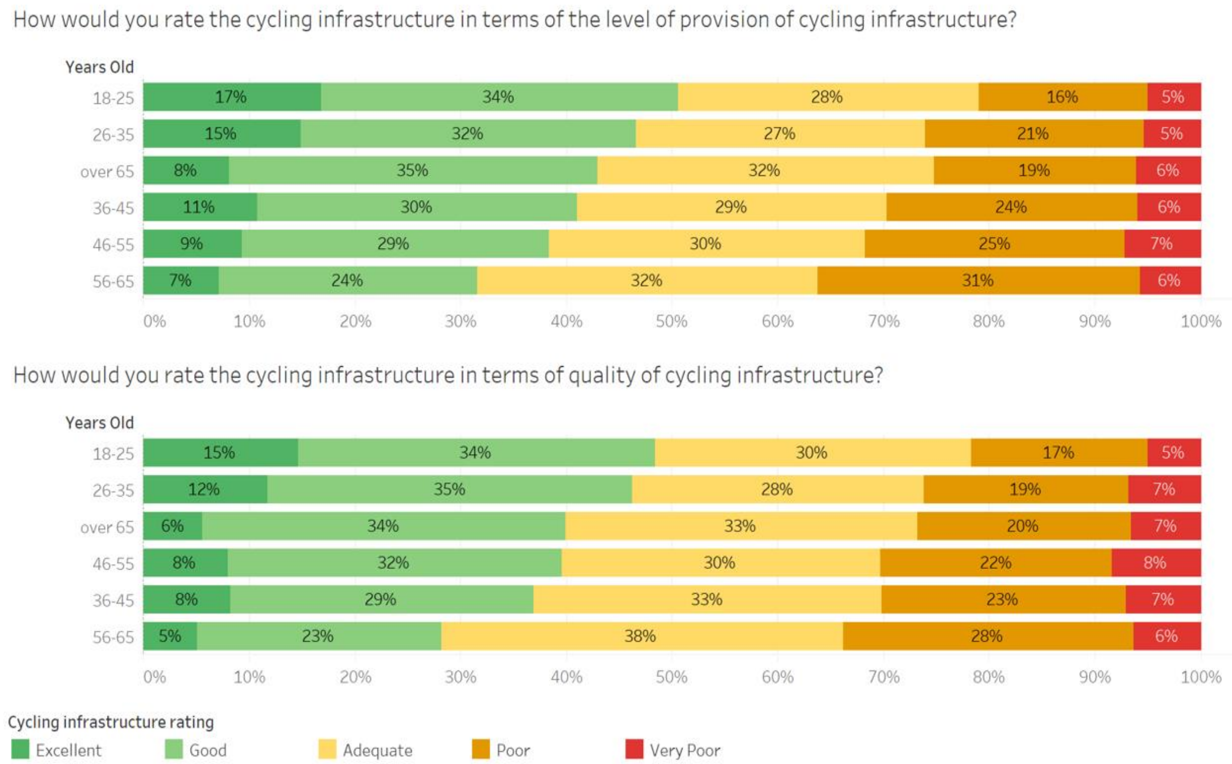


Figure 21. Cycling infrastructure rating by age band. Note: Percentage values rounded.

The two items investigating the cycling infrastructure in terms of both the level of provision and the quality of cycling infrastructure were highly related (r = .87). Therefore, we decided to compute an average rating of criticism of cycling infrastructure.

2.7.1.5 Perceived discomfort on different types of roads

The highest level of discomfort was expressed for riding on a 4-lane road (2 lanes in each direction) without a striped or separated bike lane – 59% of respondents declared they feel very uncomfortable or uncomfortable when using this type of road. The lowest level of discomfort is experienced on a cycling path separated from the street, only 3% of participants felt very uncomfortable or uncomfortable on this type of road. For a more complete overview of the results please see Annex 3.

2.7.1.6 Risk perception

The participants compared their risk of being involved in a traffic accident to other cyclists on a scale from 1-m*uch smaller* to 5-*much higher*. Hungarian cyclists had the highest number of responses *much smaller* and *a little smaller* - 35% (and 5% of responses *much higher* and *a little higher),* on the other hand, 18% of Spanish cyclists responded *much smaller* or *a little smaller,* while 14% of them responded *much higher* or *a little higher* (Figure 22).

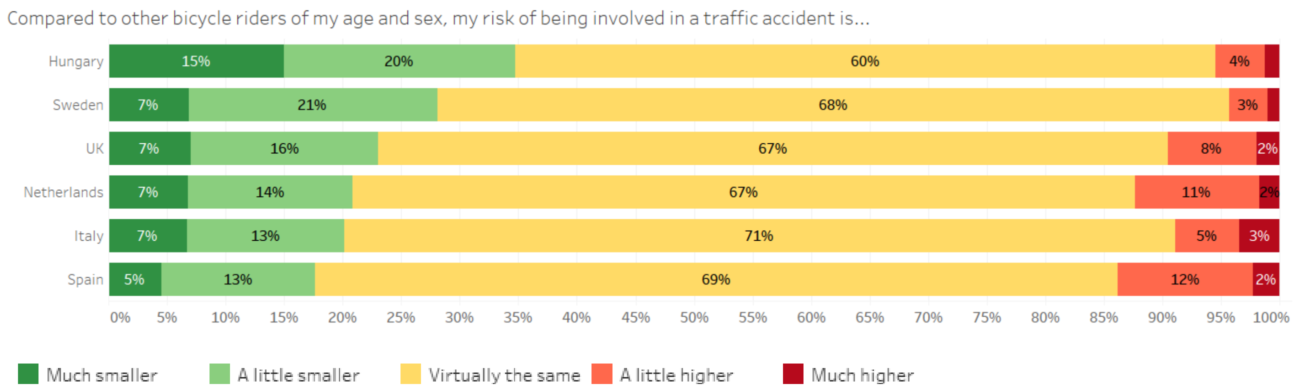


Figure 22: Risk perception. Note: Percentage values rounded. Values lower than 3% not shown.

Descriptive statistics regarding risk perception and age band (Figure 22) shows younger participants (18-25yo and 26-35yo) to be the most optimistic with 35% of them answering "*a little smaller*" or "*much smaller*" when asked about their probability to be involved in an accident if compared to other cyclists of the same age and gender. Cyclists aged between 56 and 65 years old are the third most optimistic category with 24% of participants reporting their risk to be "*a little smaller*" or "*much smaller*" if compared to other cyclists of the same age and gender.

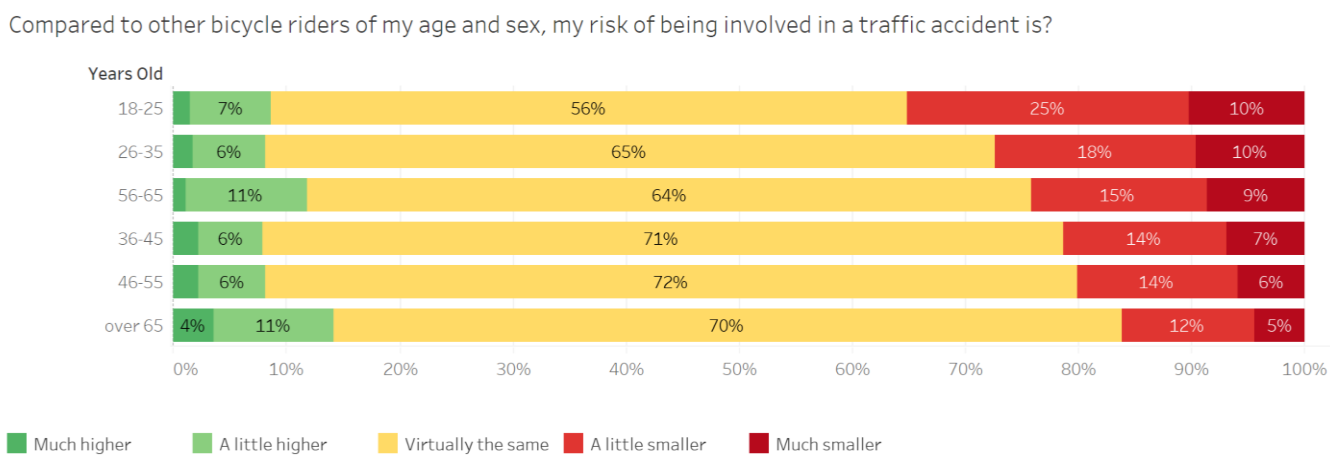


Figure 23. Risk perception by age band. Note: Percentage values rounded. Values lower than 3% not shown.

When evaluating the impact of the on-bike systems on the risk of being in a road accident, the Italian cyclists were the most optimistic. 75% of them answered the risk would be *much smaller* or *a little smaller* if their bicycle was fitted with the passive technology, for the active technology we see the same results. If both systems were to be installed (i. e. both active and passive psychology), the impact on risk perception is most visible for Swedish cyclists, with 88% of them stating that their risk would be *much smaller* or *a little smaller*. Furthermore, elderly (65+ yo) cyclists tend to report a decreased risk perception with the active or passive technology, while reporting the lowest positive ratings when thinking about both the system. For full overview of changes in risk perception in relation to the technology used by country and age, see Annex 4.

2.7.1.7 Attitudes towards new technologies

The participants were asked to report their attitude towards new technologies on a scale from *1-I like to be one of the first people to have a new tech gadget* to *5-I'm usually one of the last people I know to buy a new tech gadget.* The mean score on this scale for all participants was 2.79 (SD=0.76) and data was distributed normally (Figure 24).

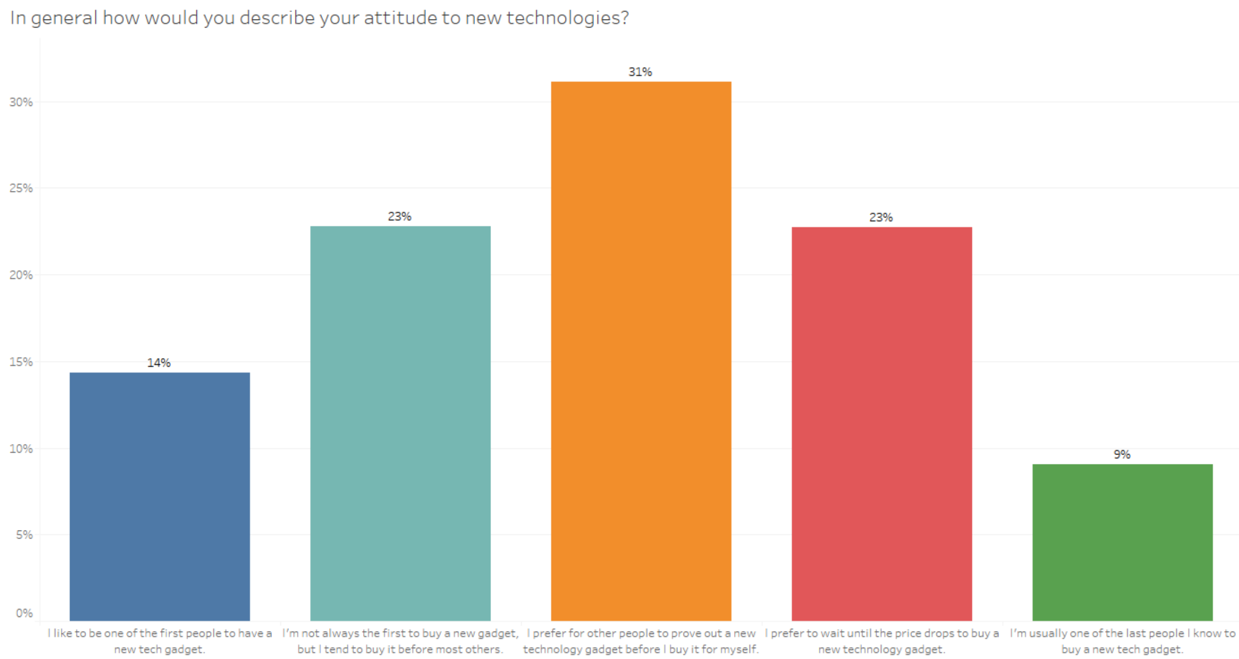


Figure 24: Attitude towards new technologies. Percentage values rounded.

2.7.1.8 Intention to buy

Participants had the option to indicate if they would buy the system for each type of system indicated (passive bike tag, active with audio-visual warning, active with handlebar vibration warning, active with combined audio-visual and vibration warning). Passive bike tag was the most popular among the respondents (68% would buy), followed by active system with audio-visual warning (68%), active system with handlebar vibration warning (65% would buy) and active system with combined warning (66%).

2.7.1.9 Correlation between variables

Table 6 displays descriptive statistics and correlations among the measures of behaviour, attitudes and risk perception. On average cyclists use the bicycle for more than 100 days per year. The scores on positive attitudes to cycling were medium to high. The score on the cycling infrastructure was slightly below the mid-point ("adequate"). The score on driving behaviour of motorists and van/truck drivers was slightly higher than the mid-point ("adequate"). Cyclists tended to report having virtually the same level of risk of being involved in a traffic accident compared to other bicycle riders of their age and sex. Cycling levels were positively related to positive attitudes to cycling and with the rating of the cycling infrastructure. The ratings of the cycling infrastructure and the driving behaviour of motorists and van/truck drivers were positively related. Positive evaluations of the cycling infrastructure and of the driving behaviour of motorists and van/truck drivers were associated with lower scores on risk perception.

Table 7 reports the mean values for the Responses to the question “How comfortable would you be to cycle in the following scenarios?” On average, cyclists reported to be comfortable riding on a path separated from the street, on a bike lane separated from traffic by a parked car or a kerb added to a major urban or suburban street with 4 lanes, and on a striped bicycle lane added to a two lane (one in each direction) residential commercial shopping street. In addition, cyclists tended to feel uncomfortable riding in a major urban or suburban street with 4 lanes (2 each direction), on street parking, traffic speeds of 30 miles an hour and no bike lane.

	MIN	MAX	*M*	*SD*	1	2	3	4	5	6
1. Cycling levels	2	365	114,82	110,23	—					
2. Personal benefits - Positive attitudes to cycling [a]	1	5	3,19	0,83	,19**	—				
3. Mobility benefits - Positive attitudes to cycling	1	5	4,08	0,70	,13**	,59**	—			
4. Overall rating of the cycling infrastructure [b]	1	5	2,84	1,04	-,14**	-,13**	,03	—		
5. How would you rate the driving behaviour of motorists and van/truck drivers within the environment you mainly cycle in? [b]	1	5	3,15	0,93	-0,04	-,10**	,08**	,44**	—	
6. Compared to other bicycle riders of my age and sex, my risk of being involved in a traffic accident is? [c]	1	5	2,79	0,76	-0,04	-0,00	,06**	,11**	,14**	—

Table 6: Descriptive statistics and correlations among the measures of behaviour, attitudes and risk perception

Note. [a] Response options ranged from 1 = Completely disagree to 5 = Completely agree. [b] Response options ranged from 1 = Excellent to 5 = Very poor. [c] Response options ranged from 1 = Much smaller to 5 = Much higher.

	MIN	MAX	*M*	*SD*
A path separated from the street	1	5	1.62	0.79
A two lane (one in each direction) residential commercial shopping street, with traffic speeds of 30 miles an hour, on street parking and no bike lane	1	5	3.18	1.14
What if a stripped bicycle lane was added	1	5	2.02	0.88
A major urban or suburban street with 4 lanes (2 each direction), on street parking, traffic speeds of 30 miles an hour and no bike lane	1	5	3.59	1.16
What if a striped bike lane was added	1	5	2.37	0.93

What if it a bike lane separated from traffic by parked car or a kerb was added	1	5	1.72	0.82

Table 7: Responses to the question "How comfortable would you be to cycle in the following scenarios?"

Note. Response options ranged from 1 = Very comfortable to 5 = Very uncomfortable.

Figure 25 displays the percentage of cyclists who reported having had an accident causing personal injuries in the past 2 years while cycling. About 9 out of 10 cyclists did not have an accident causing personal injuries in the past 2 years while cycling, while 4% of cyclists had to go to the hospital (as an outpatient or as an inpatient).

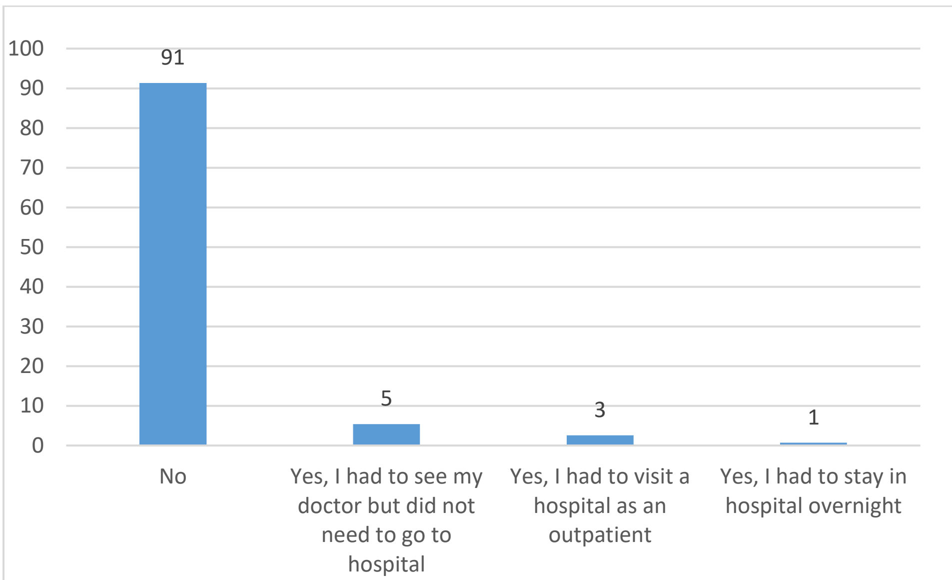


Figure 25: Percentage of cyclists who reported having had an accident causing personal injuries in the past 2 years while cycling.

Figure 26 displays the percentage of cyclists who reported having had an accident causing damages to the bicycle in the past 2 years while cycling. About eight out of ten cyclists did not have any accident causing damages to the bicycle. Three percent of cyclists reported having more than one accident causing damages to the bicycle in the past 2 years while cycling.

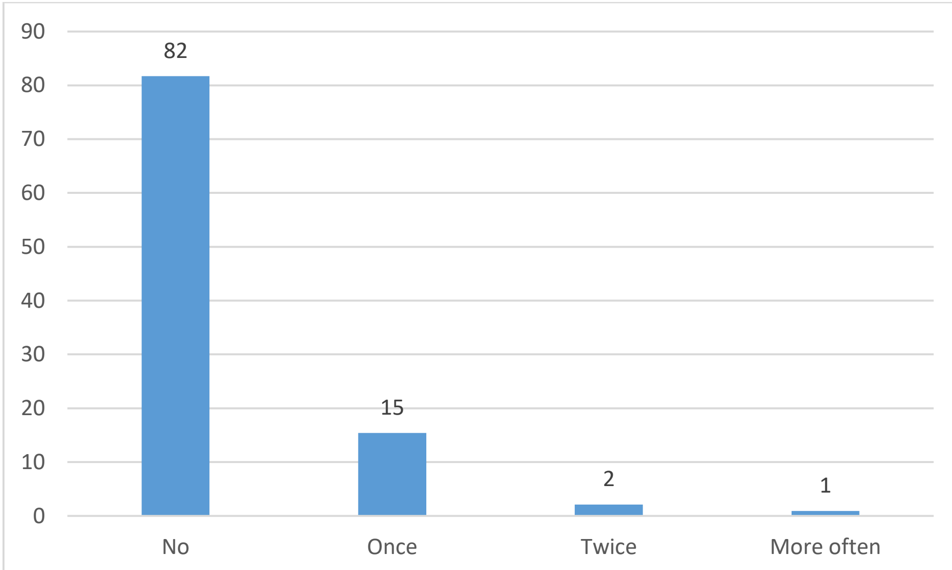


Figure 26: Percentage of cyclists who reported having had an accident causing damages to the bicycle in the past 2 years while cycling.

2.7.1.10 Segmentation

The segmentation of participants is a standard application of cluster analysis. Cluster analysis is a method for identifying homogenous groups of participants called clusters. Participants in a specific cluster share many characteristics but are very dissimilar to participants not belonging to that cluster.

In the present study, cluster analysis will be used to group participants by identifying different patterns of cycling levels, cycling patterns, attitudes to cycling and infrastructures, risk perception and exposure to accidents. The aim of this segmentation is to find groups where individuals within each cluster are more closely related between themselves than individuals assigned to different clusters. After having decided on the clustering variables, we needed to decide on the clustering procedure to form our groups of objects.

We used the two-step cluster analysis developed by Chiu et al. (2001) because it has been specifically designed to handle the issue of analysing variables measured on different scale levels. In the two-step cluster analysis procedure, a joint multinomial-normal distribution can be placed on categorical and continuous variables. The algorithm of the two-step clustering is based on a two-stage approach: 1) pre-cluster the cases into many small sub-clusters in a way that is very similar to the k-means algorithm; 2) cluster the sub-clusters resulting from pre-cluster step into the desired number of clusters using a modified hierarchical agglomerative clustering procedure that combines the objects sequentially to form homogenous clusters. As the distance measure between two clusters, we used the Log-likelihood because it can be used for categorical and continuous variables. To select the number of clusters to retain from the data, we calculated two measures of fit: the Akaike's Information Criterion (AIC) and the Bayes Information Criterion (BIC).

Both the AIC and the BIC revealed the presence of two clusters. The silhouette measure of cohesion and separation (an overall goodness-of-fit measure) provides information on the quality of the cluster solution.

The silhouette measure of cohesion and separation reached a value between 0.20 and 0.50, indicating a fair solution.

The first cluster concerns regular and frequent users, that is, people who use the bicycle every day for different purposes. The second cluster includes people who use the bicycle less frequently and mainly for recreational/sport purposes. We decided to name the first cluster "everyday cyclists" and the second cluster "competitive/recreational cyclists". Annex 1 reports plots of the distribution of the data for each variable used as input sorted in descending order of overall importance.

2.7.2 Willingness to Pay Analysis

2.7.2.1 Stated Preference

Models were estimated using BIOGEME as a standard fixed coefficients Multinomial Logit Models with standard errors accounting for the panel nature of the data. We present 2 versions of the results in Table 8 The first model (Model 1) includes the basic attributes. The second model (Model 2) introduces a number of interactions with the cost term in order to derive segmented values for WTP by country, gender and journey purpose. These interactions are as follows:

bco_hu – cost interacted with Hungary dummy
bco_it – cost interacted with Italy dummy
bco_ne – cost interacted with Netherlands dummy
bco_sp– cost interacted with Spain dummy
bco_sw– cost interacted with Sweden dummy
bco_male– cost interacted with Male dummy
bco_com– cost interacted with Commuter dummy

	MODEL 1		MODEL 2	
Name	Value	Robust t-test	Value	Robust t-test
bact	-0.291	-3.46	-0.311	-3.67
bcost	-0.0111	-27.43	-0.00944	-10.73
bdetection	1.69	19.68	1.7	19.64
bfalse	-1.11	-8.6	-1.11	-8.58
bpas	-0.612	-7.78	-0.632	-7.95
bco_hu			0.00	0
bco_it			0.00347	2.86
bco_ne			-0.00976	-6.88
bco_sp			0.00567	3.69
bco_sw			-0.00848	-6.2
bco_male			-0.00147	-1.7
bco_com			0.00338	3.62

Number of estimated parameters:		5		12
Number of observations:		19112		19112
Number of individuals:		2389		2389
Null log-likelihood:		-20996.7		-20996.7
Final log-likelihood:		-19885.9		-19641.1
Adjusted rho-square:		0.053		0.064

Table 8: SP Analysis model results

Both models in Table 8 give robust parameter estimates on the key attributes. Model 2 gives a better fit as measured by the adjusted rho-squared suggesting that the inclusion of the additional cost segmentations improves the model.

From Model 1 we were able to derive the following WTP values:

WTP_{pas} = 55.4 Euros

WTP_{act} = 99.5 Euros

Overall respondents are willing to pay around 80% more for the active technology than for the passive technology.

Model 2 allows us to derive differential segmentations for WTP values. Using a base group of UK Male non-commuters we generated the following WTP values:

$\mathrm{WTP}_{\mathrm{pas}}$ = 55.2 Euros

$\mathrm{WTP}_{\mathrm{act}}$ = 100.2 Euros

:	WTP UPLIFT FACTORS
Hungary:	1
Italy	1.47
Netherlands:	0.53
Spain:	2.08
Sweden:	0.56
Females	1.16
Commuters	1.45

Table 9: WTP uplift factors

From this base group we were able to estimate a number of uplift factors for different segments of the sample population, as reported in Table 9. This suggests that WTP values for the technologies are almost half the UK values in the northern European countries of Sweden and Netherlands and strikingly higher for the southern European Spain and Italy. Obviously, these differences reflect tastes, underlying road conditions, cycling infrastructure and income differentials between the countries. But clearly the income differences are more than offset by other factors differing by countries as the WTP values are higher in the lower income countries. Females have 16% higher WTP values compared to males, and commuters 45% higher than non-commuters.

2.7.2.2 Comparison between field study and online survey in WTP and WTA using a contingency values approach

In this section we compare the values of WTP and WTA obtained in the field study and in the online survey using a contingency values approach. To do so, we selected the data from Italian participants and from the Active Audio/Visual System in the online survey. In the field study, participants were willing to spend on average 63.00€ (SD = 50.72€), while in the online survey, participants were willing to spend on average 46.47€ (SD = 53.03€). Figure 27 reports the values of WTP for both studies. Analysis of Variance revealed that the evaluations of WTP in the field study and in the online survey were not statistically different, $F(1, 428) = 2.38$, $p = .123$

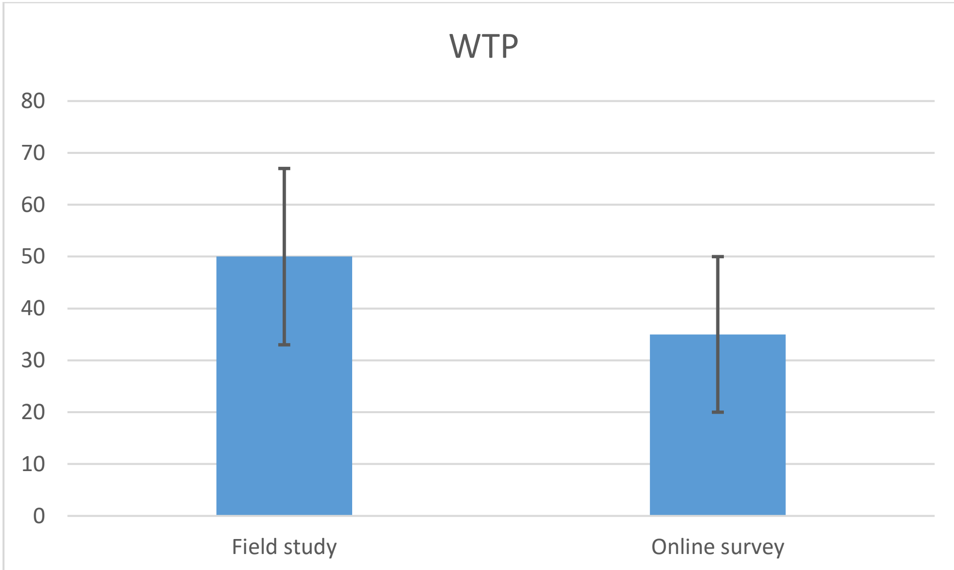


Figure 27: Medians (and Interquartile ranges) of the WTP evaluations in both studies

In the field study, the mean lowest price for which participants were willing to sell the on-bike system was 46.25€ (*SD* = 31.73€), while in the online survey, WTA was on average 30.33€ (*SD* = 35.35€). Figure 28reports the values of WTA for both studies. Analysis of Variance revealed that the evaluations of WTA in the field study were significantly higher than those in the online survey, $F(1, 428) = 5.01$, $p = .026$.

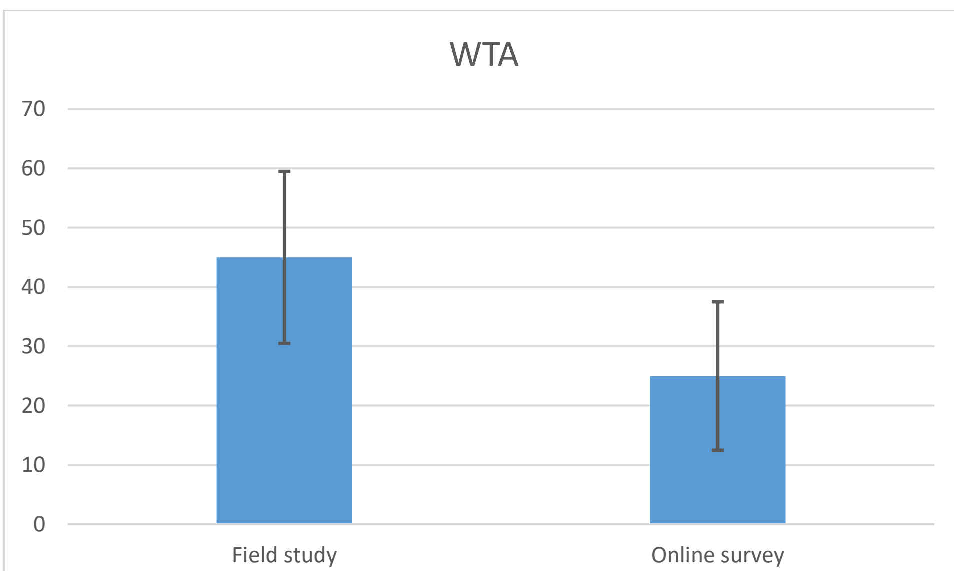


Figure 28: Medians (and Interquartile ranges) of the WTA evaluations in both studies

2.7.2.3 Impact on Behaviour

In this section we examine how the new technology discussed above might impact upon respondent's cycling behaviour, e.g. number of cycle trips made. In order to do this a question was asked towards the end of the survey as at that point the respondents were familiar with the different technologies offered. The question investigated whether the new technology *would alter the respondents' current cycling behaviour.* The responses are outlined in Table 10.

Overall 48% of the participants indicated that they would not change their current cycling behaviour if their bike were equipped with the new technology. This response varied across countries, with the UK and Spain considerably more likely to change their cycling behaviour (60 and 66% respectfully) compared to other countries. This may reflect the lower baseline of cycling behaviour within both of these countries and therefore the potential to make more trips.

There appears to be a greater propensity (more than double) to change cycling behaviour associated with the active technology as compared to passive technology, at least for those people who would be influenced by only one of the two (rows 3 and 4 in Table 10). At the same time a significant percentage of people (11% overall) appear ambivalent to the type of technology and would change behaviour regardless (row 6 in Table 10).

A change in cycling behaviour may or may not result in a change in cycle trips, e.g. it may mean people are more confident to make some of their existing trips on major, faster roads as opposed to smaller, slower roads. A further specific question was therefore asked to understand what the impact of the new technologies was on the number of bicycle trips made Table 11 to Table 13).

BEHAVIOUR	ALL	UK	NL	ESP	HUN	ITA	SWE
No change	1,155 (48)	161 (40)	203 (51)	134 (34)	225 (56)	198 (49)	234 (60)
Only change - passive tech	153 (6)	35 (9)	26 (7)	33 (8)	13 (3)	24 (6)	22 (6)
Only change - active tech	335 (14)	64 (16)	52 (13)	52 (13)	67 (17)	62 (15)	38 (10)
Diff. change – passive & active tech	477 (20)	97 (24)	95 (24)	98 (25)	50 (13)	73 (18)	64 (16)
Same change – passive & active tech	269 (11)	42 (11)	22 (6)	80 (20)	45 (11)	46 (11)	34 (9.0)
Total	2,389 (100)	399 (100)	398 (100)	397 (100)	400 (100)	403 (100)	392 (100)

Table 10: If your bike were equipped with the new technology how might you alter your current cycling behaviour?

Note: figures reported are respondents and (%)

BEHAVIOUR	ALL	UK	NL	ESP	HUN	ITA	SWE
Same number of cycle trips	386 (61)	81 (61)	91 (75)	71 (54)	44 (70)	46 (47)	53 (62)
More cycle trips	237 (38)	48 (12)	27 (22)	60 (46)	19 (30)	51 (53)	32 (37)
Less cycle trips	7 (1)	3 (1)	3 (3)	0 (0)	0 (0)	0 (0)	1 (1)
Total	630 (100)	132 (100)	121 (100)	131 (100)	63 (100)	97 (100)	86 (100)

Table 11: If your bike were equipped with the passive technology how might you alter your current cycle trips?

Note: figures reported are respondents and (%)

BEHAVIOUR	ALL	UK	NL	ESP	HUN	ITA	SWE
same number of cycle trips	427 (53)	76 (47)	108 (74)	75 (50)	64 (55)	52 (39)	52 (51)
more cycle trips	378 (47)	83 (52)	38 (26)	73(49)	53 (45)	82 (61)	49 (48)
less cycle trips	7 (1)	2 (1)	1 (1)	2 (1)	0 (0)	1 (1)	1 (1)
Total	812 (100)	161 (100)	147 (100)	150 (100)	117 (100)	135 (100)	102 (100)

Table 12: If your bike were equipped with the active technology how might you alter your current cycle trips?

Note: figures reported are respondents and (%)

BEHAVIOUR	ALL	UK	NL	ESP	HUN	ITA	SWE
same number of cycle trips	131 (49)	22 (52)	16 (73)	30 (38)	24 (53)	19 (41)	20 (59)

more cycle trips	135 (50)	20 (48)	5 (23)	50 (63)	21 (47)	27 (59)	12 (35)
less cycle trips	3 (1)	0 (0)	1 (5)	0 (0)	0 (0)	0 (0)	2 (6)
Total	269 (100)	42 (100)	22 (100)	80 (100)	45 (100)	46 (100)	34 (100)

Table 13: If your bike were equipped with both the passive and active technology how might you alter your current cycle trips?

Note: figures reported are respondents and (%)

The emerging picture from Table 11 to Table 13 is that active technology generates significantly more cycle trips than passive technology. There is a strong likelihood that this reflects the active system's higher functionality and performance levels, leading to a greater trust in the system and therefore an increase in the propensity to cycle (47% increase of overall trips vs 38%). Other key findings include: (1) For the majority of cyclists the main benefits of both systems do not translate into changes in cycle trips and must manifest themselves as other behaviour changes as discussed earlier; and (2) There are differences in behaviour across countries, for example their appears to be a strong preference for active technology particularly in the UK (52% making more trips vs 12% with passive technology), whilst the impact of both technologies is highest in Italy.

To try to quantify this effect further another question was used. It asked respondents to estimate how many more or less journeys would they make as a % change on current journeys. We report the average changes in Table 14. Note we have discounted the minor impact of respondents making fewer journeys.

BEHAVIOUR	ALL	UK	NL	ESP	HUN	ITA	SWE
Passive	32 *30* [237]	30 *25* [48]	31 *25* [27]	36 *30* [60]	29 *25* [19]	34 *30* [51]	31 *30* [32]
Active	35 *30* [378]	33 *30* [83]	35 *30* [38]	35 *25* [73]	32 *30* [53]	39 *38* [82]	33 *30* [49]
Both	37 *30* [135]	34 *28* [20]	27 *25* [5]	37 *30* [50]	43 *30* [21]	42 *30* [27]	25 *20* [12]

Table 14: Average % increase in trips for those reporting making more trips as a result of their bicycles being equipped with the new technology

Note: figures reported are Mean, *Median* and [sample]

Table 14 shows that for those respondents for whom the installation of new technology on their bicycles would lead to more trips, the increase in trips would be just over a third, suggesting a considerable latent demand for cycling.

2.8 Conclusions

In this section we outline some of the key findings emerged from the analysis.

2.8.1 General Characteristics, Attitude and Behaviour

In terms of the characteristics of the data we are confident that the sample is reflective of the cycling populations within the six countries surveyed. In general, cycling is more prolific in the Netherlands, Hungary and Italy (and in Sweden, to an extent) and much less so in Spain and the UK.

There appears to be a good cross-section of different types of cyclists from across each country, ranging from occasional cyclists to the committed. Urban cycling accounts for around 65% of the sample, with village and rural cycling for the rest. Despite this, nearly 70% of the respondents report that they sometimes cycle for leisure/training reasons, whilst just less than 30% undertake some level of commuting activity.

In terms of attitudes towards cycling there was a strong agreement: 86%, that respondent cycled because it was pleasant. Other positive reasons for cycling included relaxation (81%), saving money (81%), health benefits (74%) and environmental benefits (74%). Less positive reasons for cycling include social status (21%), personal security (29%) and traffic safety (30%). A factor analysis attempted to distil this further, finding significance coefficients for seven of the reasons for cycling (these are outlined in Table 5.1.).

It appears that the level of cycling infrastructure provision and the quality of that infrastructure are highly related, r=0.87, with the highest level of criticism expressed by the Italian respondents, with the Dutch the least critical.

The highest level of discomfort was expressed for riding on a 4-lane road (2 lanes in each direction) without a striped or separated bike lane (59% of respondents). Contrarily, the lowest level of discomfort is experienced on a cycling path separated from the street (3% of participants).

A range of correlations was calculated to examine the measures of behaviour attitudes and risk perceptions. Some of the key findings were: (1) Cyclists tended to report to have virtually the same risks of being involved in a traffic accident compared to other bicycle riders of their age and sex; (2) Cycling levels were positively related to positive attitudes to cycling and the rating of the cycling infrastructure; (3) The ratings of the cycling infrastructure and the driving behaviour of motorists and van/truck drivers were positively related; and (4) Positive evaluations of the cycling infrastructure and of the driving behaviour of motorists and van/truck drivers were associated with lower scores on risk perception.

2.8.1.1 Willingness to Pay

The Stated Preference experiments provided highly plausible models with robust parameter estimates for the key attributes. Model 2 gives a better fit as measured by the adjusted rho-squared suggesting that the inclusion of the additional cost segmentations improves the model.

From Model 1 we were able to derive the following WTP values at a European wide level for the Passive and Active technologies respectfully, which signify that overall respondents are willing to pay around 80% more for the active technology (note these are one off purchase costs – excluding running costs associated with replacing batteries and/or USB charging):

WTP_{pas} = 55.4 Euros

WTP_{act} = 99.5 Euros

Model 2 allows us to derive differential segmentations for WTP values. Using a base group of UK Male non-commuters, we generated the following WTP values:

$\mathrm{WTP}_{\mathrm{pas}}$ = 55.2 Euros

$\mathrm{WTP}_{\mathrm{act}}$ = 100.2 Euros

From this base group we were able to estimate a number of uplift factors for different segments of the sample population. This suggests that WTP values for the technologies are almost half of the UK values in the northern European countries of Sweden and Netherlands and strikingly higher for the southern European Spain and Italy.

Obviously, these differences reflect tastes, underlying road conditions, cycling infrastructure and income differences between the countries. Although clearly the income differences are more than offset by other factors differing by countries, as the WTP values are higher in the lower income countries. Overall, we would argue that the better the cycling infrastructure and/or the safer the underlying road conditions, the lower the WTP, reflecting a lower requirement for XCYCLE systems.

Other key findings are that females have 16% higher WTP values compared to males and that commuters 45% higher than non-commuters. Again, the intuition behind these values seems plausible, with males overconfident about their own cycling ability and perceived risks as compared to females and commuters being aware that they have a lot more exposure to potential risk than non-commuters.

In general SP models tend to estimate higher WTP values than revealed preference (RP) models and this is likely to be the case here. Despite this, SP models do tend to provide strong evidence on relative valuations and we believe that to be true in our study.

Returning to the issue of higher WTP values from the SP models, a useful comparator can be found in the form of the Contingent Valuations (CV) from both the online panel survey and the field trials run in Italy. The key focus here was on the Italian participants in relation to the Active Audio/Visual System. In the field study, participants were willing to spend on average 63.00€ (SD = 50.72€), while in the online survey, participants were willing to spend on average 46.47€ (SD = 53.03€). Figure 5.4 reports the values of WTP for both studies. Analysis of Variance revealed that the evaluations of WTP in the field study and in the online survey were not statistically different, $F(1, 428) = 2.38$, $p = .123$. Both values are lower than the SP WTP and a case might possibly be made for using the CV values to scale the former.

2.8.1.2 Impact on Travel Demand

Overall 48% of the sample indicated that they would not change their current cycling behaviour if their bike were equipped with the new technology, with strong variation across countries, e.g. UK and Spain more likely to change their cycling behaviour (60 and 66% respectively).

There appears to be a greater propensity (over double) to change cycling behaviour associated with the active rather than passive technology, at least for those people who would only change their behaviour due to usage of only one of the two. There are differences in behaviour across countries, for example there appears to be a strong preference for active technology (particularly in the UK with 52% of participants making more trips vs 12% with passive technology), whilst the impact of both technologies is highest in Italy.

At the same time a significant percentage of people (11% overall) appear ambivalent to the effects of the type of technology.

A change in cycling behaviour may or may not result in a change in cycle trips, e.g. it may mean people are more confident to make some of their existing trips on major, faster roads as opposed to smaller, slower roads.

For those respondents for whom the installation of new technology on their bicycles would lead to more trips, the increase in trips would be just over a third, suggesting a considerable latent demand for cycling amongst this group specifically related to safety and the risk of an accident.

3 Evaluation of the effects of the XCYCLE systems (T6.3)

3.1 Green wave

3.1.1 Introduction

For decades, cars have been benefiting from reasonable implementation of traffic signal solutions in areas where "green wave" for vehicles was implemented. Cyclists, a group of vulnerable road users, have not benefitted as much yet. However, to stimulate cycling to achieve a modal shift, they should not need to encounter constantly braking for red phases, but to experience unimpeded, safe and comfortable riding. Knowing this, the XCYCLE project (Advanced measures to reduce cyclists' fatalities and increase comfort in the interaction with motorised vehicles) uses GLOSA (Green Light Optimal Speed Advisory) with adaptive control, to achieve the same benefit towards cyclists as to motorised vehicles. This will reduce the time cyclists have to wait at intersections and thus, reduces the red-light violation of cyclists, increases the comfort and thereby encourages the use of this green mode of transport (XCYCLE Consortium, 2015). Respecting design and implementation, a GLOSA for bicycles is successfully applied on a single intersection in Groningen.

This chapter describes the implementation of the green wave system on the site in Groningen, as well as the technical and behavioural evaluation of the system. In section 3.1.3 the green wave system is described. In the following two sections the observational evaluation studies and the experimental studies are reported.

3.1.2 Site description

The site selected for implementation of the prototypical system was the intersection Paterswoldseweg/Parkweg in Groningen.

The intersection had to fulfil several requirements:

- Under control of Dynniq, and located in the Netherlands, for easier communication between Dynniq and the municipality.
- No other measures planned for the intersection.
- A dedicated traffic light for cyclists.
- A physically separated cycle path, such that cyclists could be detected reliably.
- No possibility to provide a better routing for cyclists into the city, away from traffic and intersections.
- An approach of at least 300 m to 400 m without any major traffic flow into or away from the cycle path leading up to the intersection, such that the camera monitoring the cyclist stream would be able to deliver reliable results to the back-end.
- Preferably at a convenient distance to the University of Groningen, to simplify observations and the semi-controlled study.

The selected site consisted of the main road Paterswoldseweg, leading northwards into the city of Groningen and southwards towards the southern suburbs, and Parkweg, a smaller road leading westward into a park and eastward to a residential area close to the city centre and the main station. Most traffic travelled on Paterswoldseweg, and there were clear peaks during the morning and afternoon rush hours (see Figure 29, Figure 30 and Figure 31).

For the investigated traffic direction, there was one car lane in each direction, one dedicated bus lane on the right-hand side of the car lane, a dedicated cycle lane physically separated from the road by a two-metre-wide elevated cycle/car parking area, and a pedestrian walkway separated from the cycle path by a kerb stone edge. Near the intersection the cycle path had separated lanes for going straight on and for turning right. The traffic light for the cyclists was positioned on the left of the cycle path, just behind the zebra crossing after the stop line for cyclists. In the baseline condition, the traffic light on the left-hand side of the cycle path was equipped with a standard system for cyclist traffic lights in Groningen. Left of the red, amber, and green lights, a vertical strip of LED-lights was incorporated in the traffic light (see Figure 49). This strip of LED-lights gives an indication of the time that it would take for the traffic light to turn green, with more lights lit indicating a longer waiting time. However, the traffic control algorithm behind the LED-lights is not very optimal and causes irregularities such as a sudden stop of the countdown or the traffic light suddenly turning green without accompanying countdown (for a detailed description in the drawbacks of the old traffic algorithms see section 3.1.3). In the treatment condition, the XCYCLE sign was placed on the right-hand side of the cycle path, approximately 3 metres behind the traffic light. The vertical strip of LED-lights that was integrated in the traffic light was switched off during the treatment condition.

Traffic from the right had two lanes, one combined for traffic turning left and going straight, and one for traffic turning right. Adjacent to the latter was a cycle lane.

The cycle path on Paterswoldseweg was painted through the intersection with red colour and white markings, but of course without physical separation.

Figure 29: A closer look at the location of the sign and the detection camera.

Figure 30: Impression of the intersection where the green wave has been implemented.

Figure 31: Cycle path with sign is on the right next to the houses in northern direction © Google maps.

3.1.3 System description and implementation

Intelligent Transportation Systems (ITS), including the possibility to wireless information exchange among vehicles and between vehicles and infrastructure, offer a broad range of applications (Willke, Tientrakool and Maxemchuk, 2009) . Traffic lights are one of the dominant factors for traffic flow dynamics in urban areas. ITS solutions in these areas should therefore be efficiently sought in cooperation with traffic light controllers (Blokpoel and Lu, 2017). For motorised vehicles, GLOSA is a commonly used application for eco-driving (Katsaros, Kernchen, Dianati and Rieck, 2011). Such a GLOSA system was shown in Passchier et al. (2014) and Blokpoel, Islam and Vreeswijk (2014) to have a potential CO2 reduction of up to 7.0%.

Over the last 10 years, Dynniq has been involved in development of GLOSA systems. The aforementioned traffic control algorithm ImFlow prevents vehicles from stopping and starting, which saves fuel and pollutant emissions that can cause health problems for people especially in congested urban environments (Kunzli, Kaiser, Medina, Studnicka et al., 2000). With sufficient research and practice, it was shown that this GLOSA application is not restricted to vehicles. However, the difference between GLOSA for vehicles and bicycles needs to be addressed and related problems need to be solved.

The basis for effective GLOSA functionality, is the time to green prediction, which is given by the traffic light controller, and this prediction has to be stable. For instance, a driver only needs to receive a GLOSA once, for example, around 250 meters ahead of the stop line, in the form of speed advice (km/h), process and accept this information by adjusting the speed of the vehicle referencing the speed shown on the in-vehicle dash board. Meanwhile, an average cyclist has limited understanding of its own speed. Thus, a cyclist relies on the GLOSA constantly along the route until the stop line. A constantly available, reliable and stable GLOSA with time to green count-down is important to the cyclist to adjust its speed to catch a green wave. ImFlow has the option of configuring the predictability, which is used to enable this GLOSA for cycling.

In practice, it is difficult to present the advice to a cyclist on a dedicated personal display, e.g. smart phone or navigation system. Therefore, a large display at the stop line (shown in Figure 29) is presenting a reliable count-down in seconds to the approaching cyclists. Note that there is a bus symbol on the display in Figure 29. This bus symbol will only light up when a priority to bus on the conflicting direction is just processed and granted. It intends to inform cyclists why the time to green for them has suddenly changed. This is because public transport usually has a higher priority in the policies of a road operator than a cycling green wave. By informing cyclists about this priority, cyclists' trust in the system shall not deteriorate.

As shown in Figure 32, the basic idea is that when a cyclist is at 200 metres from the stop line with 60 seconds to green remaining, it may have to stop if continue to cycle at the speed of 20 km/h (travel time is only 36 seconds at this speed). With a remaining time to green count-down advice (shown in Figure 29), cyclists can slow down to 12km/hour (i.e. ease down on peddling and cruising forward), which will take around 60 seconds to the stop line and therefore, can continue cycling without stopping. This paper intends to expand this practice from a single to multiple coordinated consecutive intersections, with the goal of predictable adaptive traffic control for cyclists on the network level.

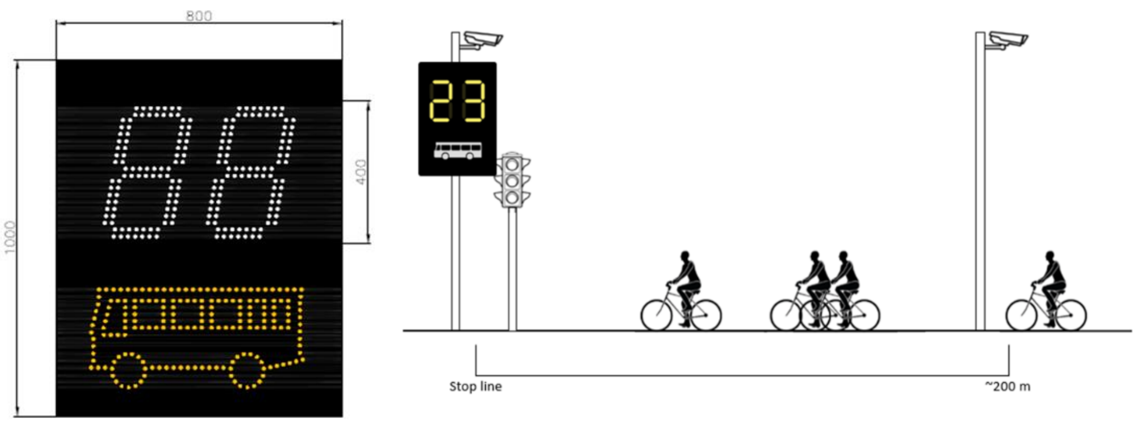


Figure 32: Speed advice sign and detection system in Groningen intersection

Adaptive GLOSA is feasible through configuring the traffic control algorithm for additional predictability. Fluctuations in the prediction about when the light will turn green directly lead to fluctuations in the speed advice. In order to control the quality of the time to green prediction, a trade-off between predictability and flexibility must be made. Less flexibility generally results in a higher average delay, which is also undesirable (Blokpoel and Niebel, 2017). Similarly, a stable speed advice is also important when considering green wave for cars. Slow and small changes may be acceptable when at a large distance from the traffic light, but large fluctuations will deteriorate the fuel savings and user trust in the system.

There is limited scientific research in the domain of increasing the predictability of traffic control methods, such as stabilizing GLOSA to enable green wave. Researchers often focused on macro level where the process of speed changes is ignored. Often the control system is not specified. Most previous studies only target the sustainability evaluation of eco-driving through simulation (Blokpoel and Lu, 2017). Even fewer studies are focusing on optimization and predictability of GLOSA for cycling green wave, nor the related adaptive control algorithm. Adding an extra cost function to the adaptive control algorithm ImFlow to control the predictability, shows a reduction of perceived change for GLOSA users from an average 9.0% to 2.3% (Blokpoel and Niebel, 2017).

3.1.3.1 Simulation study 1: Scale up simulation study for the green wave system

Intrigued by the promising results of the simulations and field trial in Groningen, this study continues the research on multiple intersections. The results also give more accuracy to the cost-benefit analysis as they are based on more data than just a single intersection. The results of this study were also presented in a paper at the ITS World congress in Copenhagen.

3.1.3.2 Background

A variety of different control systems are used to accomplish smooth and safe traffic. Based on the research of (Blokpoel and Lu, 2017), there are several primarily types of traffic light controller, listed in Table 1. An arbitrary comparison with relevance to GLOSA is given here. In Table 1, symbols from “--” to “++” are used as a scale of five, “--” is the worst and “++” is the best, to demonstrate the performance of a traffic control on a respecting criteria. Table 15 shows that adaptive GLOSA can achieve both predictability and flexibility, or the feasibility to provide a trade-off between them.

Table 15: Traffic control strategies evaluation overview

	Level of complexity	Maintenance cost	Predictability	Flexibility
Static control	++	--	++	--
Actuated control	0	-	--	+
Semi-fixed time control	0	-	+	-
Adaptive control	-	++	0	++
Adaptive GLOSA	-	++	+	+

The theory of various traffic controls and the control algorithm of ImFlow is described in paper Blokpoel and Lu (2017). This study explores the effect of adaptive GLOSA for bicycles using the state-of-the-art application, ImFlow.

The principle concept of ImFlow system is the optimiser, which uses the cost formula to optimize traffic signal timing, see the following schematic formula as reference:

$$StateCost = Cost_1 + Cost_2 + Cost_3 \dots + Cost_n \quad (1)$$

This $StateCost$ is applied to each signal group of each intersection to calculate the intersection cost for the planned signal timing. The optimiser will compare many alternative signal-timing plans and execute the plan with the lowest intersection cost. Specific policies can be configured by the user, respectively from $Cost_1$ to $Cost_n$. The extensibility of this adaptive control algorithm allows for adding new elements to the cost function. In the scope of this study, it means that adding new elements of cost can overcome excessively frequent changes of signal plan timing and increase the reliability and accuracy of predictions for the green phase. Furthermore, it helps cyclists modifying their speed to meet the green phase of the traffic light. A patent for a new algorithm adding this predictability configuration was applied, targeting on making the control algorithm more suitable for GLOSA at little to no cost for other traffic. Additionally, public transport priority calls can still be configured as more important than predictability (Blokpoel and Lu, 2017).

The core of this new methodology (that has been implemented in ImFlow), is to prevent the optimizer from changing the planning frequently or by a large deviation. Therefore, the aim is not to give more priority to bicycles, but rather making the planning more predictable - particularly close to the green phase - so that bicycles receive reliable speed advice in order to pass the green light (Blokpoel and Lu, 2017).

The implementation of this cost function (C) is further explained in the following formulae (Blokpoel and Lu, 2017):

$$C = \frac{SBW.d^2}{TTG_{t-1}} \tag{2}$$

$$d = TTG_{t-1} - TTG_t - T \tag{3}$$

SBW: The configured weight for predictability. It allows the traffic engineer to configure the importance of predictability with respect to other control targets.

d: The deviation. It is calculated using the difference between the time to green (*TTG*) of two consecutive time steps. The quadratic characteristic to the deviation means that higher deviations are increasingly worse for the user acceptance of a speed advice.

TTG_{t-1}: The time to green of a time step (*t-1*). The cost C is inversely proportional to TTG_{t-1}. This means that the closer to green, the more impact a change has on the plan. This is a major improvement compared to semi-fixed time strategies, which allow for flexibility around the stage transition and could therefore still change the prediction very close to the actual moment of the transition.

TTG_t: The time to green of a time step (*t*)

T: The time period of a time step (*T*). It is used for the expected decrease (time elapsing) of the *TTG*.

Since this cost function can be activated on a per signal group basis, it is particularly beneficial to the case study in this study. It is often difficult to realize green waves consecutively for multiple intersections, as distances between intersections vary. With this methodology, a green wave along a string of intersections could be achieved with individual cost functions with optimal *SBW* parameter. Consequently, different speed recommendations (remaining time to green count down) for each intersection will compensate for varying intersection spacing and varying traffic demand on conflicting traffic streams. In this way, the proposed methodology gains both predictability and flexibility.

The implementation of extension level (*EL*) refers to different levels of vehicle actuated (VA) control. *EL* can be set to 0 or 1. When *EL* is set to 0, VA extension is enabled as the baseline scenario setting of the network; When *EL* is set to 1, VA extension is disabled if the next planned stage has a signal group with GLOSA, which will be indicated as a "GLOSA signal group" in the remainder of the study.

3.1.3.3 Simulation method

City of Helmond is a small/medium-sized (90.000 inhabitants) city in the south-east of the Netherlands, a region also known as the "brain port" region. This study chooses Helmond network because of its characteristics of multiple intersections on a corridor in the city centre of Helmond, shown in Figure 33.

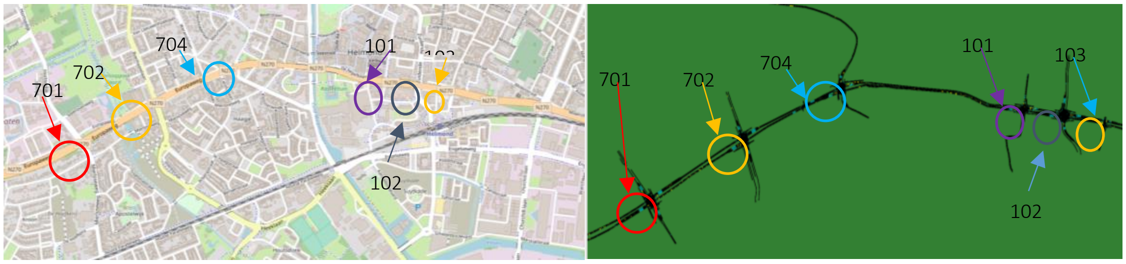


Figure 33: Six consecutive intersections of the case study in Helmond (left) and the corresponded simulation network in SUMO (right)

- Intersection 701, Hortsedijk/ Europaweg
- Intersection 702, Boerhaavelaan/ Europaweg
- Intersection 704, Prins Hendriklaan/ Kasteel-Traverse
- Intersection 101, Zuid Koninginnewal/ Kasteel-Traverse
- Intersection 102, Zuidende/ Kasteel-Traverse
- Intersection 103, Penningstraat/Smalstraat/ Kasteel-Traverse

In Figure 33, the real-world network and corresponding simulation network are depicted. The points of interest on this real-world network layout are six consecutive intersections that contain bicycle lanes (only the east-west/west-east directions are considered here). The Helmond-based simulation network is modelled and calibrated in SUMO and it focusses on the traffic control related scenarios, primarily bicycle traffic controls. Supported by predictable adaptive control, a new approach of bicycle detections is applied to the case study. Current approach of detection type at these intersections are either no detection or actuated, which is a push-button at the stop line. Providing speed advice using a push button is nearly impossible, because the arrival of the cyclist cannot be predicted, and the traffic light controller will try to give green as soon as possible after the button is pressed. In this solution upstream detection will be used to predict arrivals and plan the green phase in advance.

As shown in Figure 34 these bicycle lanes are composed of dual carriageway (car lanes in the middle) with one-way/two-way bicycle lanes, for example, link 27, 28 and link 24 on intersection 101, or link 27, 28 and link 23, 24 on intersection 702. Additionally, they can be composed of single carriageway with one-way/two-way bicycle lanes, for example, link 27, 28 on intersection 704, or link 24 on intersection 103 (Referred to as Link 103_{24}, see Note 1 below for the detailed numbering convention).

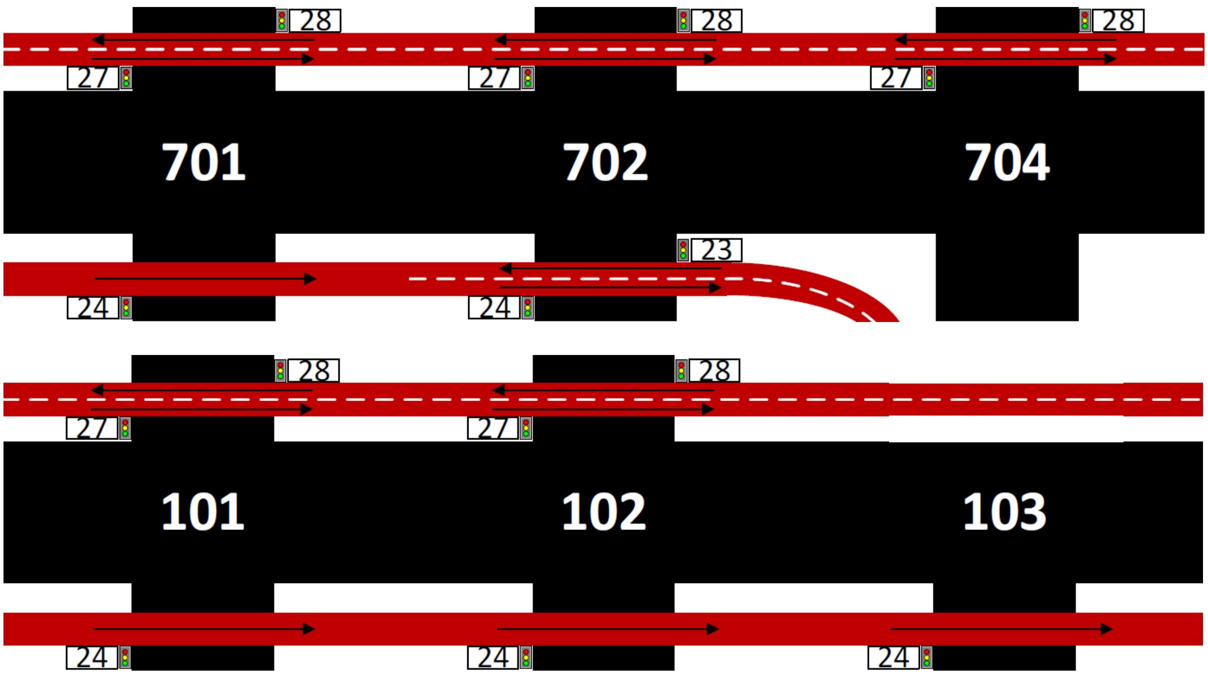


Figure 34: From west to east, schematics of six consecutive intersections road layout, showing only the bicycle lanes (red) and corresponding signal controls

Note 1: The numbering of signal controls replicates real world signal group situation. Signal group number 24, 23, 27 and 28 are used here. The bicycle link segment at the intersection also follow this numbering convention, i.e. $701_{27,28}$ refers to the two-signal head 27 and 28 at intersection 701; Link $701_{27,28}$ refers to the two-way bicycle lane segment at intersection701.

The goal of simulations in this study is to compare the performance of the current signal control plan with a control plan including GLOSA functionality, targeting the bicycle signal groups. Six scenarios, scenario 0 to 5 are designed in order to compare the effect of baseline (scenario 0), single and multiple intersections with GLOSA, as shown in Table 16.

Table 16: Simulation scenario designs overview

	Description	Traffic control configuration	GLOSA
Scenario0	Baseline, do nothing	Current control plan	NO
Scenario1	$701_{27,28}$	Adapted control plan	YES
Scenario2	$701_{27,28}$+$702_{27,28,24,23}$+$704_{27,28}$	Adapted control plan	YES

Scenario3	$101_{27,28,24}$	Adapted control plan	YES
Scenario4	$101_{27,28,24}+102_{27,28,24}+103_{24}$	Adapted control plan	YES
Scenario5	$701_{27,28}+702_{27,28,24,23}+704_{27,28+}$ $101_{27,28,24}+102_{27,28,24}+103_{24}$	Adapted control plan	YES

The adapted control plan consists of three elements, the first is adding detection upstream in order to predict the arrival of cyclists. Additionally, constraints in the control plan that conflict with predictability have been removed and finally, the possibility to configure a weight for predictability as indicated in formulae 2 and 3 was added. For each scenario, sub-scenarios of different parameter sets (different *SBW* and *EL*) are configured and respective simulations are performed with 10 runs/sub-scenario and 2-hour simulation/run during the evening peak. The speed advice that is given to the cyclists in this simulation is assumed to be fully complied by the cyclists, as an estimate of their behaviour. Speed advice is applied from 200 meters before each stop line and they are subject to a speed range of 6- 20 km/h. Slower or faster speeds are not considered realistic.

During the simulation, delay time and the number of stops is tracked for every traffic participant. Average impact for each traffic participant (*s*) is defined by the following formula [3] to emphasize the punishment on full stops of bicycles.

$$impact = \frac{\sum_{i=0}^{i=I} delay_i + 8\ stops_i}{I} \qquad (4)$$

- *Delay time*: this is a basic measure for evaluating the traffic efficiency. It compares the actual travel time with the free flow travel time. It is important to note that waiting time is different from this as delay is also incurred when a road user slows down without stopping.

- *Number of stops*: they greatly contribute to user discomfort and when used for a specific signal group, stops reflect the green wave success rate. For bicycles, there is a risk of red-light violation during a stop and for motorized traffic there is an additional CO_2 emission due to reacceleration.

The formula (4) sums over all traffic participants and calculates the average impact. It can both be applied to the total network or to a single signal group [3]. In this study, the impact is applied to the total network to see the effect on all traffic participants when GLOSA is considered for vulnerable road users: bicycles. Due to the high value of impact itself, a unified impact (*Impact_unified*), the quotient of sub-scenario impact divided by scenario 0 impact is calculated later in the result section, to obtain comprehensible results. And the *unified* character of *Impact_unified* indicates each scenario/sub-scenario refers to the baseline.

A mean square error (*MSE*) is calculated as a good indicator for overall reliability of the data. Here, a mean relative error (*MRE*) is used, which divides the error by the remaining *TTG* and expresses this as a percentage, because deviations close to the actual moment of switching needs to be penalized more. A last predictability measure is the Perceived Change (*PC*), which represents the percentage change between two consecutive predictions relative to the remaining *TTG*. The calculation of this measure is described in the formula below [8]:

$$pc = \frac{\sum_{t=1}^{T} \frac{\alpha |TTG_{t-1} - TTG_t - T|}{min(TTG_{t-1}, TTG_t)} 100\%}{\sum_{t=1}^{T} \alpha} \quad (5)$$

$$\alpha = \begin{cases} 0, TTG > 60 \\ 1, TTG \leq 60 \end{cases} \quad (6)$$

The *PC* measure serves to estimate the users' perception of the system. A low value is preferred for users' perception. Similar to impact, *MRE* and *PC* can both be applied to the total network or to a single signal group. In this study, due to the complexity of sub-scenarios, applying them to the total network level (all signal groups at intersections) show a quick overview of performance, but it is not fair comparison among different sub-scenarios. Therefore, *MRE_unified* and *PC_unified* are introduced. *MRE_unified* is the quotient of sub-scenario *MRE* on GLOSA signal groups divided by the *MRE* of the baseline scenario on GLOSA signal groups, to make sure to follow the consistency of extracting *MRE* on the same GLOSA signal groups within the scope of each sub-scenario. Results of *PC_unified* is defined the same as *MRE_unified*. Together with *Impact_unified*, a unified figure of merit (low is better in this study) can be expressed in the formula below:

$$FOM\_unified = Impact\_unified \times MRE\_unified \times PC\_unified \quad (7)$$

3.1.3.4 Results

The results showed a clear success for the green wave by applying GLOSA. In the baseline cyclists could pass the green light without stopping in only 44% of the cases. The effect on green wave success was already optimal when *SBW*=60 was configured for all intersections. This resulted in 64% green wave success rate. At the same time the effect on traffic efficiency was limited with an increase of the impact by 4.9% from an average impact of 26.6s to 27.9s. The MRE dropped from 35% to 12% and PC from 7.6% to 4.1%. With higher values of *SBW* and setting *EL*=1, this could decrease further to an MRE of 9.1% and PC of 2.7% (*SBW*=480, *EL*=1). However, this was at the cost of traffic efficiency, with an increased impact of 32.6s. Looking at the subnetworks, the scenario of 701, 702 and 704 was most successful with GLOSA success of 72%. When only 101, 102 and 103 were enabled the success rate was 60%. Enabling isolated intersections was less successful than several intersections in a corridor with 64% success for only 701 enabled.

Looking in more detail, the figures of merit: Impact, MRE and *PC* are extrapolated, and results are analysed for traffic efficiency and GLOSA functionality. Comparing to baseline scenario 0 (flat line with FOM value of 1), Figure 4 shows that for all other scenarios (with adaptive GLOSA), the synthesized performance figure *FOM_unified* decreases with increasing weight in the cost function to configure for predictability. When increasing the weight from 0 to 720, the figure of merit for scenario1-5 tends to converge at a low value around 0.16, which showed 84% decrease comparing to the baseline and around 60% decrease comparing to *SBW*=0. The case of *SBW*=0 already has the adjusted configuration where cyclists are detected upstream and certain control constraints are removed. Unexpectedly, there is one exception: scenario1 (only intersection 701 with GLOSA) already shows good results with *SBW*=0; increasing the weight to 60 induced a worsened result from 0.10 to 0.17. Intersection 701 is the entry intersection of the network with a high traffic demand. While other intersections receive the vehicles in platoons from upstream, this intersection has vehicles arriving from the west through a Poisson arrival process. Increasing *SBW* was therefore less effective.

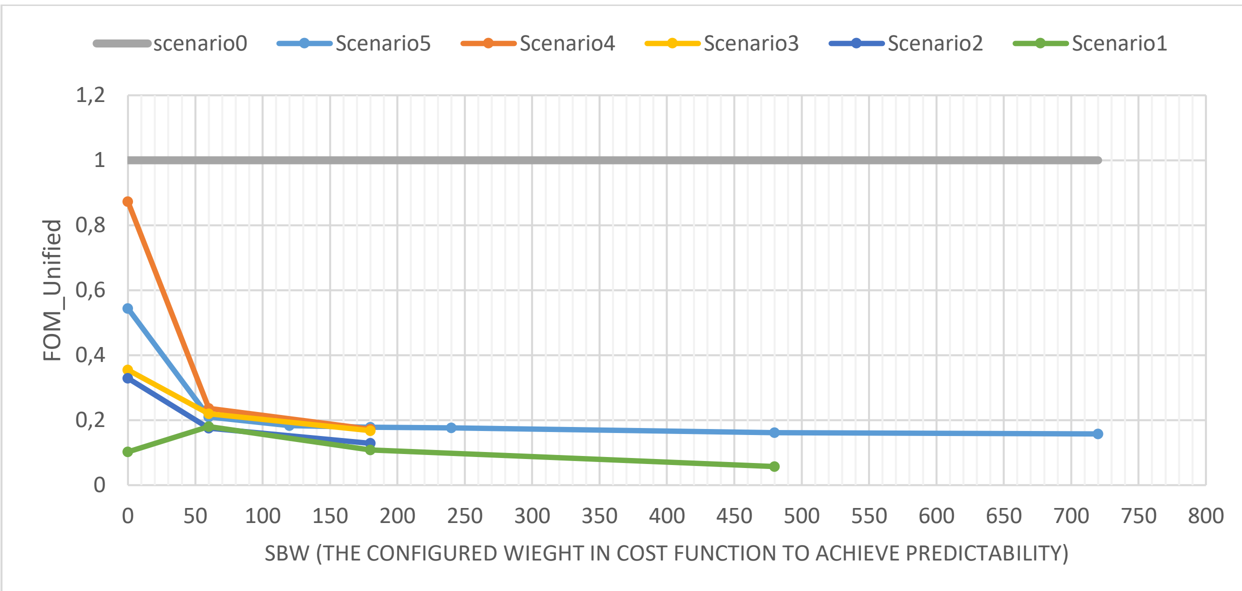
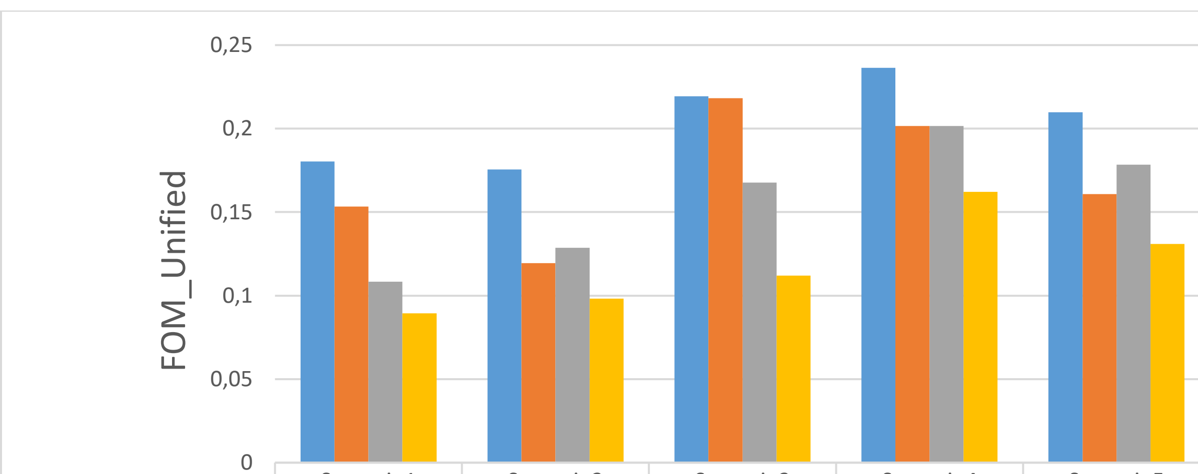


Figure 35: Relation of FOM unified to different weight in scenario 0-5



	Scenario1	Scenario2	Scenario3	Scenario4	Scenario5
SBW=60, EL=0	0,180316312	0,175446132	0,219372128	0,23644643	0,209742995
SBW=60, EL=1	0,153337473	0,119485371	0,218223139	0,201479579	0,160773701
SBW=180, EL=0	0,108307982	0,128689068	0,167735825	0,201479579	0,178443446
SBW=180, EL=1	0,089466847	0,098152337	0,111918918	0,162213211	0,130886656

Figure 36: Relation of FOM unified with different weight in scenario0-5 for *EL*=0 and 1

Furthermore, results of simulations with *EL*=0 and 1 are shown in Figure 36. With EL=1, which means extension of vehicle actuation for the next stage is disabled to have a more predictable plan, a visible decrease ranging from 10% to 20% can be observed for almost all sub-scenarios of scenario1-5. This feature is an effective way to configure more predictability for GLOSA for those signal groups because it can be customizable down to the level of a signal group at an intersection. Simulations for scenario 5 (six intersections with GLOSA) are conducted the most. Optimistic result of Scenario 5, with extension level (*SBW*=720, *EL*=1) shows a 9.65% decrease comparing to Scenario 5, without extension level (SBW=720, EL=0). Combining with Figure 35 it demonstrates that when *SBW* is at extreme high value, doesn't bring much benefit to further lowering *FOM unified*. Setting *EL* to 1 can still have a better result.

3.1.3.5 Conclusions about system implementation

This study investigates the GLOSA function for a cyclist green wave on multiple intersections and demonstrates the related impacts on all traffic participants on the network. It shows a high potential with green wave success increasing from 44% in the baseline up to 72% when the GLOSA function is used. At the same time impact on other traffic is kept minimal with an increase of only 4.9%.

It is important to consider the cyclist's behaviour was modelled in these simulations. While real cyclists are probably better at interpreting the countdown and aiming for the green, the tolerance to fluctuations of the behaviour model is higher than in reality. Therefore, the success rate is expected to be better in reality with the lower MRE and PC values that could be achieved by configuring more importance to predictability. The results also showed that consecutive intersections are more effective and very closely spaced intersections are less effective.

The trade-off between predictability and traffic efficiency was captured in a figure of merit measure. Increasing weight in the adaptive control algorithm and imposing rigid plan of no extension in the next stage, shows that green wave for cycling is feasible with ImFlow without deteriorating the performance of other conflicting traffic too much. Nonetheless, the configuration of constraints and the upstream detection of cyclists are essential for this application, especially for large-scale deployment, which needs careful calibration on the scenario 0 first before configuring the importance of predictability in the algorithm.

Future research on this topic can be carried out on this aforementioned attention point, to study if more flexibility of adaptive control can be kept regarding the trade-off between flexibility and predictability.

3.1.4 Observation Study: Natural behavioural effects of the green wave system

The green wave system was evaluated for effectiveness, acceptance and safety with an observational study and a semi-controlled field study, the observational study is described in this section, the semi-controlled study in the next section.

3.1.4.1 Objectives

The observational studies were carried out to determine the effects of the green wave cycle system on the road on a large group of cyclists. The goal was to study the effects of the system on natural behaviour with respect to waiting times, stopping frequency, grouping of cyclists, route choice behaviour and anticipation of the green phase based on the predicted time displayed to the cyclists. These effects were compared to the standard traffic light system for cyclists in Groningen, which contains a vertical strip of LED-lights predicting the waiting time for a green light.

3.1.4.2 Method

Procedure

There were four observation weeks (Table 17). A first baseline was carried out in the 3rd week of May 2017, a considerable time before installation of the system. This was planned well before, but due to delays in system implementation (road closure due to sewer works, winter conditions) the installation of the system took place later than expected. Therefore, a second baseline was carried out in the 3rd week of April 2018. Directly after this baseline the system was activated. The system had already been installed and tested before this 2nd baseline. In the first week of activation of the system an effect observation week took place. This observation was mainly planned to see whether cyclists encountering the sign for the first time would behave differently or more dangerously compared to when they had encountered it more frequently. We would be able to see whether any initial effects occurred when comparing the first effect observation week to the effect observation week that was planned a few weeks after activation of the system. We were especially interested in the effects of the entire population encountering the system when it was still new to them. Of course, there will always be cyclist that encounter the system for the first time, but only in the first week this would hold for the entire group. In the 3rd week of May 2018 a 2nd effect observation week took place after the system had been in use for more than three weeks. Most of the cyclists on the route are travelling back and forth at working hours and are presumed to use the cycle path for their daily commute. We may assume that many of them had already encountered the sign at least a few times in this second effect measurement week.

Table 17: Overview of observation weeks

Time	Type	System
May 2017 3rd week	Baseline 1	Off
April 2018 2nd week	Baseline 2	Off
April 2018 2nd week end	System activation	
April 2018 3rd week	Effect 1	On
May 2018 3rd week	Effect 2	On

In all observation weeks, observers were present on workdays during rush hour in the morning (7:30-9:00) and off-peak hours during a quiet period (10:00-11:00). This means that for every week there were five periods of 1.5 hours that can be marked as busy periods and five periods of 1 hour that were classified as quiet periods.

Apparatus and material

The observation study can be separated into two parts. One part was performed with a specifically developed smartphone application and accompanying analysis software. Within this part, observers stood on the street to record arrival moments, departure times, violations and traffic light changes. Because the observers used a smartphone as recording device and it looked like they were waiting for something or someone instead of observing, they were not very conspicuous and therefore their presence is assumed to have little or no influence on the cyclists' behaviour. The other part of the observational study was based on capturing video and analysing these videos with special software afterwards, focussing on anticipatory behaviour of cyclists. The video was recorded at the same time as the observations took place. In the next two sections, these separate methods are described consecutively.

To be able to calculate waiting times for cyclists and record violations a smartphone application was developed that the observers could use while doing their observations. Waiting times were defined as the time between when cyclists would put a foot on the ground to wait for the green light and when the light would turn green. In the application it was possible to indicate for each cyclist that arrived when he/she would stop or if they were passing through green. Also, the current phase of the traffic light could be indicated. Passing through the intersection (without stopping) when the traffic light was green, would be a "pass through green without waiting", passing while the traffic light indicated red was recorded as a red-light violation. Special buttons for a public transport bus arriving and for cyclists that left at a red light after stopping were also implemented. The special bus button was to help analyse the disruption of public transport that has priority in the traffic light algorithm over other traffic and therefore creates additional waiting time for cyclists when present. Results were calculated with MatLab based on the recorded observations.

Figure 37: A screenshot of the smartphone application that was used to record cyclist arrival and departure times.

The part of the observation study based on video analysis is described next. The videos were captured with Contour+ action cameras that were mounted on a lamp post 200m away from the intersection along the cycle path. Two cameras were used, one aimed at the traffic light and one aimed at the rest of the cycle path. The cameras were placed 4 metres above the ground to get a good view over the entire path. See Figure 38 for an impression of the situation.

Figure 38: Mounting the cameras on the lamp post.

The recorded videos were analysed with Kinovea (https://www.kinovea.org/), software developed mainly for sports movement science, but which lends itself very good for analysis of cyclist behaviour (Westerhuis et al., 2017). An overlay grid (Figure 39) was placed over the videos (markers on the cycle path indicated where to position the grid). With the overlay in place it was possible to indicate where cyclist started to slow down when approaching the intersection. We defined stopping to pedal as the onset of slowing down. Marks on the overlay grid would indicate the start position of the change. Exporting the data from the Kinovea software gave a numerical summary of these moments (Figure 40). From the exported data it was possible to calculate an average moment when cyclist changed their speed, as well as an indication of how many cyclist pedalled through the intersection, rolled through the intersection without pedalling and how many had to stop and wait for green at the traffic light.

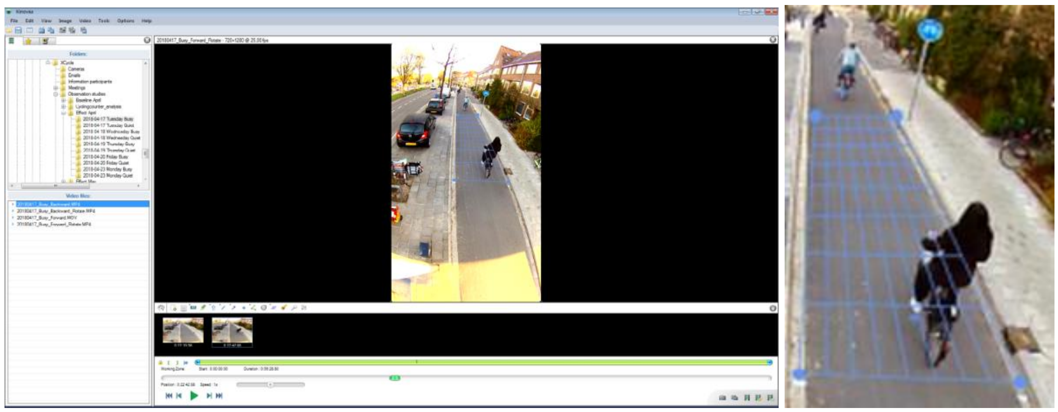


Figure 39: An image of the cyclepath in Kinovea (left) with the overlay grid (right).

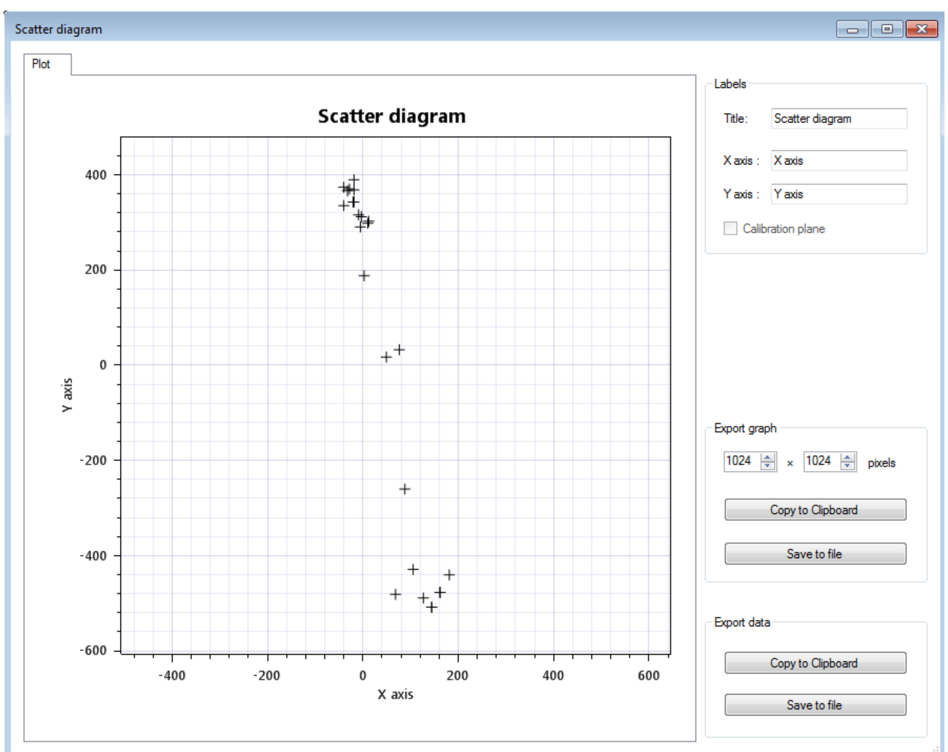


Figure 40: Example overview of the distribution of where cyclists stop pedalling when approaching the traffic light. On the Y-axis distance to the intersection is displayed, on the x-axis lateral position on the cycle path.

3.1.4.3 Results

This section describes the results of the observation study. No real difference was observed between the first and second effect observation weeks. Some dangerous conflict situations with other traffic were observed in the first effect measurement week. Based on reports of the observers there were however not more or even less conflict situations than in the second effect week. This means that the introduction of the system caused no problematic initial effects. The results below are therefore restricted to the second effect measurement week and the second baseline week. These two periods were close together in time and any initial effects that might remain (more variability in waiting times in the initial period due to learning effects) are not included in the second effect period.

The busy periods represent 5 days of 1.5 hour of observing cyclists, which means the total numbers are based on 7.5 hours of data. The quiet periods lasted 1 hour, which means that the data of a whole week represent a total of 5 hours. Duration of busy and quiet periods were the same in the baseline and effect period, which means that total numbers between baseline and effect are very well comparable.

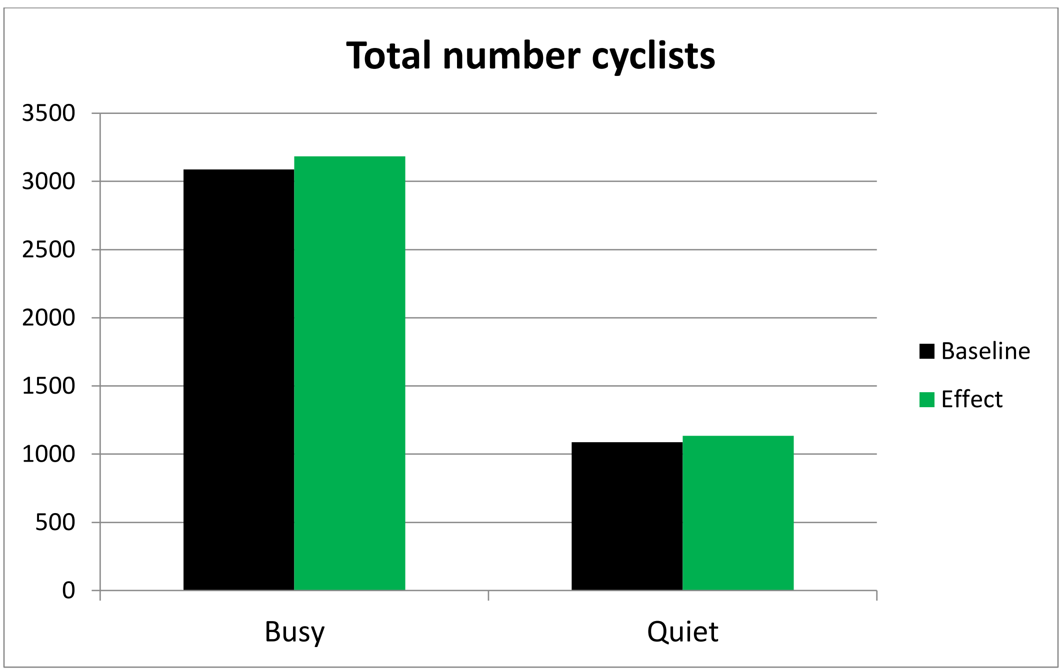


Figure 41: Total number of cyclists in observation in one week of busy and quiet sessions during baseline week (week directly before sign activation) and effect week (starting 3 weeks after sign activation) (5 times busy of 1.5 hour and 5 times quiet of 1 hour).

Figure 41 shows the total number of cyclists that passed the intersection in the direction where the system was located, separate bars indicate baseline and effect periods. In the busy periods (rush hour) around 400 cyclists pass each hour (400 * 5 days * 1.5 hr = 3000). In the quiet period the total number of cyclists lies around 200 cyclist per hour (200 * 5 days * 1hr = 1000). Differences in number of passing cyclists between the baseline and effect period are small.

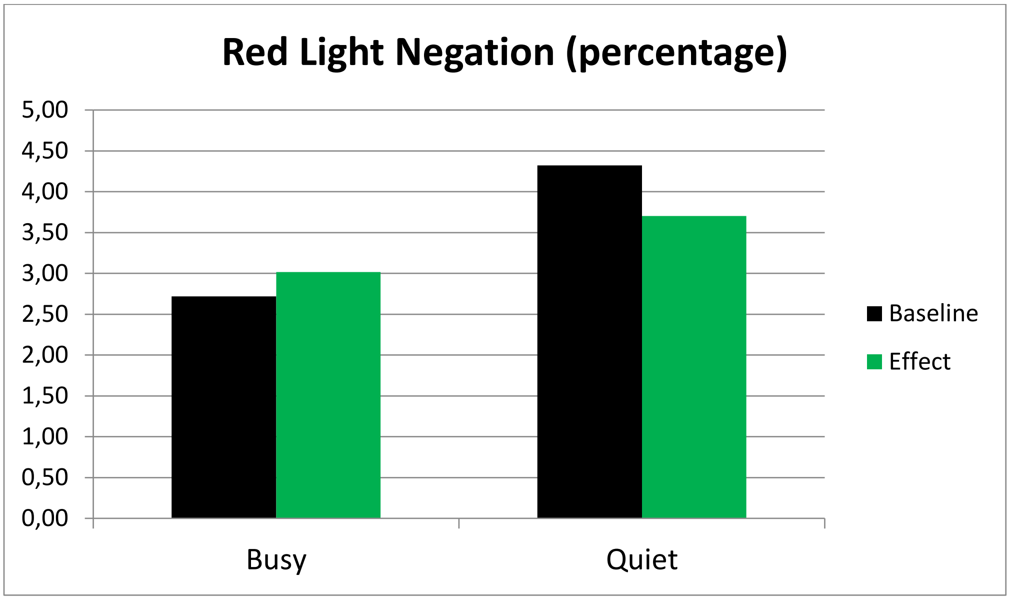


Figure 42: Percentage of cyclists violating a red traffic light.

Figure 42 shows the percentage of cyclists that jump the red traffic light. The overall percentage lies around 2.7% in the busy period, which means 1 in 40 cyclists jumps a red light. In the quiet period the percentage is slightly higher, in those periods 1 in 25 cyclists does not stop for a red light. The figure shows some differences between when the system was activated and when it was not, these are not statistically significant according to a chi-squared test (busy period: X^2 (1, N=6272) = 0.50, p > 0.20; quiet period: X^2 (1, N=2221) = 1.28, p > 0.20).

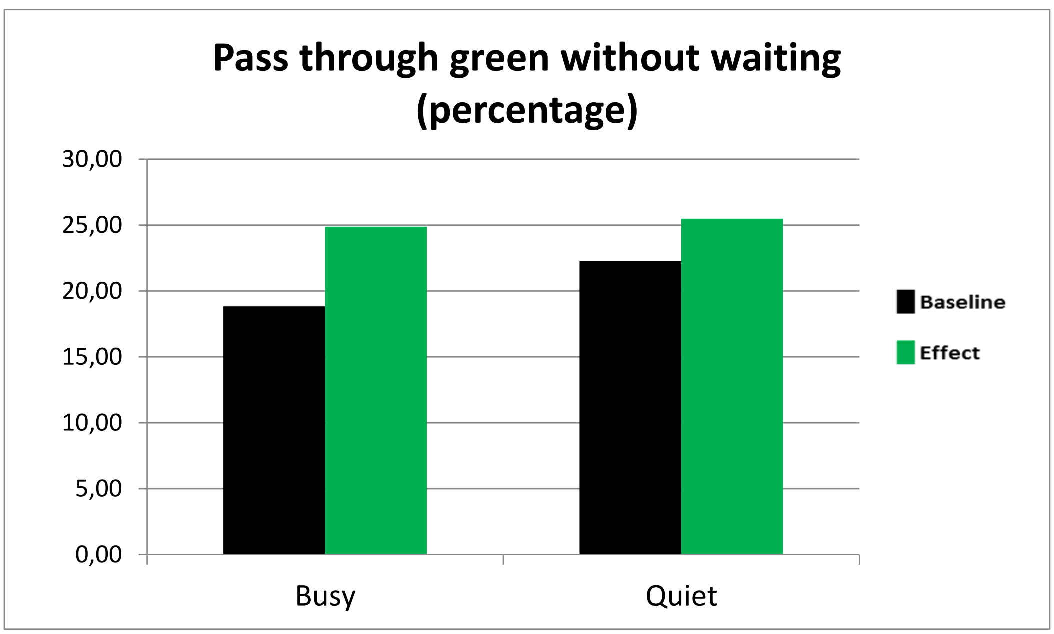


Figure 43: Percentage of cyclists that do not have to stop at the traffic light.

Figure 43 displays the percentage of cyclists that could cycle through the intersection without having to stop at all for the traffic light. An increase can be seen in the busy period of around 6%, from 19% to 25% (X^2 (1, N=6272) = 33.2, p <.0.001). The number of cyclists that can pass through the intersection without stopping is already higher in the baseline of the quiet period but still increase modestly with 3% to about the same value as in the busy period (X^2 (1, N=2221) = 3.13, p <.10).

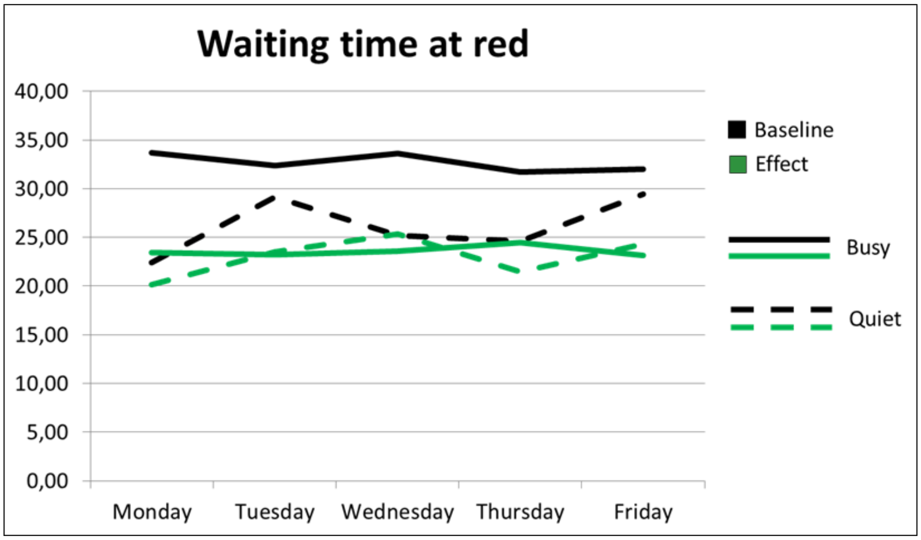


Figure 44: Average waiting time (seconds) for cyclist waiting for a red traffic light.

The average waiting time fluctuates slightly over days of the week as can be seen in Figure 44. Waiting times in the busy period with the system activated (M = 23.6, SD = 16.0) were 9.1s shorter than in the baseline period (M = 32.7, SD = 21.3), t (4607) = 16.4, p<.001. As can be seen the waiting times in the quiet period in baseline are already shorter on average, there is no difference between the baseline and effect.

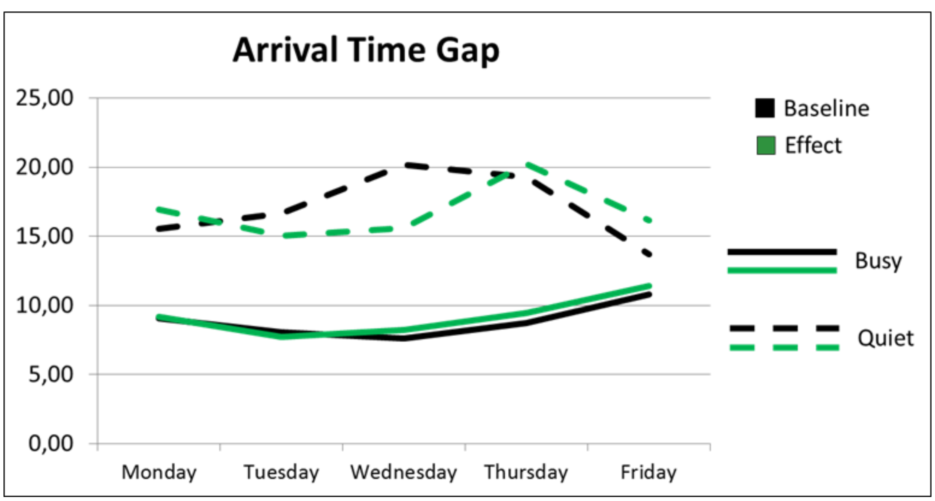


Figure 45: The average time (in seconds) between cyclists arriving at the traffic light.

The arrival time gap is calculated as the average time between two cyclists arriving. It gives an indication of grouping behaviour, i.e. whether the distance between cyclists changes in one of the conditions. Cycling closer together can be more dangerous or uncomfortable, although cycling with a few cyclists together may increase safety because they are better visible for motorised traffic. Figure 45 shows that the average arrival time between cyclists does not change depending whether the system is active or not.

The following results are calculated based on the analysis of the video data that were collected and analysed as described in the method part of this section.

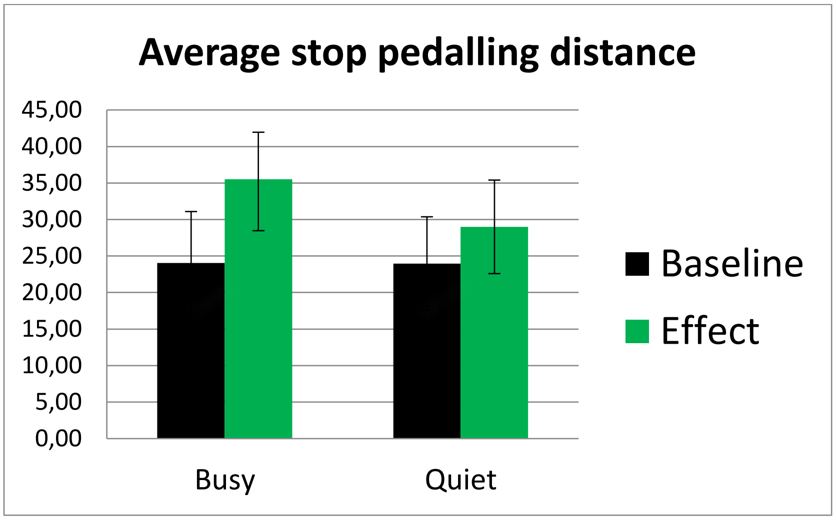


Figure 46: The average distance (in metres) at which cyclists stop pedalling

There will always be a group of cyclists that will not make it through a green light without slowing down or stopping. In Figure 46 the average distance at which those cyclists stop pedalling is displayed. Especially in the busy period, cyclists start to anticipate their stops earlier with the system activated.

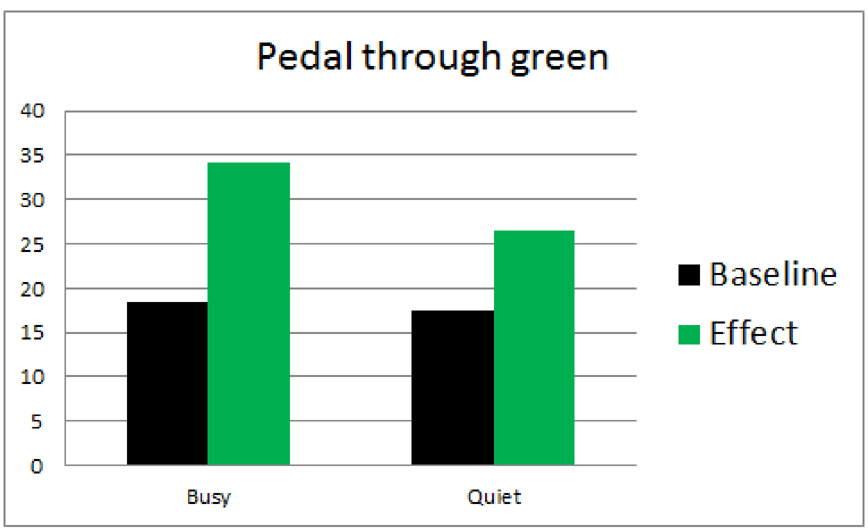


Figure 47: Percentage of cyclists that can pedal through the intersection without having to stop for a red light.

Figure 47 reveals that the number of cyclists that do not have to stop for the traffic light at all (violations excluded) almost doubles in the busy period (X^2 (1, N=1227) = 39.2, p <.001). In the quiet period cyclists also have to stop less (X^2 (1, N=383) = 4.3, p <.05).

3.1.4.4 Discussion observational study

The total number of cyclists counted during the observation week is practically the same as those counted in the baseline week. This is a positive confirmation of the validity of the found results. Apparently, the observations in the two weeks were very comparable. We did not expect to find a difference and indeed we cannot confirm one of the possible positive effects of the green wave, which is to increase the number of cyclists on this route. This is not surprising since it takes a long time for people to change macro level behaviour such as route choice. As described in the introduction of this section, an increase of cyclists on this route would be a positive effect of the system. On the one hand because it could mean cyclists avoid other routes, which are seen as more dangerous or less comfortable (limited view, higher speed of other traffic, no traffic light). On the other hand, it could mean, car drivers have switched to cycling, which can also have a positive effect on safety. Both changes can be expected to take very long to take place however and could therefore not be expected to be found.

Fewer red-light violations were seen in the quiet period, although the change in numbers is very small. There is however also a slight increase in cyclists violating the red light during busy periods. Looking at the individual departure times of these violating cyclists did not reveal one clear type of violation.

Although it cannot be said that the increase in violations is due mainly to cyclists leaving early, some cyclists are leaving early. They probably leave early because they know the traffic light will turn green soon. Because of the good prediction of the green wave system it becomes possible to predict quite reliable when the light will turn green (in the eyes of the cyclists at the very least). This means they start to anticipate the green light and start leaving a few seconds before the light turns to green. There are a few negative aspects to this, first since in this case the public transport still has priority over cyclists and due to filter settings, it was possible that below 10 seconds the countdown would still pause again. The cyclist would leave without the traffic light turning green and come into conflict with a bus. More stringent filter settings on the traffic algorithm can prevent this.

The second dangerous aspect is that in the few seconds before the light turns green, the other directions have amber light, which means that some drivers will speed up trying to catch the amber light and cross the intersection at a higher speed than normal. Combined with a cyclist leaving early this may result in a conflict as well. It is very difficult to prevent this from happening since it is almost inherent to any traffic light countdown system giving information about when the light will turn green. A similar phenomenon has been observed with current green light predictors (e.g. the LED light strip used in Groningen on many cycle traffic lights). Cyclists also tend to leave early with these predictors. The current research shows no change in red-light violations with the XCYCLE system, so it cannot be concluded that the system has a negative effect on red-light violations. One solution to the potential problem could be to not provide any information to the cyclist but only incorporate the other benefits from the green wave system developed here (early detection, arrival time prediction, and stabilisation). Lastly, since the sign and the traffic light are not integrated, and the sign was placed slightly behind the traffic light, it is possible that cyclists did not check whether the traffic light actually turned green but relied on the countdown sign only.

It looks like cyclists can adapt their behaviour to reduce their general number of stops and waiting times. The average distance at which cyclists stop pedalling, an indication of speed adaptation, increases with the green wave system from around 24 metres to around 35 metres in the busy periods. In the quiet periods it also increases, but only to 29 metres. The number of cyclists that can pedal through the intersection without having to stop at all doubles from the busy baseline period to the busy effect period.

The waiting time decreases almost 30 percent from around 33 seconds to approximately 24 seconds, a substantial change. This is another indication that the system functioned as it was designed and therefore can help increase comfort for cyclists. Together with the reduction in number of stops it can be said that those goals of the green wave system have been met.

One of the worries when developing the green wave system was behavioural changes other than reduced waiting and stopping. For example, gaze behaviour, which is studied in the experimental study described in the next subsection. One behavioural change that was studied was called grouping or herding. Since all cyclists may try to change their speed to arrive at the intersection when the traffic light turns green or is green, it is possible that more cyclists will arrive simultaneously and that they will cycle more in large groups. When the cycle path gets too crowded that can potentially be dangerous, this means that grouping or herding behaviour may have a negative impact on safety on the cycle path itself. Studying the arrival times of the individual cyclists revealed that there is no difference between the baseline and the effect observation. The preliminary conclusion is therefore that herding or grouping does not really form a problem for the green wave system. It is a preliminary conclusion, because cyclists may improve adapting their speed over time as they learn how fast to go when a certain time is left that this phenomenon may still start to occur.

3.1.5 Semi-controlled study

As a complement to the observation study, a semi-controlled field study was run to obtain detailed information about cyclists' reasoning in relation to the XCYCLE sign, and to understand more about the motives for their behaviour. For a more detailed description of the method and its advantages and drawbacks see Kircher, Eriksson, Forsman et al. (2017). Also, in such a study more diverse behavioural aspects can be investigated, and cyclists can be followed all the way from the approach through the junction. The drawbacks are that the number of participants is smaller, and that cyclists are aware of being observed. Therefore, validation against the observation study for those aspects where this is possible has been done.

The baseline study was run in May 2017, but the delay of the system implementation led to the treatment being postponed to May 2018. Therefore, in D4.3 only the method employed in the baseline study was described. For completeness' sake, the method of the whole study will be described here.

For a green wave system to be effective, cyclists must be willing and able to follow its advice, and for it to be safe, it should not attract so much attention that information sampling from other relevant areas is impaired. Analogously to eco-driving advice (Ahlstrom and Kircher, 2017; Birrel and Fowkes, 2014; Kircher, Fors, and Ahlstrom, 2014) in car driving, it is possible in principle to integrate additional information without necessarily degrading the road user's attention to traffic.

3.1.5.1 Method

The evaluation was run as a baseline/treatment within-subjects semi-controlled field study. For the baseline study, 28 participants were recruited via business cards that were handed out at the research intersection. In the study, they cycled four times along a roughly 1 km long route, which passed the intersection where the green wave equipment would be installed later. Out of those, 26 participants returned one year later for the treatment study, where they again cycled the route four times each. Due to road constructions, the route had to be shortened a bit (see Figure 48), but this did not affect the behaviour in the intersection of interest. In the following, the participants, the research equipment and the procedure are described in detail. Baseline and treatment procedures were kept as equal as possible, and all differences are highlighted below.

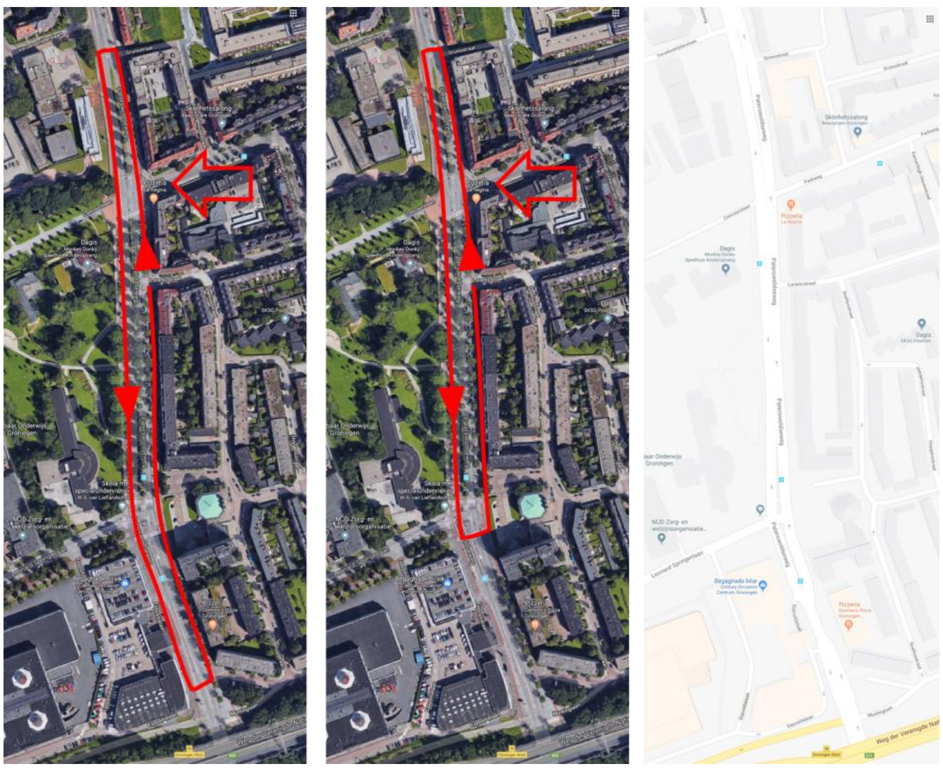


Figure 48: The route used in the semi-controlled study (baseline: left hand side; treatment: middle). The filled arrows indicate the cycling direction, the unfilled arrow indicates the studied intersection.

Participants

Twenty-eight participants took part in the baseline condition, eleven of which were women. Their mean age was 33 ± 14 years. An inclusion criterion was that they were familiar with the research intersection, cycling through it on a regular basis, that they should have lived in Groningen for at least half a year, and that they could bring their own bike to the study location. For practical reasons connected to usage of the eye tracker, the participants could not have more than ±4 dioptres of vision correction, if they did not have contact lenses. The participants were recruited via business cards that were distributed to cyclists in the research intersection, via flyers distributed in the area, and an announcement on the university home page.

They were invited through personal contact by one of the experimenters and booked into a time slot within the study week. For the treatment condition, all baseline participants were contacted by e-mail. Two people did not participate in the treatment session, such that the final sample consisted of 26 cyclists (eleven women) with a mean age of 35 ± 15 years.

Route and research intersection

The intersection Paterswoldseweg/Parkweg and its approach (Figure 48; see also Section 2.8.1 in Deliverable 4.3) was the focus point of the study. For the baseline data collection a cycle route of about 1 km in length was selected, such that the intersection was still well out of sight in the beginning of the approach. Around 100 m behind the intersection, the route turned around and led back to the starting point. A dedicated cycle path was available along the whole route, and the main street (Paterswoldseweg) had to be crossed twice along the route. For the treatment condition, the route was shortened somewhat (see Figure 48) due to road constructions in the area.

In the baseline condition the intersection was regulated by a standard Dutch traffic light for bicycles, in combination with a LED strip (upper right in Figure 49). This strip is theoretically intended to indicate the remaining waiting time to green, however, it can jump up and down erratically, as well as stop the countdown, therefore it is not as helpful as it could be. Also, it is rather small and cannot be seen from a distance.

In the treatment condition the green wave sign was mounted on the right hand side of the cycle path. It displayed large numbers, indicating a countdown in seconds to the next green phase. In addition, it displayed a bus symbol, if the countdown had to be stopped for an approaching bus, which had priority over the traffic light cycle (lower right hand corner in Figure 49). The sign was visible from approximately 80 m. During the treatment phase the LED strip was deactivated.

There had been major roadworks between baseline and treatment, such that the design of the approach was affected, with the most noticeable being the colour of the cycle path, which was red in baseline and dark grey in treatment. Also, in baseline there were lane demarcation lines for the cyclists' right turn, which were not in place in treatment (Figure 49).

Figure 49: Approach of the intersection in baseline (above) and treatment (below), with the traffic light and the XCYCLE sign (for treatment) showing.

Equipment

Each participant brought his or her own bike to the study, to ensure familiarity with the bicycle used. The bike was equipped with one Garmin Virb camera facing forward and a similar camera facing the cyclist. One experiment leader followed the participant on a bike which was equipped with a forward-facing camera, capturing the participant and the surrounding scene from behind. Each participant was equipped with a head-mounted eye tracker (SMI 2.0; Senso-Motoric Instruments, Teltow, Germany; Figure 50).

Figure 50: The bicycle of a participant equipped with the two cameras (left), and a test leader calibrating the eye tracker to one of the participants (right).

Procedure

Upon arrival at the research base, situated close to the route, the participant received written instructions and was given the possibility to ask questions. Then, he or she signed an informed consent form, explicitly stating that participation was voluntary and could be terminated at any time. Afterwards, the participant and the bicycle were equipped with the eye-tracker and cameras. The route was explained, and the participant was instructed to cycle just like he or she would have done on a ride to work, without minding the following experimenter. The participant was free to choose his or her own speed, and to stop or cycle on as desired in the current situation. The participant then set off on the route, followed by the experimenter. After having passed the research intersection, the participant stopped and was asked a number of questions about the passage. This included the colour of the traffic light, whether the participant had adapted his or her speed, whether anything special occurred, and their estimated delay time due to the intersection. Afterwards, the participant was asked to cycle another lap along the route, following the same procedure, until four laps were completed. Then, the participant and the experimenter cycled back to the research base, the equipment was removed from participant and bicycle, and the participant was asked questions about his or her typical behaviour in traffic-light controlled intersections in general, in the research intersection, and possible improvement suggestions. Before leaving, the participant then filled in a form to be reimbursed with 20 € for the effort in baseline, and another 40 € in the treatment condition. In between baseline and treatment, the participants were asked to fill in a questionnaire about their background and cycling habits, and their opinion on cycling in groups of people, for which they were compensated with another 20 €. This was also meant as compensation for having to reschedule the treatment study, and for some inconveniences that occurred when paying the reimbursement for the baseline phase.

3.1.5.2 Results

At first a descriptive overview of the results is presented, followed by a more detailed analysis of aspects related to efficiency, comfort, safety and acceptance.

3.1.5.2.1 Descriptive overview of overall behaviour

Each of the 26 participants cycled through the research intersection four times per condition, such that 104 passages per condition were available for analysis. In Table 18 the distribution between passages without and with a stop is indicated per condition, showing that stops decreased with a count of three for the green-wave sign, which is a non-significant change (Chi-square(1) = 0.19; $p > .05$). Stopping implies that the cyclist either put down a foot or held on to a post.

Table 18: Number and percentage of passages including no stop or a stop.

	Not stopping	Stopping
Baseline (104)	34 (32.7 %)	70 (67.3 %)
Treatment (104)	37 (35.6 %)	67 (64.4 %)
Total (208)	71 (34.1 %)	137 (65.9 %)

For analyses, the passage through the intersection was divided into sections demarcated by landmarks L0 to L5, where L0 lies around 85 m in front of the crossing, just before the point where the XCYCLE sign could be reliably coded based on the camera view for the first time, and L5 demarcates the end of the intersection. The whole passage through the intersection from L0 to L5 is 123 m long (Figure 51).

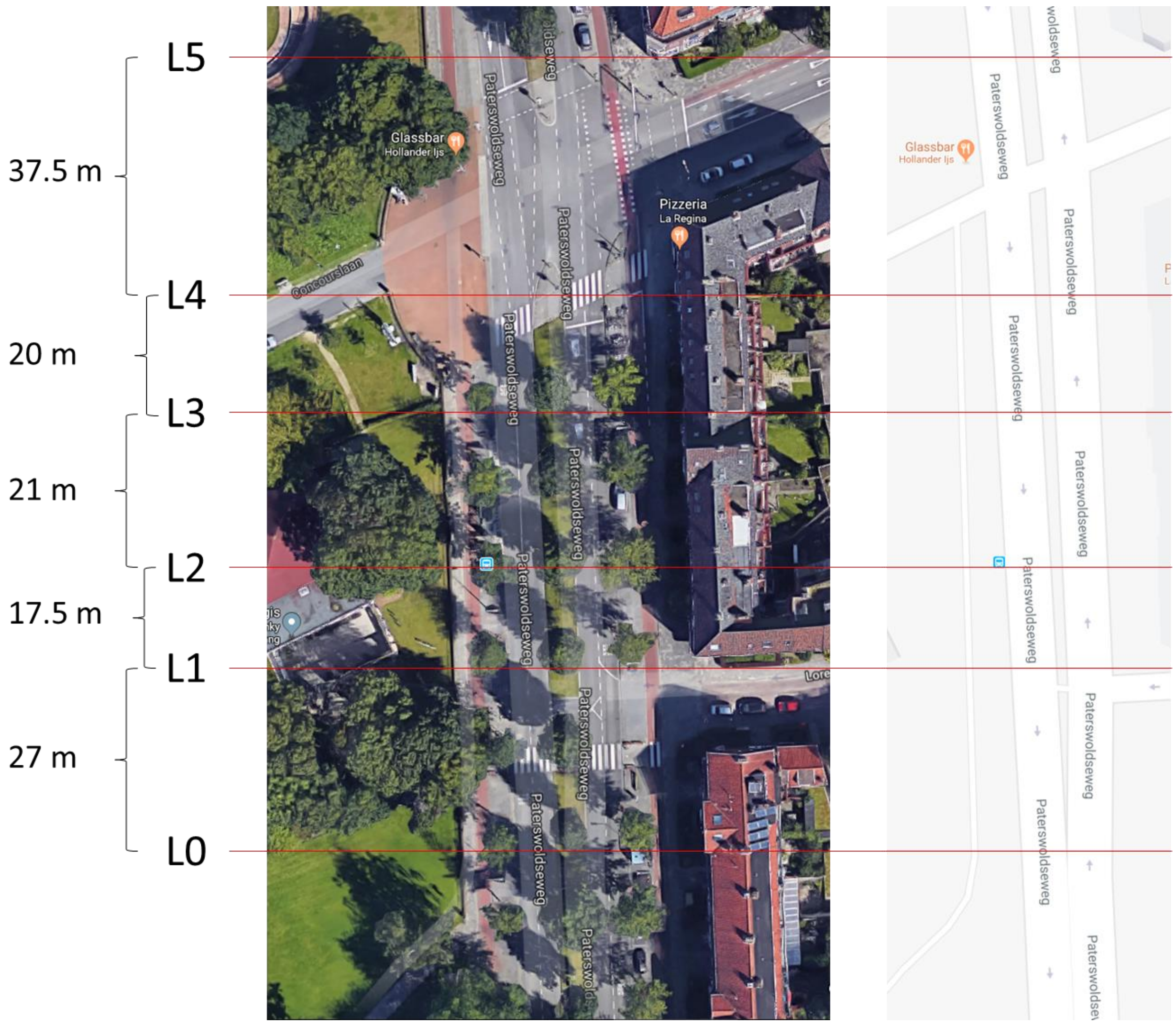


Figure 51: The approach and crossing of the intersection Paterswoldseweg and Parkweg in Groningen, in map view and satellite view (Google Maps, 2018). L0 to L5 demarcate different landmarks along the way. The distances between them are indicated on the left.

Figure 52 shows where upon approaching the intersection the traffic light changed colour, separated into baseline and treatment, for those passages that did not require a stop. Ocular inspection reveals a different progress in baseline and treatment. In the treatment condition the traffic light tended to turn green at a later stage during the approach, indicating that the participants made use of the countdown information such that they timed their arrival at the stop line with the expected change to green.

In combination with the speed progress and pedalling (Figure 53) activity it becomes apparent that the average speed 100 m in front of the traffic light, was slightly lower during treatment than baseline. In baseline, the cyclists decelerated slightly more between L1 and L3, which is also reflected by the greater percentage of cyclists who stopped pedalling during this phase. The acceleration onset occurred around 10 m later in treatment than baseline, in connection to the timing with the traffic light turning green.

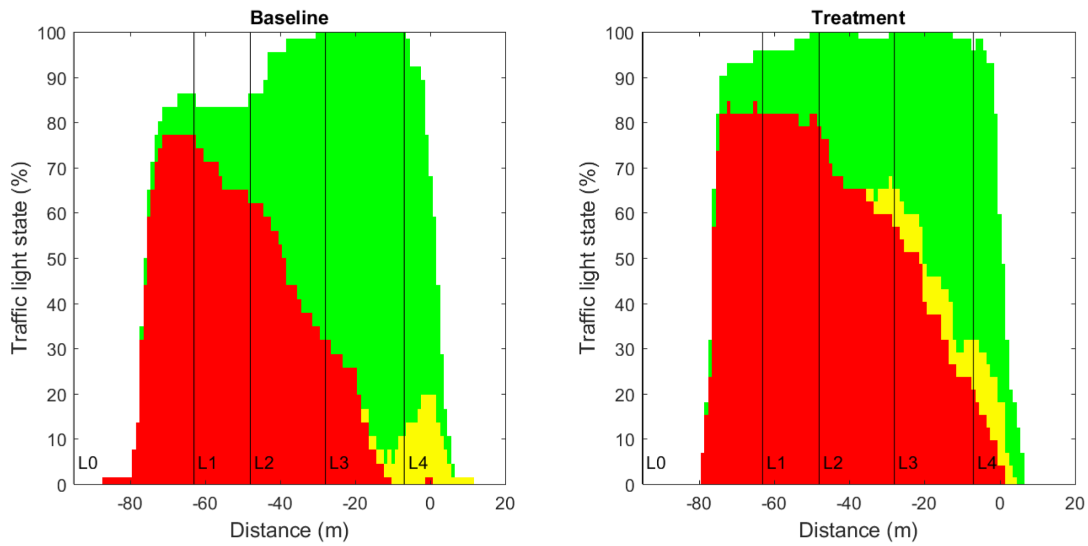


Figure 52: Traffic light state, indicated by the colour in the graph, depending on distance to the location of the traffic light, accumulated over passages and separated for conditions, for all passages without stop. White indicates that the traffic light could not be seen or its state identified.

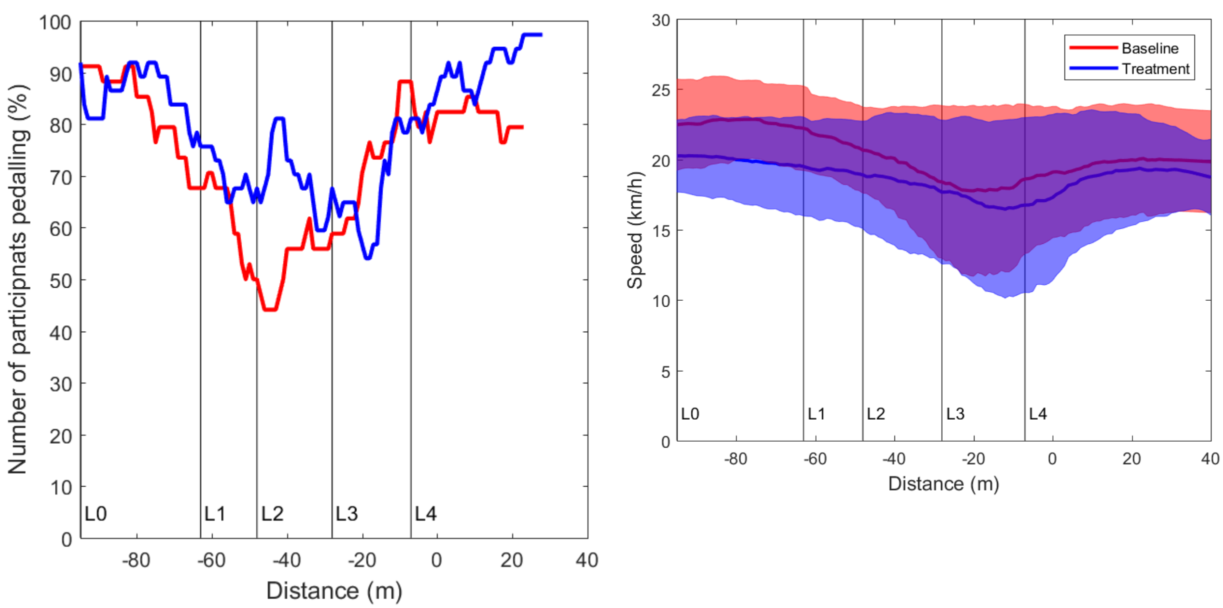


Figure 53: Percentage of participants pedalling per condition (left) and mean speed and standard deviation (right) averaged over all passages that did not include a stop, per condition.

3.1.5.2.2 Efficiency and comfort

Efficiency describes how long it takes to negotiate the complete intersection, that is, the time that is actually used, regardless of how it is distributed between different sections. Thus, a cyclist who approaches the traffic light at high speed, then brakes and stops, and then continues when the light turns green, has the same efficiency as a cyclist who distributes the same amount of time such that he or she slows down and coasts towards the traffic light, letting it turn green such that the cyclist then can pick up speed again and go through the junction. Having to stop is considered as less comfortable, though, as this disrupts the flow of movement and demands more power to pick up speed again. Therefore, here both efficiency across the whole road stretch, time spent in different zones upon approach, and actual stopping and waiting time are analysed.

Efficiency: An analysis of variance with the factors “stopping behaviour” (stopped/did not stop) and “condition” (baseline/treatment) on the duration of passage, that is the time it took to negotiate the section from L0 to L5 showed that the passage duration was significantly longer (57.0 s) when the cyclists had to stop, than when they did not stop (25.5 s; $F(1, 204) = 287.1$; $p < .05$). The duration of passage in the treatment condition was not significantly shorter (45.9 s) than during baseline (46.6 s, $F(1, 204) = .1$).

Comfort: As mentioned above, the number of cyclists who stopped did not decrease significantly in treatment. The actual stopping duration was 27.1 s in baseline and 23.8 s in treatment, which is a non-significant difference ($F(1, 135) = 1.6$), as shown by a oneway analysis of variance. The longest duration of passage (119 s vs 99 s) and the longest stopping time (86 s vs 72 s) were found in the treatment condition.

3.1.5.2.3 Safety

Running red lights is a manifested safety hazard, whereas insufficient attention is a potential safety hazard. A well-functioning green wave system should have the capability to reduce red light violations, as it reduces the likelihood that cyclists will arrive on red in the first place. However, a green wave system could potentially also lead to red light violations, if cyclists feel encouraged to start going already during the late phase of the countdown, which is especially problematic if the countdown stops in the last seconds to let a bus go past. Thus, red light violations are counted for baseline and treatment, and it is analysed in which phase of the countdown they occurred.

Out of the 104 passages per condition, there was one red light violation in the baseline and six in the treatment condition. This difference approaches significance (chi-square(1) = 3.7; $p = 0.059$). These figures correspond approximately to what was found in the observation study. In the baseline case, the participant went through red without stopping. In treatment, five different participants stood for the six red light violations, one of whom was also responsible for the baseline case. In four of the six treatment cases, the cyclists did not stop at all, going through the red light just after the green phase. In one additional case, the participant stopped for less than a second and then decided to continue anyway. Finally, one participant left early, before the signal switched to green, after having waited at the red light for more than 16 seconds.

Focusing too much on monitoring the countdown may lead to neglecting other traffic-relevant information sampling, therefore actual glance behaviour was compared to a set of minimum attentional requirements. This analysis was based on the MiRA theory (Kircher and Ahlstom, 2017), that describes how static and dynamic minimum information sampling requirements and actual information sampling interact for drivers to be classified as attentive or inattentive. In the present study, static MiRA-requirements were used as follows:

Figure 54: Illustration of the MiRA-zones "to the right" and "to traffic light". The traffic light had to be checked before passing it, but could be done so over a longer approach area. The road to the right could first be checked for potential traffic when the house on the side was passed, and had to be done so at the latest before reaching the lane coming from the right.

Based on traffic regulations applied relating to the actual infrastructural circumstances, the static MiRA-requirements were established by on-site inspection. Thus, obstructing houses and other constructions could be considered. Each zone was classified as either "necessary", meaning that not sampling information from the target area while in the zone results in the road user being labelled as "inattentive", or as "useful", meaning that the target information is not legally necessary to sample, but either provides additional information for efficient or safe negotiation of the road stretch under examination. Static MiRA-zones have been used in (Nygårdhs, Ahlstrom, Ihlstrom and Kircher, 2018), but the procedures and guidelines for establishing MiRA zones are still under research and development, as the theory is rather new.

The zones used for the intersection Paterswoldseweg/Parkweg are described in Table 19.

Table 19: Description of MiRA-zones used in the study.

MiRA zone	description
to traffic light (cycle)	Classified as "necessary", as road users are only allowed to proceed on green. Thus, the traffic light has to be sampled. The zone starts at L3, ca. 20 m before reaching the traffic light, and ends at the traffic light. If the light is red, another sampling from the traffic is required after the light turning green and the cyclist passing the traffic light.
to zebra crossing	Classified as "necessary", as cyclists have to yield to pedestrians. The zone differed depending on the colour of the traffic light. For a green light it started at L3 and ended at the stop line for the traffic light. For a red light it starts where the cyclist had stopped and ends either at the stop line, or when the cyclist starts to move, whichever comes last.
into intersection	Classified as "necessary", as the traffic light could show four-way green for cyclists and pedestrians, such that traffic could come from anywhere on the intersection on green. The zone starts either at the stop line (L4) or when green, whichever comes last, and ends at the start of the intersection.
to the left	Classified as "necessary", as traffic can come from the left side on the cycle/pedestrian crossing behind the intersection on four-way green. The zone starts behind the zebra crossing in front of the intersection and ends after having crossed the intersection, where the painted cycle path becomes separated from the roadway again.
to the right	Classified as "necessary", as traffic can come from the right side on four-way green. The zone starts at the end of the zebra crossing and ends at the yield markings in the intersection, indicating the beginning of the lane from the right.
to XCYCLE sign	Classified as "useful", as the intersection could be negotiated without making use of this information, but it could provide additional input for a more efficient intersection negotiation. The zone starts where the sign became visible and ends at the sign itself or where the cyclist stops.

Thus, for both the baseline and the treatment condition each cyclist had to attend to five "necessary" MiRA-zones, which sums up to 520 attentional requirements per condition. For the treatment-condition the XCYCLE sign was counted as an additional "useful" MiRA zone. Cyclist behaviour was coded manually with the video coding software Observer XT 14.1 (Noldus Information Technology bv, Wageningen, The Netherlands). Of the 520 requirements per condition, 49 (9 %) could not be coded for baseline and 136 (22 %) could not be coded for treatment because of data loss for the eye tracker, which could be temporary or related to a software crash in the recording. The remaining 471 data points for baseline and 408 data points for treatment were classified into whether the cyclist had fulfilled the MiRA requirement by visually attending to the required target, whether he or she behaved in a way that strongly suggested attention to the target, or whether he or she probably had not attended to the required target (Table 20).

Behaviour in relation to the XCYCLE sign could not be coded in 24 cases (23 %). The remaining 80 cases are also presented in the table.

Table 20: The left side of the table shows for which percentage of the "necessary" MiRA zones the required target was attended to, the right side shows this for the XCYCLE sign.

	Baseline (471 cases)	Treatment (408 cases)	XCYCLE sign (80 cases)
yes, visually attended to	65%	66%	83 %
assumed by behaviour	25%	24%	4 %
probably not attended to	10%	10%	14 %

Within the different necessary MiRA-zones, behaviour in baseline and treatment was very similar, with the maximum difference being 6 % across all behavioural categories. Between MiRA-zones, behaviour different somewhat, with the requirement to attend "into intersection" not being fulfilled in almost 40 % of the cases. All other requirements were met for at least 93 % of the cases, and in two thirds of these cases this happened via at least one glance towards the target.

The XCYCLE sign was glanced at in 83 % of the coded cases. For an additional 4 % the cyclist's behaviour suggested that the sign had been attended to, whereas in 14 % of the cases it is likely that the sign was not paid any attention to. Of the coded cases in which the cyclist stopped at the traffic light, 78 % had paid visual attention to the XCYCLE sign, and of those who could ride through green without stopping, 90 % had paid visual attention to the XCYCLE sign. In comparison, amongst the cyclists that stopped, 18 % had probably not paid any visual attention to the sign, and of those riding through green, 7 % had not paid any attention to the sign. For the remaining four respectively three per cent, their behaviour led to the assumption that they had attended to the sign. According to a Chi-square test this difference is not significantly different (Chi-square(2) = 2.37).

3.1.5.2.4 Acceptance

Without user acceptance, function alone is not enough. Therefore, both user acceptance of the system itself and of the system's intended effect – riding in a group – was investigated via standard forms and interviews.

Preference of cycling in a group

Between the baseline and the treatment study, a web questionnaire was sent to the participants. One of the questions was: "When cycling without a companion, what is your preference concerning cycling in a group with people you do not know?" 25 out of the originally 28 participants answered well before the treatment study, while the remaining 3 cyclists answered in connection to their participation in the treatment study. None of the cyclists stated that they did not like it at all and most of the cyclists were neutral, as shown in Figure 55.

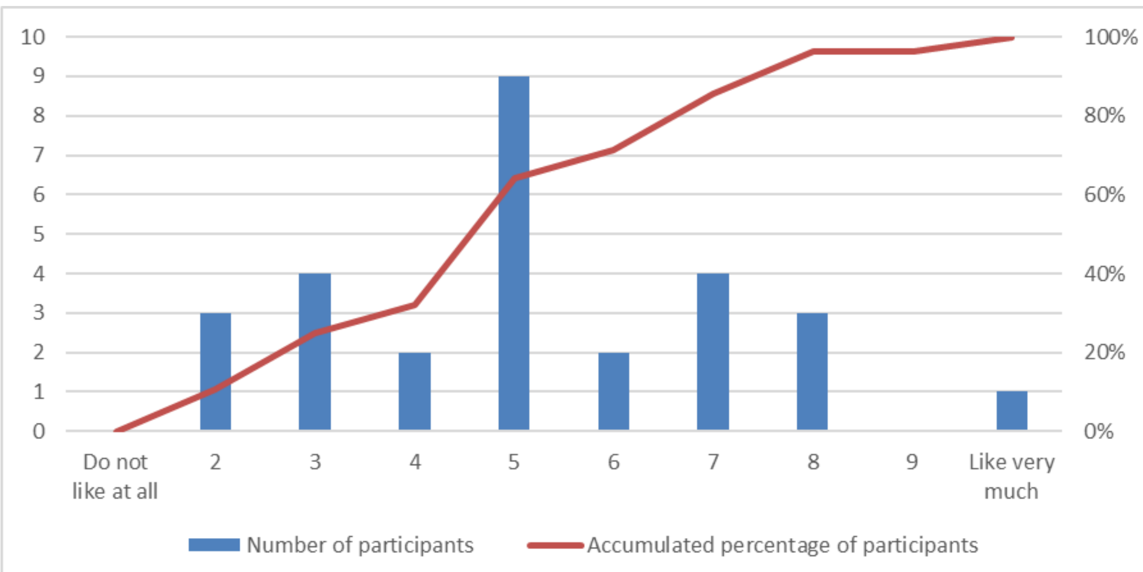


Figure 55: Preference of cycling in a group.

Experienced benefits with adapting to the information of the sign

The participants could in principle see two main benefits with adapting their behaviour to the sign of the green wave system. The first benefit is traffic flow related, where cyclists expressed that they could avoid coming to a full stop by adapting their speed by going faster or slower, and that other cyclists also adapt their speed so that the flow is kept. The other main benefit was a feeling of relaxation, in which participants expressed less frustration, that they could use their phone if there is much time left and not being tempted to go early or late. There were also participants who thought that there was no actual benefit with adapting to the sign, because the regular traffic lights with LED dots had the same function or that a new sign does not improve waiting times. Almost half of the cyclists (11) thought that the waiting times were shorter with the new system compared to the standard solutions, almost half (11) thought it was the same and a few cyclists (2) thought that the waiting times were longer.

Improvement suggestions

There were many improvement suggestions for the new system, of which the spontaneously most mentioned was to place the count-down sign together with the traffic light. The improvement suggestions could be categorized as follows:

- No improvement suggestion
- Improvements related to using another system
- Improvements of the placement of the count-down sign
- Improvements concerning the appearance of the count-down sign
- Improvements concerning the functionality of the count-down sign
- Improvements concerning the system as a whole
- Competence improvements.

For those who reported no improvement suggestion, thoughts were that numbers are quite ideal, that it is good with count-down, and that it is better than the regular systems.

Improvements related to using another system were building other kinds of infrastructure, such as a roundabout where cars had to yield to cyclists, or different levels for cyclists and other traffic, so cyclists did not have to stop at all. Both of these suggestions were however immediately considered unrealistic by the persons suggesting them.

Improvements of the placement of the count-down sign mainly included different versions of stating that the traffic light for cyclists should be on the same side or even incorporated into the count-down sign. About one third of the participants spontaneously mentioned this as an improvement.

Improvements concerning the appearance of the count-down sign included to make the sign smaller, to use different colours of the digits depending on how much time there was left to green or depending on if there was a bus coming or not.

Improvements concerning the functionality of the count-down sign that were given by participants include wishing for the sign to start showing how long time there is left when the cyclists are about 100 m away and to show the time to red light as well.

Improvements concerning the system as a whole mainly regarded the accuracy of the system. The traffic light and the count-down sign not being synced was regarded as leading to confusion, as well as the irregularity of the counting down. Other suggestions were that the sign should always show numbers and not be off when there is a red light, or that it should never be off and show count-down to red too.

Some improvement suggestions concerned competence, where the participant wished that there would be some kind of education for how to use the system, because other cyclists did not adjust their speed according to the information.

Overall system acceptance

The cyclists were asked to describe their overall opinion of the traffic sign system of the intersection, bearing in mind that the interviewers were not the manufacturers of the system. This was clarified so that the participants would feel that they could express their real opinion without being judged. The outcome of this was that 24 of the cyclists were positive, e.g. mentioning that it is a good improvement, that they like it but that there are some bugs to fix, and that they know how long they would have to wait on their approach. The remaining 2 cyclists were indifferent stating that it doesn't add anything compared to the LED traffic lights. None of the cyclists were negative in their overall opinion.

In addition, the participants were asked to fill out the van der Laan acceptance scale (Van Der Laan, Heino, & De Waard, 1997), as shown in Figure 56. There was an option of filling it out in Dutch too. Reliability tests showed that Cronbach's α was sufficiently high (above 0.65) for both the usefulness scale and the satisfying scale, and so the averaged scores could be computed.

I find the traffic light system I have experienced (please tick a box on every line)

1	Useful	|__|__|__|__|__|	Useless
2	Pleasant	|__|__|__|__|__|	Unpleasant
3	Bad	|__|__|__|__|__|	Good
4	Nice	|__|__|__|__|__|	Annoying
5	Effective	|__|__|__|__|__|	Superfluous
6	Irritating	|__|__|__|__|__|	Likeable
7	Assisting	|__|__|__|__|__|	Worthless
8	Undesirable	|__|__|__|__|__|	Desirable
9	Raising Alertness	|__|__|__|__|__|	Sleep-inducing

Figure 56: The van der Laan scale used after the treatment study.

The range of the scale goes from -2 (totally negative) to +2 (totally positive), with 0 being neutral. The results for the 26 cyclists completing the whole study were as follows:

- Usefulness scale: 1.46±0.49
- Satisfying scale: 1.19±0.61.

Hence, the participants seem to think that the system is quite useful but has improvement potential. This will be further discussed in the section below.

3.1.5.3 Discussion semi-controlled study

While the results for efficiency and comfort did not show any actual improvements in travel time or waiting time for the participants in the semi-controlled study, they still had a positive opinion about the system in general. This may have to do with a feeling of control – if the cyclist knows about the time remaining to green, he or she can plan ahead, which is clearly done, as shown by the longitudinal plots. Specifically, for those passages that did not require a stop, the cyclists were closer to the traffic light when it turned green, fewer passed the traffic light on amber, and the onset of amber was less concentrated to the area just in front of the traffic light. These facts taken together indicate that the cyclists understood and made use of the information provided by the sign. Early onset amber indicates a higher speed upon approach, which is likely a result of knowing that the light will switch colour soon, such that the cyclists do not have to brake as much. Similarly, an onset of green closer to the traffic light indicates that cyclists position themselves ready to cross the intersection as soon as the light turns green. This may influence their perceived control and waiting time.

Information sampling was not affected by the presence of the XCYCLE sign, which indicates that the cyclists' attention was not captured inappropriately much. In general, cyclists were attentive to their environment, which is in line with previous findings (Ahlstrom, Kircher, Thorslund, and Adell, 2015; Nygårds et al.) and which can be taken as a sign that cyclists are aware of their vulnerability. Interestingly, however, for many passages the cyclists were observed not to check the intersection. This can either be due to a lack of understanding that relevant traffic can show up there, a reliance upon that the other traffic will behave as subordinate, or possibly that the cyclists did check earlier on and/or with peripheral vision, which cannot easily be picked up with the measuring equipment used. Here, either the measurement equipment must be improved, possibly by adding the think-aloud technique (van Someren, Barnard and Sandberg, 1994), or, in the long run, by increasing the understanding of the processing of peripheral visual information.

On the positive side, cyclists did not neglect attending to the traffic light in the treatment phase despite the XCYCLE sign being present and in an ideal world conveying the same, but augmented, information as the traffic light. This is an important finding and must be confirmed for better-functioning systems, as it is still the traffic light, which delivers the legally reliable information. The positioning of the XCYCLE sign on the right-hand side and the traffic light on the left-hand side of the intersection aided coding, but is otherwise not optimal, as discussed below.

Overall, according to the van der Laan scale the participants were positive towards the XCYCLE system, whereas they had several remarks and improvement suggestions when interviewed. This putative discrepancy could possibly be explained such that the participants answered the rating scale with a perfectly functioning system in mind – rather judging the intended functionality than the actual implementation – while they discussed the actual implementation when interviewed specifically about the system at hand. If so, it can be taken as a sign that the concept is worth pursuing, if it is possible to get rid of the issues related to the prototypical system used here.

To integrate the count-down sign with the traffic light was the most common improvement suggestion put forward by the interviewed participants. An integrated count-down would lead to that cyclists only have to check one location to find all the information that they need about if they can go and for how long they will have to wait otherwise. This of course presupposes that the traffic light and the count-down work flawlessly together. A crucial aspect of the count-down part is that it should be reliable, which was a concern for many of the cyclists. Without reliability, the users will not accept the system and use it as intended. If the traffic light and the count-down sign are not synced together, this can lead to cyclists disrespecting the system or, worse, to unsafe behaviour. Looking at the count-down and not start cycling until the count-down is finished although the traffic light is green some seconds before will lead to frustration among the cyclists behind. Going into the intersection when the count-down is done although the traffic light is red can however have fatal consequences, especially considering that car drivers that arrive late at their traffic light might want to drive faster to catch the light before it turns red. Irregularities in the count-down, such as stopping at a certain number or to suddenly skip numbers in-between could harm cyclists' pro-active behaviour. If they predict that the count-down will continue at a regular pace they might start pedalling at an earlier stage to be ready and go when the light is green. A possible remedy could be not to stop the count-down when it is below for instance five seconds.

A few of the cyclists mentioned that they really would like some other kind of infrastructure, so that cyclists could go by their own pace and would not need to stop at all. This ideal infrastructure for the cyclists would however be more expensive and might not be accepted by other road users if they will be more delayed as a consequence thereof.

That the count-down sign should always be on, showing the time left to green, and counting down to red too, are logical wishes from the cyclists. Features such as these might however lead to increased reliability problems, because the system algorithms would have to take longer periods of time into account for calculating the count-down. Counting down to red is probably more of a comfort than a safety benefit, since it can infer that cyclists try to catch the green light although there is not much time left.

Concerning future research, it would be interesting to investigate the effects of longer chains of green-wave lights, that are linked together for several intersections. Better effects might be expected for lights that cooperate.

3.1.6 General discussion

The overall results of both studies show that the XCYCLE system improved cycling efficiency and quality, mainly in the busy periods, without negative effects on cyclist attention. Also, cyclists were positive towards the system, indicating that an improved version of the prototype used here is likely to be accepted and used.

While both study types tapped into different aspects of the XCYCLE system, a few measurements could be used to validate the behaviour of the recruited cyclists in the semi-controlled study against the observed cyclists. Most of the cycling in the semi-controlled study took place in what corresponds to the quiet hours in the observation study, so comparisons are made with the figures for the quiet hours.

The percentage of cyclists who cycled through green without stopping was about 8-10 % higher in the semi-controlled study than in the observation study. This is still in the same ballpark. An explanation for the difference could be that the lunch and afternoon hours possibly were even more quiet than the quiet period in the observation study, allowing for a better timing of the green signal. If the cyclists in the study had tried harder to make use of the XCYCLE sign, this should have led to an increase of passing through green in treatment only. Average stopping times at the red light are practically equal for both study types, with a slight but non-significant improvement in the treatment phase for quiet periods. Red light violations occurred approximately as frequently in the semi-controlled study, but were rare in general, therefore quantitative comparisons are not meaningful. To conclude, as the system effect was greater in busy periods, the results from the semi-controlled study underestimate the effect of the system on efficiency and comfort. However, the comfort and efficiency data, as well as the actual occurrence of red-light violations in the semi-controlled study indicate that the recruited cyclists acted according to the instructions to behave naturally.

While grouping did not increase measurably in the observation study, cyclists did not object to it in principle. This is promising, as it can be expected that grouping effects will become more pronounced when several consecutive traffic lights work together along a cycling stretch.

There are some safety-related issues to consider. One of them is people leaving early, i.e. going into the intersection although the light is not yet green. The more reliable the sign, the more it could potentially become a problem. The percentage of red-light violations was about the same both before and after the installation of the green-wave system. In the semi-controlled baseline phase, a lower percentage was found than in the observational study. This is probably due to the "observer effect", or "Hawthorne effect" (McCambridge, Witton, and Elbourne, 2014), where the participants know that they are being observed when they take part in the study and therefore want to show good behaviour. In the treatment phase, the percentages were more similar between observation and semi-controlled study. Possible explanations are that the participants were more familiar with the setup at their second participation, that they "dared" more in the treatment phase, or that they wanted to catch the end of the green light.

Comparing the intersection before and after the installation of the green-wave system, there is no indication of impaired attention because of the new system. People do not blindly fly across the intersection. Most of the necessary attentional targets were attended to, both before and after installation. Hence, the count-down sign as used in the study did not have detrimental effects on attention. It is possible that numbers shown continuously on the sign as proposed by some participants, either when red or also when green, counting down to red, would have an effect.

The location of the count-down sign in relation to the traffic light, i.e. that they were on different sides of the cycle path in the study, means that cyclists stopping in front of the stopping line could be in a position where they could only see the sign. This could possibly infer that those cyclists will react to the sign only, without checking the traffic light. However, the fact that there are more cyclists that do not leave may prevent such behaviour. The solution is to integrate the sign and the traffic light or at the very least put them in the same place.

Some problems were encountered with the bus-logo on the XCYCLE sign. First, the sign communicated with the transponders within public transport busses. These transponders have to be activated manually by the bus driver, which was not always the case, resulting in a delay in detection of the bus, which then occurred on the loop in the road. Due to the delayed detection of the busses, the XCYCLE sign count down number could be interrupted, even at low numbers, giving the bus right of way while cyclists might already have anticipated on a green light within the next few seconds. This caused some dangerous situations and might have decreased the trust that cyclists had in the system. Second, the bus-logo did not always disappear from the sign after a bus had passed, resulting in possible unclarity for cyclists. Third, there were occasions in which the number on the XCYCLE sign would count upwards because of an approaching bus, which could be confusing for cyclists. These problems can be solved by for example giving similar priority to cyclists and public transport or by improving both the transponder technology and tuning the algorithm.

Comparing the observation and experimental results with the technical evaluation of the green wave system, shows that the system does indeed improve the comfort for cyclists by reducing waiting times and reducing number of stops. The technical simulation does seem to give an overestimation of improvements, but also used higher percentage of cyclists passing through green than found in the observational studies. So even despite the complexities of reality the direction of prediction was correct and still a substantial improvement has been realised.

3.1.7 Required conditions to efficiently implement the Green wave system

Installing a green wave on an intersection sets certain demands on that site specifically. For some sites it will be more beneficial to install a green wave than on others. In this section we describe a aspects that are deemed necessary or important for installation.

Essential is a dedicated traffic light for cyclists, if already installed the traffic light and traffic control algorithm can probably be adapted for the green wave, if only a general traffic light for the intended direction is present a separate traffic light for the cyclists needs to be installed. A separated bicycle lane makes the system probably more effective, because it is likely to create a better throughput of cyclists and may make it easier for cyclists to adapt their speed, as they do not have to take other traffic into account. However, a bicycle lane that is not physically separate but still distinguishable from the road (other surface colour, road markings separating the bike lane) may also work. The situation that is not desirable is when there is no room for cyclists to choose their own speed, for example because cars are standing still in front of the traffic light and cyclists cannot pass them.

The traffic algorithm behind the green wave can improve the situation for the cyclists without them even knowing about it. This is because of better incorporation of the presence of the cyclists in the algorithm which already reduces waiting times according to the simulation results of the XCYCLE project. However, most benefits are achieved when the cyclists can also adapt their speed based on the information given to them. If the information is given through a sign, as was done in the installation of the XCYCLE project, this sign needs to be visible from at least 200m to 300m. This means the situation has to be such that this can be realised. If this is not possible, different methods of giving the information may help, e.g. a dedicated device on the bicycle (which has his own drawbacks, e.g. negative effects of distraction) or signs placed further away from the intersection giving the information earlier to the cyclists.

In principle the system will be beneficial in most traffic compositions (many/few cars, many/few cyclists). It will have the most impact on overall waiting times in busy periods because more cyclists will experience the benefits. The observation study in this project has shown however that during quieter periods it is able to reduce waiting times for cyclists more than in busier periods. The system will only be economically viable with enough cyclists present. The amount of cars is less relevant; with few cars, it is easier to create more green time with the green wave system and it will therefore have a large effect on cyclist's waiting time. With much motorised traffic, waiting times for cyclists can potentially be very high, giving great opportunity to reduce them. A larger amount of traffic that has priority over cyclist, e.g. public transport in the XCYCLE case, will have a negative effect on the benefits of the system. When the presence of priority traffic disrupts the stability of the traffic flow algorithm too much, predictability of the system goes down drastically, and ad hoc waiting times will increase too much for the system to be effective.

Traditionally green wave systems work by synchronising consecutive traffic lights. The XCycle green wave system works with one traffic light and it is therefore possible to implement it in more situations. However, simulations carried out in the project have shown that the effectiveness of prediction and therefore of the system becomes better when consecutive traffic lights are used.

3.2 Amber light

3.2.1 Objectives

Cycling is a cheap, convenient, healthy, and environmental-friendly mode of transportation (Heckrath-Rose, 2014). It gains more and more popularity, especially in urban areas. In Germany, between the years of 2007 and 2017, possession of bicycles increased by 6.5 million (Statista, 2017). Also in 2015, 30% of urban households only owned a bicycle for mobility purpose compared to only 22% in 2003 (Destatis, 2014). In urban areas, the bicycle is the first choice of transportation for distance of 5km or less (Sinus, 2017). On the down side, single crashes with minor injuries not needing medical attention are underreported. On the other hand, crashes involving motorized traffic occur rarely, are well documented, and are known for the severe consequences for cyclists. Cyclists are often severely injured or even killed. The rate of fatalities increased over the past decade. 51% of all fatalities occur at junctions, the majority of those (81%) in intersections. The analysis of contributing factors shows that cyclists and motorists contribute equally to those crashes (Münster, 2009).

3.2.2 Study 1: Effects of the amber light on road traffic safety

It is not surprising that many crashes between motorists and cyclists occur in urban intersections when the motorists turns right and the cyclists goes straight through the intersection as manoeuvring through intersections is one of the most complex and demanding driving tasks (Braitman et al., 2007). Cyclists may easily be overlooked in this situation. Therefore, warning right turning motorists when they are about to enter a critical encounter with a crossing motorist may help preventing those crashes. The penetration rate of in-vehicle warning system is still low, so if, for example, the safety in a particular intersection needs to be improved, using an infrastructural warning may be more beneficial as every motorist can receive the message independent of the technological advances of one's vehicle. The so-called amber light was installed at the AIM Research Intersection for a time period of four weeks (09/05/2018- 05/06/2018). It was investigated whether the infrastructural warning system affected road traffic safety.

3.2.2.1 Method

<u>Data</u>

Altogether data of five weeks were included in the analyses, the first week (27/04/2018- 03/05/2018) served as reference as the amber light was not present during the time period. The experimental phase of the data acquisition took place during 09/05/2018 and 05/06/2018. During the baseline week, 363 interactions between right-turning motorists and crossing cyclists were detected. Another 1798 interactions were detected for the four week evaluation period with the amber light installed and active.

Apparatus

Infrastructural detection system As mentioned in Section 1.3, the infrastructural detection system consisted of two poles equipped with stereo cameras and lidar. The system detected and tracked right turning motorists (see red arrow) and crossing cyclists (blue arrow) in Figure 57. Cyclists and motorists were tracked for approximately 35 meters while approaching the intersection. During the approach trajectory and video data were recorded. Based on the trajectory data, the level of risk of a collision was calculated between two interacting road users (right turning motorist and crossing cyclist). In case of a critical situation (for definitions see Table 1), a warning message was transmitted to the amber light.

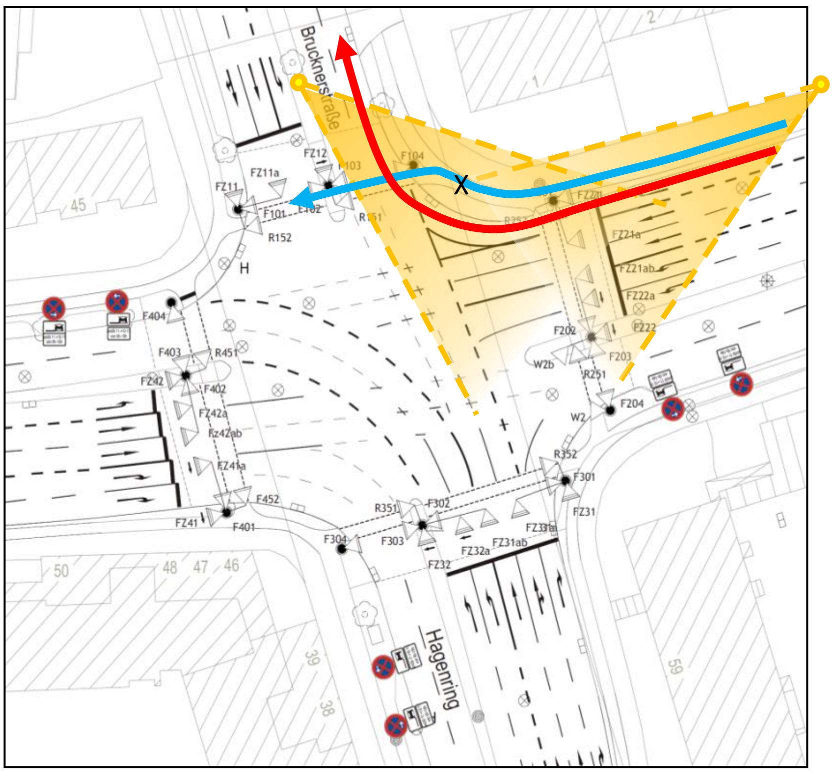


Figure 57: Schematic representation of the AIM Research Intersection including the detection area and the investigated scenario.

Amber light The infrastructural warning system was placed close to the cycling crossing in the intersection (see Figure 57) and pointed towards the right turning motorists. The amber light was a mobile and battery-operated traffic light with an incorporated bicycle emblem. This unit was able to communicate with the infrastructural detection system and receive message from there. If, based on the online risk assessment, a critical situation was calculated, a warning was transmitted via the communication module to the amber light. Depending on the level of risk, the amber light either illuminated or flashed with a frequency of 6 Hz.

<u>Design</u>

The observational study was an incomplete 5 x 4 factorial design. The independent variable *weeks* had five factor levels: pre-week, weeks 1, 2, 3, and 4 with the amber light. The second factor *risk levels* included four factor levels. A value of one corresponded to a low risk, while a level four indicated a high risk. During the five-week data collection period, the trajectory and corresponding video data of all right turning motorists and crossing cyclists were recorded. Detecting, tracking, and classifying traffic participants began approximately 35 meters before reaching the crossing point.

The experiment took place at the AIM Research Intersection in Braunschweig (Hans-Sommer-Str., corner of Brucknerstr.). Motorists turned right (red arrow in Figure 5) and cyclists crossed the intersection (blue arrow in Figure 5). In this scenario, motorists and cyclists shared the same traffic light status. Out of the log files of all pairings and risk levels, the events classified as encounter between a right turning motorized traffic participant and a crossing cyclist were extracted. For each of these encounters, the maximum risk level was recorded. The trajectory data of the pairs were used to derive measures such as post encroachment time (PET), time gap between interaction partners, and average speed.

3.2.2.2 Results

Distribution of maximum risk level The maximum risk level was the highest calculated risk. For each interaction, a value between 1 and 4 was recorded. The relative frequency of the maximum risk level was calculated dividing the number of a risk level by the total number of interactions in that week.

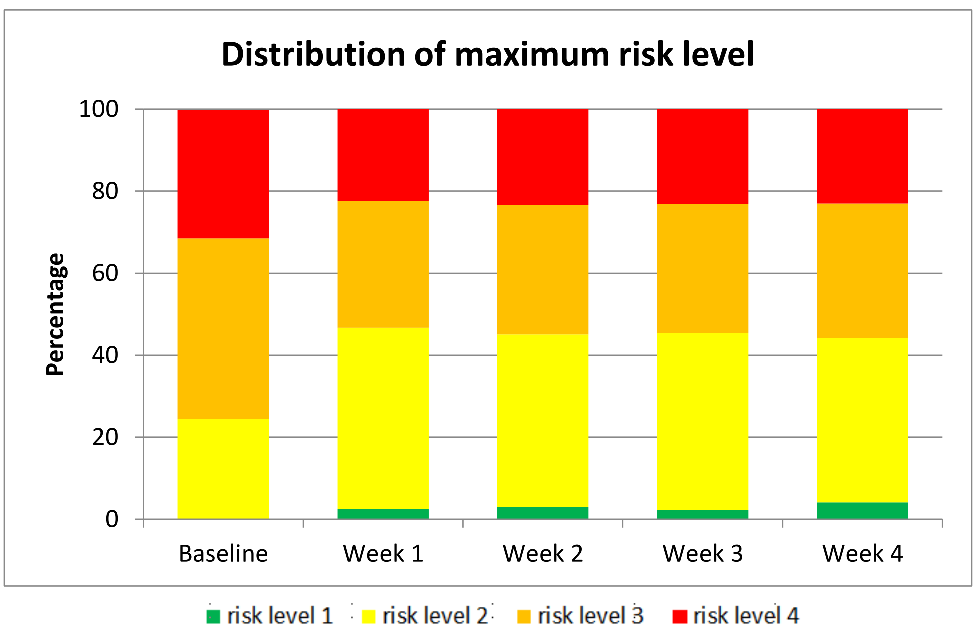


Figure 58: Distribution of the frequency of risk levels across the five weeks of data collection.

Figure 59 summarizes the findings. For the baseline week, the lowest logged maximum risk level, when a motorist and a cyclist encountered each other, was 2 and about 75% of the distribution was allocated to risk levels 3 and 4. During the amber light installation, maximum risk level 1 was also logged and the sum of risk levels 3 and 4 decreased to about 55 %. The distribution of risk level 2 was about 22% during the baseline condition and increased by approximately 20% during the amber light weeks.

Post encroachment time A Pearson product-moment correlation coefficient was computed to assess the relationship between PET and risk level. The negative correlation between the two variables was significant, r = -.288, p > .001, n = 2161, with a medium effect size. The PET decreased as the risk level increased (Figure 59 left). The average PET was around 2.4 s when a maximum risk level of 1 was logged, while the PET was around 1.6 s for risk level 4.

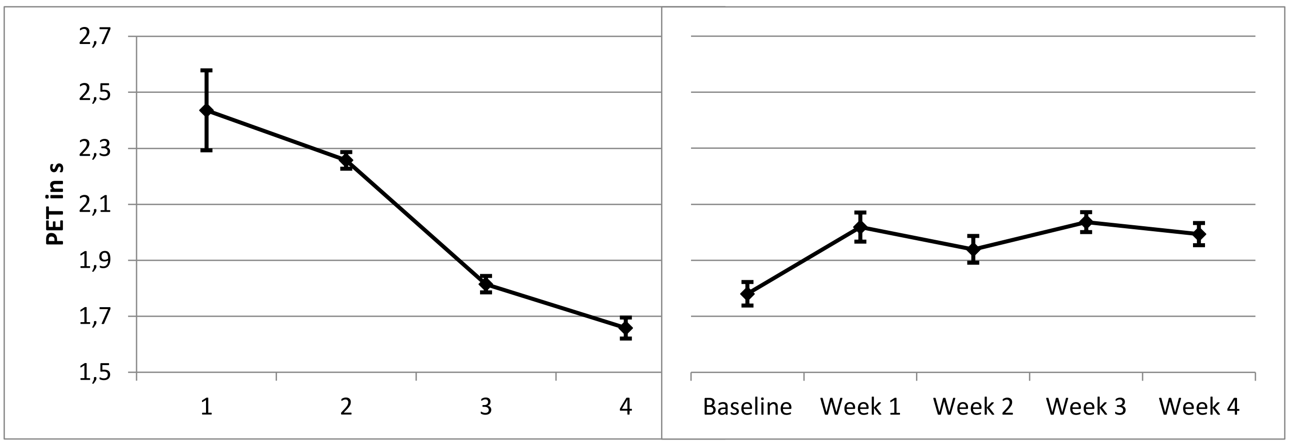


Figure 59: Left: Average PET values across risk levels 1, 2, 3, 4. Right: Average PET values aggregated by week. Error bars represent standard errors.

A positive correlation was found between the two variables PET and week, r = .072, p = .003, n= 2161, with a weak effect size. The PET slightly increased from Baseline to the experimental conditions. Figure 59 (right) summarizes the changes between the baseline week and the following four weeks with the amber light.

Average speed Pearson product-moment correlation coefficients were computed to assess the relationship between speed and weeks as well as speed and risk levels. Speed values were aggregated over the last 13 meters before reaching the crossing point. The analysis revealed significant negative correlation between the variables speed and risk level, r = -.17, p < .001, n = 2161. Generally speaking, average speed decreased as the risk level increased (Figure 60).

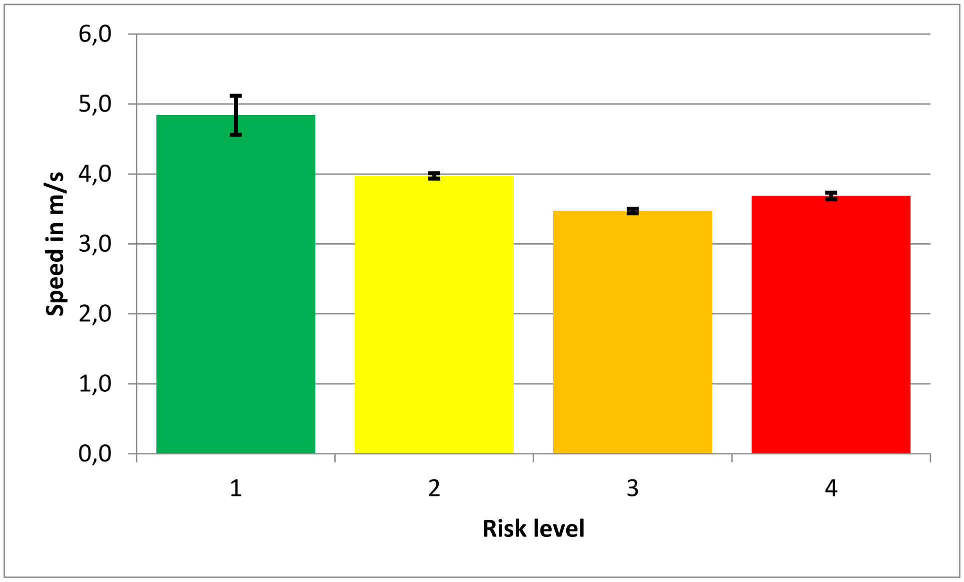


Figure 60: Average speed values aggregated by risk levels. The error bars represent the standard error.

The positive correlation between speed and weeks was also significant, r= .114, $p < .001$, n = 2161, with a weak effect size. As shown in Figure 61, average speed increased from the baseline condition to the experimental condition.

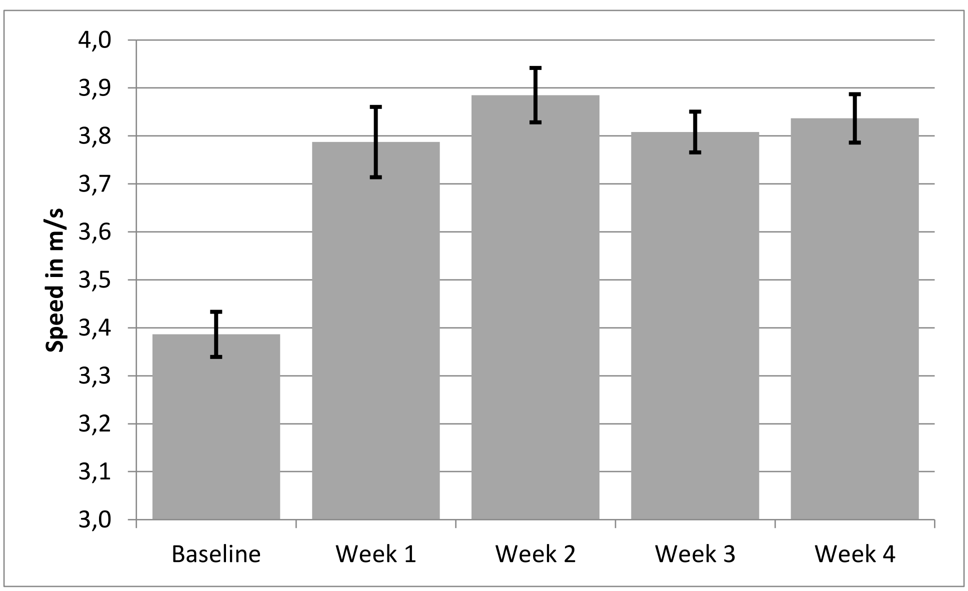


Figure 61: Average speed aggregated by weeks. Error bars represent the standard error.

3.2.2.3 Discussion and conclusion

The effects of the amber light, an adaptive infrastructural warning system, on road traffic safety were evaluated in an observational study. During a time period of four weeks, the amber light was installed and active at an urban intersection warning right turning motorist when on a colliding course with a crossing cyclist. The results indicate some positive effects on safety. A change in the distribution of risk levels was observed, meaning that risk levels 3 and 4 decreased after the amber light was installed, while risk levels 1 and 2 increased. It appears that as a response to the amber light, the criticality of encounters between right turning motorists and crossing cyclists lessened. At the same time, the analysis of the approach speed indicates some behavioural adaptation. Between the baseline condition and the experimental condition, an increase in speed of approximately 1.5 km/h was observed, while PET increased by 0.3 s. Contrary to what has been expected, higher approach speed did not result in more safety-critical situations between right turning motorists and crossing cyclists.

The experimental setup did not allow for any experimental control, meaning that no information was available on how often individual drivers passed through the intersection and noticed the amber light. But the results of the survey administered from December 2017 to February 2018 (for more details see Section 3.2.3) may imply that drivers experienced the amber light multiple times during the four week evaluation period. About 40% of the responding motorists approached the AIM Research Intersection from East and turned North at least once or twice a week within the past twelve months.

In order to better understand the effects of the amber light on road traffic safety, particularly cycling safety, more in-depth analyses need to be administered. Future analyses of the data include analysing the changes in the temporal distribution of the risk levels as the maximum risk level by itself does not allow for concluding on safety benefits. In addition to the analysis of the PET values, the minimum gap time and its numerical change to the PET at the crossing point will be analysed. The difference in minimum gap time and PET may indicate the effectiveness of the manipulation (amber light). In addition, data of the amber light post-week will also be included in order to test for any carry-over effects.

3.2.3 Study 2: Subjective assessment of the amber light

In addition to the objective trajectory data, subjective data was collected. The first online questionnaire was used to gain some information on the perceived safety and criticality at the AIM Research Intersection, in general. Respondents were asked to fill in the questionnaires form their perspective of a cyclist, motorist, or both. Of particular interest was the scenario sketched in Figure 57. Motorists had to assess their perceived safety when approaching the intersection from the East turning right at the intersection continuing their trip heading North, while cyclists travelled through the intersection from East to West. The traffic lights for motorists and cyclists were on green simultaneously. During the time period of December 2017 and February 2018, this questionnaire was online. Altogether, 1078 people completed the questionnaire. For the present analyses, data of 688 cyclists and 296 motorists was used. The second questionnaire was published shortly after the amber light was installed, so that respondents had a chance to experience the amber light before filling in the questionnaire. The amber light was positioned in a way that right turning motorists could be warned if they ran into a critical situation with crossing cyclists. The response rate was much lower than for the first questionnaire. Altogether, 148 questionnaires were completed. Data of 69 cyclists and 27 motorists could be used to gain some insight on the effects of the amber light on perceived safety. The results can only be seen as a first indication and do not allow for drawing conclusions of the effect of the amber light on safety.

3.2.3.1 Method

Participants

The first questionnaire was advertised via a newspaper article and social media. In addition, an email was sent to all participants registered to DLR's database. The second survey was also sent to all registered persons and distributed via social media.

Cyclists Altogether, 688 cyclists who regularly cycle through the AIM Research Intersection responded to the first online survey. Another 69 cyclists completed the second online survey (available while the amber light was installed at the intersection). On average, respondent of the first survey were 39.8 (SD= 12.8) years old, while respondent of the second survey were 36.1 (SD= 14.6) years old. Respondent of the first survey had about five more years of cycling experience (M_{before}= 31.2, SD= 13.6 vs. M_{after}= 26.1, SD= 12.3). 27% of the respondents of the first survey and 30% of the second study were females. Overall, cyclists indicated to be neither offensive nor defensive cyclists. Most of the respondents enjoyed cycling (M_{before}= 93.3% vs. M_{after}= 92.7%) and the majority of cyclists cycles throughout the year (M_{before}= 81.2% vs. M_{after}= 82.6%). Cyclist responding to the first survey indicated to experience conflicts with motorists about once or twice a week, while respondents of the second questionnaire reported conflicts about one to three times per month. Conflicts with other cyclists only occurred about once a month.

Motorists 296 motorists approaching the AIM Research Intersection from the East and turning North completed the first online questionnaire. 28% of those respondents were female. Another 27 respondents completed the second online questionnaire (available while the amber light installation at the intersection). One third of those respondents were female. Respondents of the first questionnaire were 45.5 (SD= 14.3) years old, while respondents of the second questionnaire were about two years younger (M= 43.3, SD= 14.4). Data with regards to conflicts, in general, are similar for the two questionnaires. Respondents indicated that conflicts with other motorists happened about one to three times per month, while conflicts with cyclists only happened about once a month.

Material & Apparatus

Demography questionnaire The demography questionnaire was used to gather information about age and gender. For cyclists, questions on general cycling behaviour were added (e.g. cycling experience, frequency of cycling, average cycling distances, cycling style and number of conflicts with other cyclists and motorists). Motorist answered questions about their general driving behaviour.

Safety questionnaire Respondent assessed their perceived safety on a 5-point Likert scale of the particular situation in the AIM Research Intersection (cyclists: riding straight through the intersection; motorists turning right, see Figure 5). Questions included were perceived safety and criticality, frequency of critical situations, and yielding violations.

Observed behavioural change This questionnaire was part of the second survey given to cyclists and used to assess changes in motorists' behaviour. It included questions about approach speed, gaze behaviour and yielding violations. Respondent indicated their agreement with the statements on a 5-point Likert scale from 1 (fully disagree) to 5 (fully agree).

Acceptance scale The acceptance scale used assesses acceptance of a system on two dimensions (usefulness and satisfaction). The scale consists of nine-Likert items such as *useful-useless* or *nice-annoying*. Corresponding scores range from -2 to +2 indicating either rejection or acceptance of a product. Therefore, zero indicates neither rejection nor acceptance. Positive or negative deviance form zero serves as an indicator of how well the system is accepted. Usefulness delivers an indication on the overall practicality and satisfaction ratings show how satisfied users are (Van der Laan, et al., 1997). This scale was part of the first and second online questionnaire for motorists. In the first questionnaire, acceptance of the idea of the amber light (cyclists assessed it as well) was assessed. In the second questionnaire, only motorists who noted the amber Light assessed their acceptance of the system.

Trust scale The trust questionnaire consisting of twelve items is based on Jian, Bisantz, und Drury (2000). Items were rated on a 7-point Likert scale ranging from 1 (do not agree) to 7 (fully agree). This scale was included in the second questionnaire for motorists.

<u>Procedure</u>

Before starting the questionnaire, respondent had to confirm that they agree to have their anonymized data saved for the analysis. If participants did not agree, they were redirected to the last page of the questionnaire and thanked. For the first questionnaire, participants indicated what mode of transport they normally use. Respondents indicating that they only cycle were redirected to the cycling questionnaire, while motorist were redirected to the driving questionnaire. Respondents indicating that they cycle and use their bicycle equally, completed the cycling and driving questionnaire. For the purpose of the second questionnaire, respondent had to decide on whether they cycle or drive predominantly and were redirected accordingly. Each questionnaire started with demography questions followed by questions regarding cycling and/or driving behaviour. In the second part of the questionnaire, respondents were asked to assess their perceived safety in the particular scenario.

Third part of the questionnaire was different for the different survey. In the first questionnaire, the idea of the amber light was illustrated and motorists as well as cyclists completed the acceptance and trust scale. For the second survey, this scale was only included in the questionnaire of the motorists who noted the amber light at the AIM research intersection. As cyclists could not experience the amber light directly, in the third part of the questionnaire, cyclists were asked to assess changes in motorists' behaviour while turning right at the intersection.

Altogether, completing the questionnaires did not take longer than 15 minutes.

3.2.3.2 Results

Mann-Whitney's U tests were administered to test for differences in subjective ratings before the installation of the amber light with ratings of time period of the installation of the amber light. Rating of perceived safety and criticality were compared as well as ratings about the frequency of critical situations and yielding violations. For cyclists, ratings of changes in behaviour are also reported (descriptive analysis only). For motorists, trusts ratings as well as acceptance ratings are reported.

Cyclists

Perceived safety The medians of the two ratings were 3.35 and 3.08 respectively. The results of the Mann-Whitney's U test indicated a trend (U= 20 742.5, Z= -1.807, p= .071, r= .06). The mean ranks of the assessment were 383.35 and 335.62. Ratings of the second assessment were slightly lower, indicating a slighter higher perceived safety.

Perceived criticality The analyses of the perceived criticality did not reveal any significant differences between groups.

Yielding violations Differences in the perceived frequency of yielding violations were significant (U= 33 198, Z= 7.188, p< .001, r= .26). Mean ranks were 359.25 and 558.95 respectively. The medians of the ratings were 3.84 and 5.71. Results of the first questionnaire were close to the neither/nor rating, while results of the second questionnaire indicated that yielding violations hardly ever occurred.

Critical situation Differences in the ratings of the perceived frequency of critical situations were also significant (U= 35 533.5, Z= 8.65, p< .001, r= .31). Mean ranks were 355.85 and 596.02. The medians of the ratings came out to 3.69 and 5.63, respectively. Fewer critical situations were observed during the time period of the installation of the amber light.

Behavioural changes Of the 69 respondents of the second questionnaire, 51 noted the amber light. The remaining 18 persons did not see the amber light and therefore did not receive the questions about the observed behavioural change. According to the results in Table 21, not all respondents were able to make a sound assessment as indicated by the 'don't know' category. Of the remaining respondents, the majority indicated that the intersection approach speed of the right turning motorists was lower, that fewer critical situations occurred, that motorists looked more for cyclists, and that motorist stopped more often before crossing.

Table 21: Summary of the absolute and relative frequencies of subjective ratings of the observed behavioural change of motorist.

Item	Don't know	Fully disagree	2	3	4	Fully agree
Right turning motorist approach the intersection slower.	23 (45%)	2 (4%)	4 (8%)	7 (13%)	11 (22%)	4 (8%)
Right turning motorist approach the intersection faster.	23 (45%)	14 (27%)	9 (18%)	3 (6%)	1 (2%)	1 (2%)
I experience fewer critical situations with right turning motorists.	15 (30%)	6 (11%)	4 (8%)	5 (10%)	15 (30%)	6 (11%)
I experience more critical situations with right turning motorists.	13 (26%)	21 (41%)	10 (20%)	5 (10%)	1 (2%)	1 (2%)
Right turning motorist look less for cyclists.	19 (37%)	10 (20%)	15 (30%)	1 (2%)	5 (10%)	1 (2%)
Right turning motorists look more for cyclists.	21 (41%)	2 (4%)	3 (6%)	6 (11%)	13 (26%)	6 (11%)

Right turning motorists stop more often before crossing.	19 (37%)	2 (4%)	3 (6%)	7 (13%)	14 (28%)	6 (11%)
Right turning motorists stop less often before crossing.	17 (33%)	16 (31%)	12 (24%)	5 (10%)	1 (2%)	0 (0%)

<u>Motorists</u>

Perceived safety The analyses of the perceived safety did not reveal any significant differences between groups. The medians were 2.14 and 2.11, respectively, indicating that motorists felt fairly safe while turning right at the AIM Research Intersection.

Perceived criticality The analyses of the perceived criticality did not reveal any significant differences between groups. The medians were 2.49 and 2.5, respectively. Generally, the type of manoeuvre is neither considered critical nor non-critical.

Yielding violations Differences in the perceived frequency of yielding violations were significant (U= 4 857.5, Z= 4.769, p< .001, r= .26). Mean ranks were 141.52 and 242.31 respectively. The medians of the ratings were 6.07 and 6.85. A rating of six indicated that yielding violations happen very rarely, while 7 corresponded with never.

Critical situation Differences in the ratings of the perceived frequency of critical situations were also significant (U= 5 060, Z= 5.01, p< .001, r= .28). Mean ranks were 151.85 and 251.95. The medians of the ratings came out to 4.77 and 6.31, respectively. Fewer critical situations were observed during the time period of the installation of the amber light.

Acceptance ratings Only 10 of the 27 respondents of the second questionnaire rated the usefulness of the amber light. The analysis of the usefulness ratings indicated a trend (U= 1 851, Z= 1.76, p= .07, r= 0,1). Mean ranks were 143.37 and 190.6. Medians came out to .65 and 1.1, meaning that the usefulness was rated slightly higher after experiencing the system. Satisfaction was rated by twelve persons compared to 279 of the first questionnaire. The Mann-Whitney's U test revealed significant differences for the satisfaction ratings (U= 2 424.5, Z= 2.64, p= .008, r= .15). Mean ranks were 143.31 and 208.54 and medians were .18 and .75, respectively. Here again, satisfaction was rated higher after experiencing the amber light.

3.2.4 Discussion and conclusion

Subjective data was collected to gain some insight in the perceived safety and criticality of the investigated situation. Especially the results of the second survey can only serve as an indication as control over what respondents experienced could not be ensured. Nonetheless, subjective ratings are somewhat in line with objective findings. Cyclists reported that motorists approached the intersection with lower speed. They also experienced fewer critical situations with motorists at the crossing point. It appeared that motorists looked for cyclists more often and stopped more frequently before crossing. Motorists also reported to have experienced fewer critical situations.

3.3 On-bike system

3.3.1 Objectives

In order to increase road traffic safety, especially for cyclists, another option may be an advanced assistant system for cyclists warning them in case of an occurring critical situation with a motorist at intersections. The so-called on-bike system (designed and developed by the University of Bologna) may be a solution for actively incorporating cyclists in road traffic safety actions. The on-bike system is based on an active tag communicating with the infrastructure detection system and is accommodated by an HMI. The bike module communicates with the infrastructure transmitting information about the position of the cyclist. When right turning motorists and crossing cyclists are on a colliding course, a warning is transmitted to the on-bike HMI. In a semi-controlled field study, at the AIM Research Intersection in Braunschweig, the on-bike system was evaluated. Furthermore, in order to gather qualitative feedbacks and insights for future improvements of the on-bike system, a focus group with cyclists was conducted in Italy.

The goal of the semi-controlled field study was to investigate differences in subjective ratings (e.g. acceptance, trust, perceived safety and criticality) between baseline and experimental condition as well as changes in ratings over time. In addition, approach and crossing speed of cyclists was also assessed and served as an indication of behavioural adaptation in response to the usage of the on-bike system.

The goal of the focus group study was threefold: (1) to gather participants' descriptions of their experiences of critical traffic situations; (2) to evaluate the on-bike warning system from a user perspective based on the participants' perceived usefulness, trust and perceived risks of the system, its benefits and drawbacks etc.; and (3) to collect the participants' comments and suggestions for further improvements of the system.

3.3.2 On-bike system semi-controlled field study

3.3.2.1 Method

<u>Participants</u>

Altogether, 15 participants between the ages of 21 and 64 years (M= 31.4, SD= 14.9) were recruited. Only cyclists who own and use a bicycle helmet were able to participant in the study. Cyclists used their bicycles in the study. On average, every other cyclist rides his/her bike on a daily basis.

<u>Apparatus and material</u>

Infrastructural detection system As mentioned in Section 0**Errore. L'origine riferimento non è stata trovata.**, the infrastructural detection system consisted of two poles equipped with stereo cameras and lidar. The system detected and tracked right turning motorists (see red arrow and crossing cyclists (blue arrow) in Figure 57. Cyclists and motorists were tracked for approximately 35 meters while approaching the intersection. During the approach trajectory and video data are recorded. Based on the trajectory data, the level of risk of a collision was calculated between two interacting road users (right turning motorist and crossing cyclist). In case of a critical situation (for definitions see Table 1), a warning message was transmitted to the on-bike system.

On-bike system The warning system for cyclists is based on an active communication with the infrastructural detection system and consists of the HMI presented in Section 1.1.2. The HMI was comprised of nine LEDS: 8 of them were equally arranged to the left and right, the 9th was placed in the middle. Those three areas could be triggered separately. For the purpose of the study, only the four LEDs on the left were triggered as the potential critical situation would arise from the left. Based on the estimated level of risk (see Table 1 for definitions), the LEDs either turned on (1st degree conflict) or started flashing (2nd degree conflict). The on-bike system was mounted on the handlebar of the bicycles.

Tablets Two tablets were used by the experimenter to document the assessment of the criticality of each crossing. In addition, the second tablet was also used by the participants for filling questionnaires after each trial. Tablets used were IPads of the 4th generation equipped with a WiFi- and 3G- module. The tablets were 241.2mm x 185.7mm x 9.4mm and a capacitive touchscreen with a diagonal of 24.63cm. The resolution of the tablets was 2048*1536 pixels (~264 ppi density). The internal storage capacity was 16 GB/ 1 GB RAM. The tablets weighted 662g.

Questionnaires The demography questionnaire was used to gather information about age and gender as well as information about the general cycling behaviour including questions about cycling experience, frequency of cycling, average cycling distances, cycling style and number of conflicts with other cyclists and motorists.

Questionnaires, assessing perceived usefulness (PU), perceived ease of use (PEOU), behavioural intention to use (BIU), and trust, based on the Technology Acceptance Model was used for this study. The five items to assess PU and PEOU are based on Davis (1989) and the review of Legris, Ingham und Collerette (2003). The four items for the assessment of BIU are based on Venkatesh und Davis (2000). The trust questionnaire consisting of twelve items is based on Jian, Bisantz, und Drury (2000). For the assessment before the start of the experimental trials, items of the questionnaires were changed into the subjunctive form. Items were rated on a 7-point Likert scale ranging from 1 (do not agree) to 7 (fully agree).

The acceptance scale used assesses acceptance of a system on two dimensions (usefulness and satisfaction). The scale consists of nine-Likert items such as *useful-useless* or *nice-annoying.* Corresponding scores range from -2 to +2 indicating either rejection or acceptance of a product. Therefore, zero indicates neither rejection nor acceptance. Positive or negative deviance form zero serves as an indicator of how well the system is accepted. Usefulness delivers an indication on the overall practicality and satisfaction ratings show how satisfied users are (Van der Laan, et al., 1997).

After each intersection crossing, participants filled in a brief questionnaire assessing their perceived safety and criticality of the situation. Additionally, when cycling with the warning system activated, participants indicated the status of the warning system and whether this status was adequate for the situation.

<u>Experimental design</u>

The semi-controlled field study was a mixed study design with repeated measures. Dependent and independent variables varied depending on the research question analysed and are described in more detail in the different result sections corresponding to the analyses.

The experiment was comprised of two conditions: baseline (deactivated system) and experimental trials (activated system). The experiment consisted of four blocks. Each block included three baseline trials and ten experimental trials. Participants completed a trial within four to five minutes. Completing an experimental block took approximately 65 minutes. Altogether, 52 trials were completed by each participant.

The experiment took place at the AIM Research Intersection in Braunschweig (Hans-Sommer-Str., corner of Brucknerstr.) between 12 pm and 5 pm on weekdays. Each day, two persons participated using their bikes. Participants approached the intersection coming from East going West, while motorists turn North at the intersection. Cyclists and motorists had simultaneous green phases. Two experimenters were present for the study. The first experimenter stood about 15 meters before the crossing. When the traffic light changed from red to yellow, the first experimenter signalised participants to start cycling. The second experimenter waited after the crossing to hand participants the tablet. Participants took turns in crossing the intersection. The order of baseline and experimental trials was randomized per day, meaning they either started with three trials of the baseline condition or ten trials of the experimental condition. Each trial included approaching and crossing the intersection (approximately 50 metres) on a green traffic light, filling in questionnaires after the crossing, and returning to the start point. In addition to wearing a helmet, participants also carried a distinguished backpack, so that they could be recognized in the video data.

For each crossing, trajectory and video data was recorded. After each crossing, participants answered questions about their perceived safety and criticality of the situation. Additionally, during experimental trials, participants also indicated the status of the warning (i.e., off, low-frequent flashing, or high-frequent flashing). After the 10th, 20th, 30th, and 40th trial with the system activated, participants indicated their acceptance of and trust in the system. After trial 20 and 40, they also indicated their PU, PEOU, and BIU (these results are not reported here).

<u>Procedure</u>

Each day, two persons participated in the study. They were greeted by the two experimenters. The experimenter explained the purpose of the study in detail. The On-Bike-System and its functionality were described to the participants. Any additional questions were answered before reading the instructions and signing the participant agreement. After that, the experimenter handed the tablets to the participant and each participant filled in some demographic details and information about their general cycling behaviour. Based on the description of the On-Bike-System, participants rated their PU, PEOU, BIU, trust, and acceptance. While filing in the questionnaires, the experimenters mounted the On-Bike-Systems to the handlebar of the bicycles. Subsequently, the experimenter and participants walked from the starting point of each trial to the intersection crossing and were instructed that each trial starts when the 1st experimenter raises her hand. Participants were also instructed to stop after the crossing to fill in some questionnaires. In addition, participants were asked to behave as they would normally do, to obey the traffic law and to not provoke critical situations.

Before the start of the first trial, participants put on their helmets and the backpacks. The first experimenter escorted the participants to the starting point. Participants started the crossing when seeing the raised hand, crossed the intersection, filled in questionnaires after the crossing, returned to the starting point, and waiting for starting the next trial. While crossing the intersection, the experimenter rated the criticality of the situation and if necessary documented any interesting observations.

The duration of the study did not exceed five hours including breaks. Cyclists were compensated for their participation and received €10/hour.

3.3.3 *Results*

3.3.3.1 Analysis of subjective data

Acceptance

Acceptance of the on-bike system was measured using the subscales usefulness and satisfaction. Acceptance was measured before the first trial and after the 10^{th}, 20^{th}, 30^{th}, and 40^{th} trial with the system activated. In a first step, dependent samples t-tests were calculated comparing pre-trial scores with the average score of the four ratings during the experimental block. In a second step, ANOVAs with repeated measures as well as repeated contrast analysis were administered.

Paired samples t-tests of usefulness ratings showed a significant difference between pre-trail ratings ($M= .51$, $SD= .92$) and experimental ratings ($M= -.34$, $SD= .86$), $t(14)= 5.1$, $p< .001$. Assessing changes over time showed significant differences in ratings, $F(4,56)= 10.7$, $p< .001$, $\eta^2= .43$. As seen in Figure 62, pre-trial ratings were higher compared to ratings after the 10^{th}, 20^{th}, 30^{th}, and 40^{th} trial with activated system; while those ratings were similar. A repeated contrast analysis revealed a significant difference between the pre-trial rating and the rating after the 10^{th} trial with the system, $F(1,14)= 16.8$, $p= .001$, $\eta^2= .55$, while changes from the 10^{th} to the 20^{th} ($F(1,14)< 1$), the 20^{th} to the 30^{th} ($F(1,14)< 1$), and the 30^{th} to the 40^{th} ($F(1,14)= 2.1$, n.s.) were not significant.

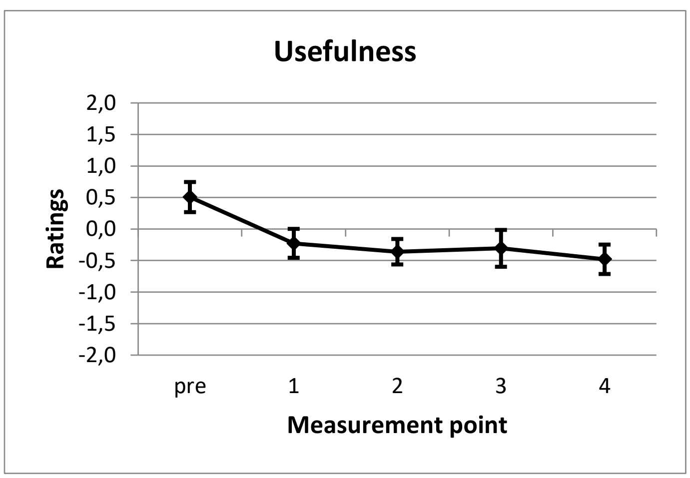


Figure 62: Average usefulness ratings before the first trial and after the 10th, 20th, 30th, and 40th trial with activated system. Error bars represent the standard error.

Assessing the differences in satisfaction ratings between pre-trail ratings and the average ratings with activated system, a significant difference was observed, $t(14)= 3$, $p= .009$. Average satisfaction ratings before experiencing the system came out to .23 ($SD= .94$) and after experiencing the system to -.2 ($SD= .55$).

Significant differences in satisfaction ratings were observed, $F(4;56)= 3,97$, $p= .007$, $\eta^2= .21$, over time. The first rating was still positive, while the second rating was equal to zero and dropped into the negative range at the third measurement point, even though ratings slightly improved after the 30th trial and slightly dropped again after the 40th trial with the on-bike system (see Figure 63). The repeated contrast analysis showed a trend in the change in ratings after the 10th trial (M= 0, SD= .73) compared to the ratings after the 20th trial (M=-.35, SD= .53), $F(1,14)= 3.18$, $p= .09$, $\eta^2= .17$.

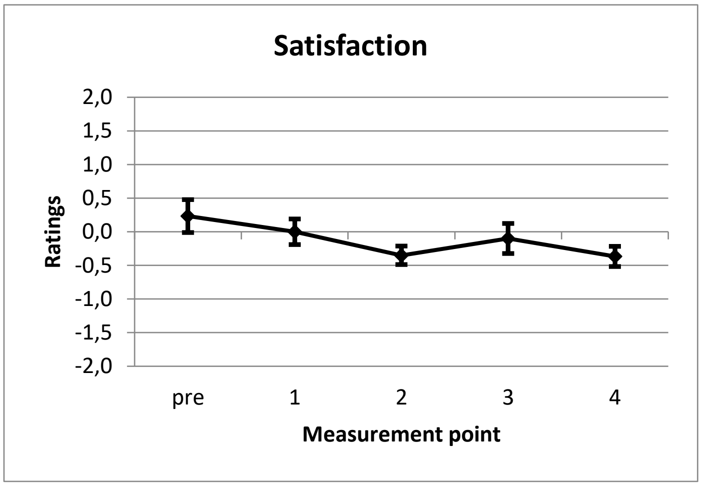


Figure 63: Average satisfaction ratings before the first trial and after the 10th, 20th, 30th, and 40th trial with activated system. Error bars represent the standard error.

<u>Trust</u>

Trust was measured five times as well (i.e. before the first trial, after the 10th, 20th, 30th, and 40th). Participants indicated their trust in the system on a scale from 1 to 7. Dependent samples t-tests were calculated comparing pre-trial scores with the average score of the four ratings during the experimental block. In a second step, ANOVAs with repeated measures (Greenhouse-Geisser corrected results are reported) as well as repeated contrast analysis were administered.

Comparing pre-trial trust ratings with the average ratings of experiencing the system revealed a significant difference, $t(14)= 3.8$, $p= .002$. Before experiencing the system, average trust ratings came out to 4.6 (SD= .9). After experiencing the system, average ratings dropped down to 3.8 (SD= .67). Results of the ANOVA with repeated measures revealed a significant effect, $F(2.12,21.58)= 4.77$, $p= .01$, $\eta^2= .25$. The repeated contrast analysis indicated a significant change in rating from the pre-trial ratings to the first rating after experiencing the system, $F(1,14)= 15.87$, $p= .001$, $\eta^2= .53$. No other significant changes from one measurement point to the next were observed (see Figure 64).

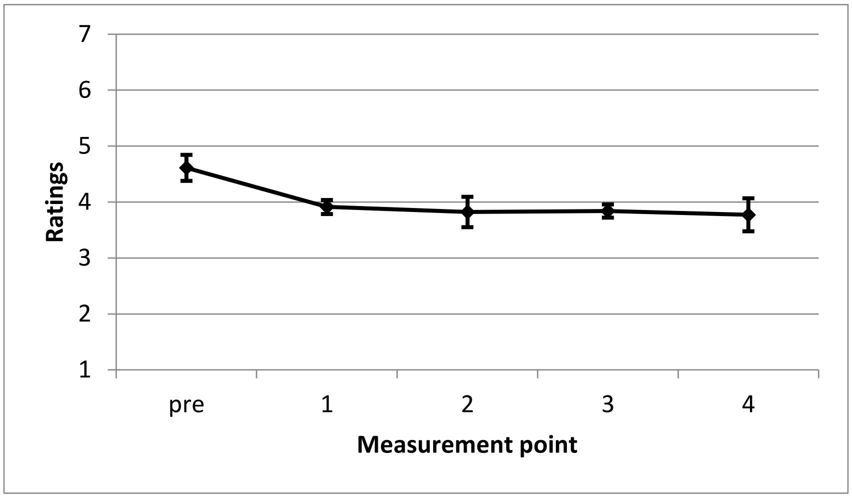


Figure 64: Average trust ratings before the first trial and after the 10th, 20th, 30th, and 40th trial with activated system. Error bars represent the standard error.

Perceived safety and criticality

Perceived safety and criticality was measured after each intersection crossing. Altogether, twelve baseline ratings as well as 4 x 10 experimental ratings were completed by the participants. For the purpose of this analysis, ratings of crossings with no interaction with motorized vehicles were excluded. Of the remaining ratings, an average per participant was calculated for the baseline condition and each experimental block. ANOVAs with repeated measures as well as repeated contrast analysis were administered using cycling style (defensive, neither nor, and offensive) as between-subject factor. The number of participants was distributed equally across groups (n=5).

Results of the ANOVA with repeated measures indicated a significant main effect of cycling style on safety, $F(2,12)= 4.1$, $p= .04$, $\eta^2= .41$. Participants indicating a defensive cycling style rated safety as 1.43 (SD= .51), offensive as 1.78 (SD= .58), and neither nor with 2.36 (SD= .67). A score of one corresponds to feeling safe, while five was associated with feeling unsafe. No other significant main or interaction effect was found. The repeated contrast analysis did not reveal any significant effects (Figure 65 left).

The same analysis was carried out testing effects of cycling style on criticality ratings. Here again, a significant main effect of cycling style, $F(2,12)= 5.7$, $p= .018$, $\eta^2=.487$, was revealed. Defensive cyclists rated the criticality of the situations as 4.43 (SD= .5), offensive cyclists as 4.02 (SD= .52), the remaining cyclists as 3.62 (SD= .41). A score of five corresponded to perceiving the situation as non-critical, while one corresponded to critical. No other significant main or interaction effects were found. The repeated contrast analysis did not reveal any significant effects (Figure 65 right).

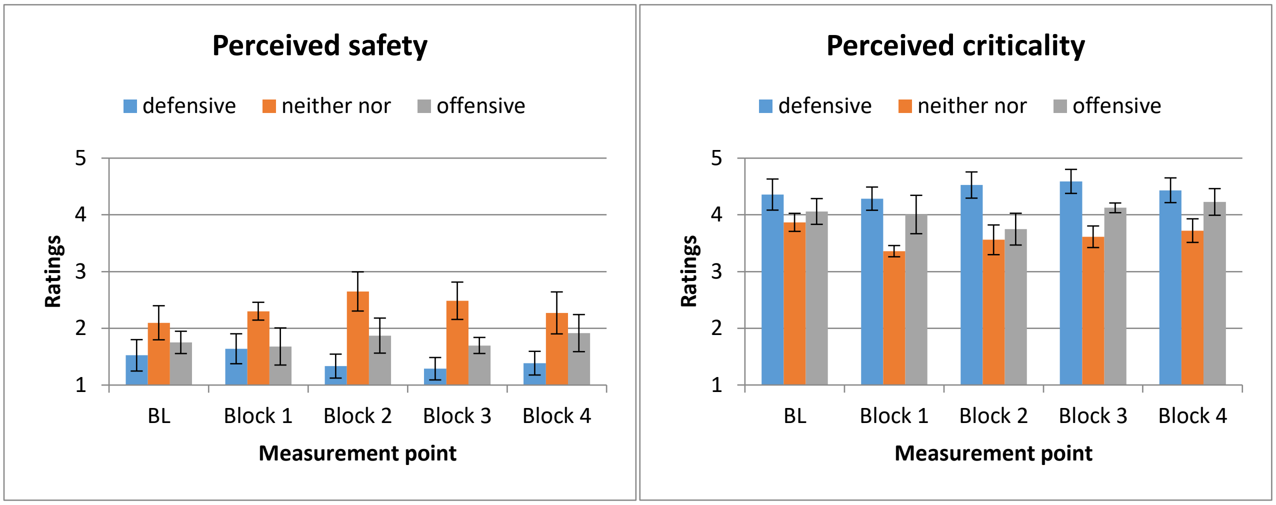


Figure 65: Left: Average ratings of perceived safety. Error bars represent standard error. Right: Average ratings of perceived criticality. Error bars represent standard error.

Critical situations

Based on the online assessment of the interaction with a motorist, the calculated risk level was logged in the files for all situations, even when the warning (during baseline trials) was not transmitted to the on-bike system. For all participants the total number of warnings during baseline and experimental trials was calculated (see Figure 66 left) as well as the relative number (total number of warnings divided by number of interactions with motorists, see Figure 66 right) was calculated. ANOVA were used to test the effect of cycling style on the number of critical situations. In a second step, the adequacy/quality of the warnings is evaluated.

Altogether, in 45 of the 142 interactions (~32%) with motorists were critical in baseline trials. During the experimental trials, 146 of the 464 interactions (~32%) resulted in transmitting a warning to the cyclists.

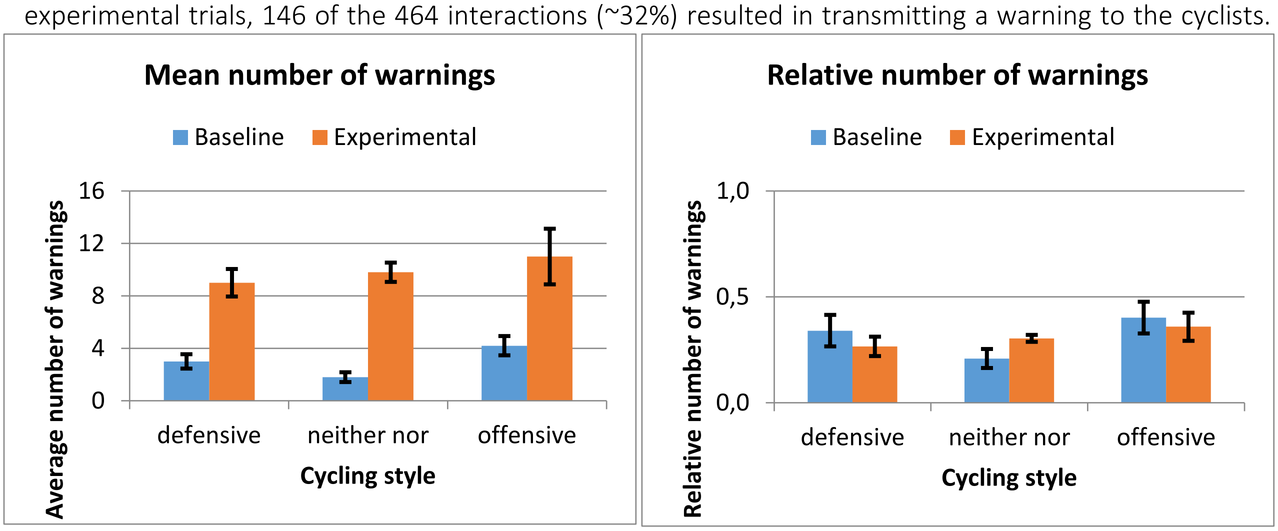


Figure 66: Left: Average number of warnings. Error bars represent the standard error. Right: Relative number of warnings (total number of warnings divided by total number of interactions). Error bars represent the standard error.

The results of the ANOVA indicated a significant difference in the average number of warnings between cycling style in the baseline condition. The offensive group experienced approximately four critical situations, the defensive group about three and the neither nor group about two. The analysis of the relative number of warnings did not yield any significant results. For defensive cyclists, about 34% of their interactions with motorists resulted in a recorded warning during baseline trials. The number was lower (27%) for experimental trials. Offensive cyclists' interaction with motorists resulted in critical situation in 40% of the cases and 36%, respectively. The neither nor group had fewer warnings during baseline trials (21%) compared to experimental trials (30%).

Participants rated the adequacy of each of the warnings (i.e., meaning warning as well as no warning). The adequacy of 146 warnings was assessed by the participants. The results are summarized in Table 22. According to the results, only every other warning was perceived as being appropriate for the situation. In about 11% of the cases, participants were not able to make a sound judgement.

Table 22: Summary of the ratings of the adequacy of the warning (n=146), when cyclists were warned.

	Don't know	Totally disagree	2	3	4	Totally agree
Total number of selection	16	19	13	14	21	64
Relative value	11%	13%	9%	9%	14%	44%

The analysis of the ratings when no warning was transmitted also revealed that in about 10% of the cases, participants were not able to tell whether the warning was appropriate. In addition, in almost 60% of the cases, participants did not agree with the appropriateness of the warning (i.e. not receiving a warning in the particular situation (see Table 23).

Table 23: Summary of the ratings of the adequacy of the warning (n=318), when cyclists were not warned.

	Don't know	Totally disagree	2	3	4	Totally agree
Total number of selection	39	19	21	25	53	161
Relative value	12%	6%	7%	8%	17%	50%

Changes in cycling behaviour

Cyclist's speed data was excluded from the analysis when no interaction with a motorist occurred. In order to assess changes in speed over time, the last 14 meters to the intersection were split into five sections of 2.8 meters each. For each of the sections, the mean speed of each participant per trial was calculated. Based on this aggregated data, mean velocity values were calculated for the baseline condition and for each of the four experimental blocks. In order to assess behavioural changes due to the on-bike system, ANOVAs with repeated measures as well as repeated contrast analyses are calculated testing changes during the approach. Cycling style and condition serve as within-subjects variables. In a second step, the effect of a warning and cycling style on approach speed was investigated. Mean velocity values were calculated for all critical (i.e. log files indicated a risk level 2 or greater) and non-critical baseline conditions as well as critical (i.e. a warning was transmitted to the on-bike system) and non-critical experimental conditions. The Greenhouse-Geisser correction is applied for the results of ANOVAs with repeated measures.

Differences in velocity over time Results of the ANOVA with repeated measures indicated a significant change in velocity, $F(2.34,140.7)= 86.95$, $p< .001$, $\eta^2= .59$, and a significant main effect of cycling style, $F(2,60)= 37.36$, $p< .001$, $\eta^2= .55$. A significant interaction of change in velocity x cycling style, $F(4.7,140.7)= 4.38$, $p= .001$, $\eta^2= .13$, was also revealed. Repeated contrast analysis showed significant changes in velocity from section 1 to 2, $F(1,60)= 28.3$, $p< .001$, $\eta^2= .32$, section 2 to 3, $F(1,60)= 144.3$, $p< .001$, $\eta^2= .71$, section 3 to 4, $F(1,60)= 15.6$, $p< .001$, $\eta^2= .21$, and section 4 to 5, $F(1,60)= 4.03$, $p= .05$, $\eta^2= .06$. The analysis of the interaction change in velocity x cycling style also revealed significant changes from section 2 to 3, $F(2,60)= 3.7$, $p= .03$, $\eta^2= .11$, section 3 to 4, $F(2,60)= 4.55$, $p= .01$, $\eta^2= .13$, and section 4 to 5, $F(2,60)= 5.3$, $p= .007$, $\eta^2= .15$. As seen in Figure 15, from section 2 to 3 as well as from section 3 to 4, the change in velocity was greater for offensive cyclists compared to other cycling styles. While defensive cyclists already started accelerating from section 4 to section 5, offensive cyclists still decelerate while the neither nor group showed a constant velocity (Figure 67).

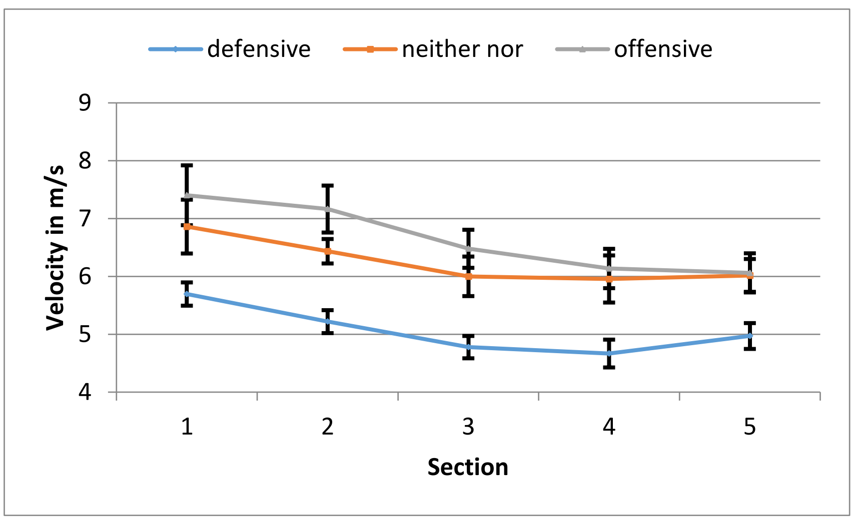


Figure 67: Mean velocity values grouped by cycling style and section. Error bars represent the standard error.

Differences in velocity in Baseline$_{crit}$ vs. Baseline$_{non\text{-}crit}$ The results of the ANOVA with repeated measure (Figure 68) revealed a significant main effect of changes in velocity over time, $F(2.39,57.5)= 13.9$, $p< .001$, $\eta^2= .37$, as well as a significant main effect of cycling style, $F(2,24)= 9.5$, $p= .001$, $\eta^2= .44$. Velocity dropped from 6.4m/s (SD= 1.07) in section1 to 5.5 m/s (SD= .99) in section 5. While defensive cyclists showed an average speed of 4.9 m/s, offensive cyclists rode with an average of 6.2 m/s, and the neither nor group with an average of 6.6 m/s. No other significant interaction effects were found.

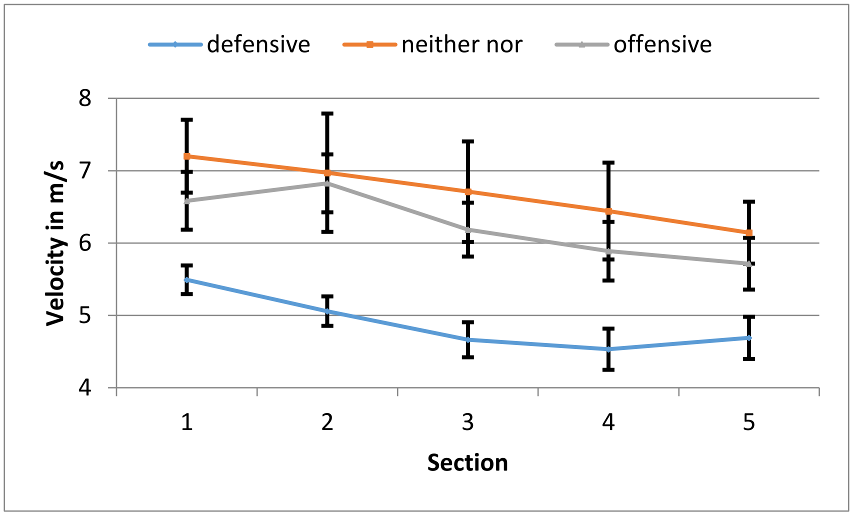


Figure 68: Mean velocity values of critical and non-critical baseline trials grouped by cycling style and section. Error bars represent the standard error.

The repeated contrast analysis indicated a significant change in velocity from section 2 to 3, $F(1,24)= 25.4$, $p< .001$, $\eta^2= .51$, and from section 3 to 4, $F(1,24)= 14.6$, $p= .001$, $\eta^2= .38$. This corresponded to a drop from 6.4 m/s (SD= 1.38) in section 2 to 5.8 m/s (SD= 1.35) in section 3 to 5.6 m/s (SD= 1.1) in section 4. No other changes were revealed (Figure 68).

Differences in velocity in OBS$_{crit}$ vs. OBS$_{no\text{-}crit}$ The analysis of mean velocity values of the experimental condition with and without revealed a significant main effect of changes in velocity, $F(1.8,44.2)= 42.1$, $p< .001$, $\eta^2= .64$, and a significant effect of cycling style, $F(2,24)= 23.3$, $p< .001$, $\eta^2= .66$. The interaction effect of velocity x cycling style, $F(3.68, 44.2)= 2.35$, $p= .07$, $\eta^2= .16$, revealed a trend. Defensive cyclists had a lower approach speed than the remaining cyclists and while defensive cyclists already accelerated from section 4 to section 5, the other cyclists still decelerated (see Figure 69). The repeated contrast analysis revealed significant changes in velocity from section 1 to 2, $F(1,24)= 12.1$, $p= .002$, $\eta^2= .33$, from 2 to 3, $F(1,24)= 77.6$, $p< .001$, $\eta^2= .76$, and from 3 to 4, $F(1,24)= 13.1$, $p= .001$, $\eta^2= .35$. Average speed was 6.6 m/s (SD= 1.15) in section 1, 6.26 m/s (SD= 1.1) in section 2, 5.72 m/s (SD= .88) in section3, and 5.53 m/s (SD= .99) in section 4. The interaction of velocity x cycling speed also turned out to be significant from section 4 to section 5, $F(2,24)= 8.8$, $p= .001$, $\eta^2= .42$ (see Figure 69).

Differences in velocity in Baseline$_{crit}$ vs. OBS$_{crit}$ Here again, a significant effect of changes in velocity, $F(10.7,49.3)= 22.6$, $p< .001$, $\eta^2= .48$, was found as well as significant differences in cycling style, $F(2,24)= 10.8$, $p< .001$, $\eta^2= .47$. The interaction effect changes in velocity x cycling style showed a trend towards significance, $F(4.1,49.3)= 2.2$, $p= .08$, $\eta^2= .16$. According to the contrast analysis, changes in velocity were close to significance from section 1 to section 2, $F(1,24)= 3.6$, $p= .07$, $\eta^2= .13$, and significant from section 2 to 3, $F(1,24)= 22.8$, $p< .001$, $\eta^2= .48$, and section 3 to 4, $F(1,24)= 23.2$, $p< .001$, $\eta^2= .49$. Average speed dropped from 6.5 m/s (SD= 1.4) in section 1, to 6.3 m/s (SD= 1.4) in section 2, to 5.9 m/s (SD= 1.3) in section 3, to 5.6 m/s (SD= 1.3) in section 4. Average speed of the defensive cyclists was the lowest with 4.8 m/s, while offensive cyclists showed an average speed of 6.4 m/s, and the neither nor group 6.6 m/s (see Figure 70).

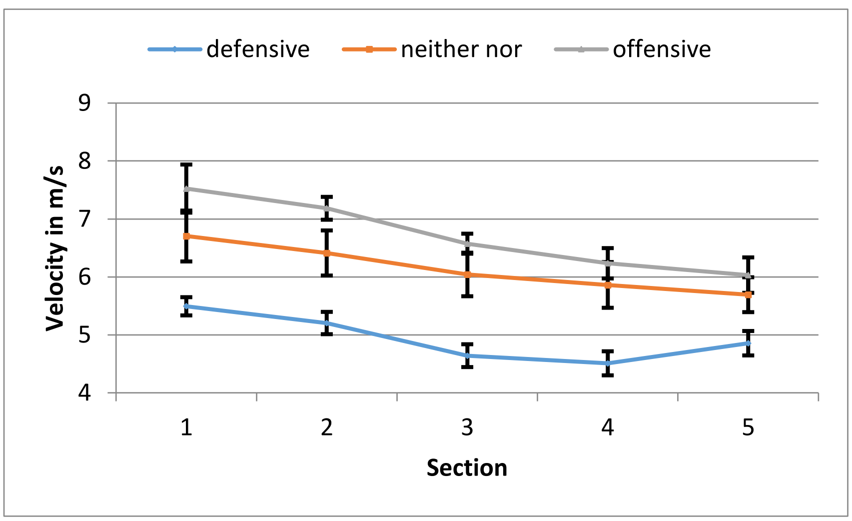


Figure 69: Mean velocity values of critical and non-critical experimental trials grouped by cycling style and section. Error bars represent the standard error.

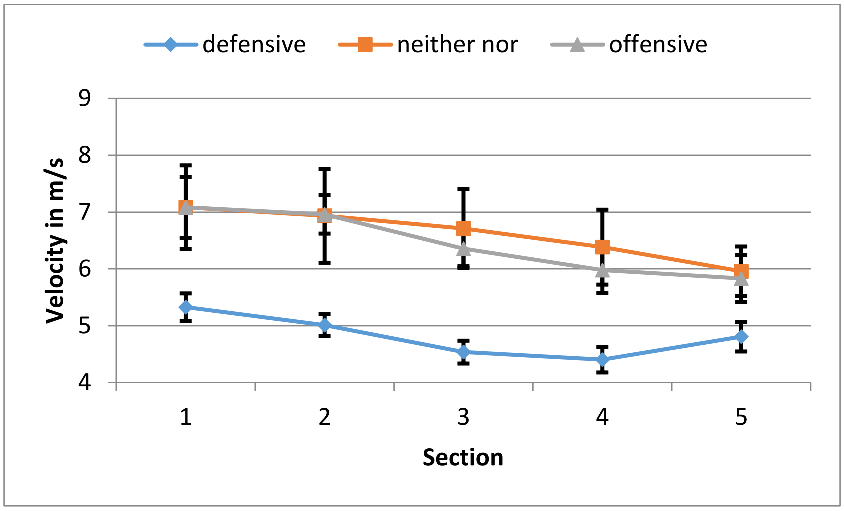


Figure 70: Mean velocity values of critical baseline and experimental trials grouped by cycling style and section. Error bars represent the standard error.

Differences in velocity in $BL_{non\text{-}crit}$ vs. $OBS_{non\text{-}crit}$ Comparing the results of non-critical baseline and experimental conditions yielded a significant effect of changes in velocity over time, $F(2,48.5)= 22.2$, $p< .001$, $\eta^2= .48$, and a significant effect of cycling style, $F(2,24)= 17.1$, $p< .001$, $\eta^2= .58$. Average velocity values decreased from 6.5 m/s (SD= 1.1) in section 1, to 6.3 m/s (SD= 1.0) in section 2, to 5.7 m/s (SD= .97) in section 3, to 5.5 m/s ($SD_4= .98$, $SD_5= .81$) in sections 4 and 5. Repeated contrast analysis revealed that the changes in velocity were significant from section 2 to section 3, $F(1,24)= 102.7$, $p< .001$, $\eta^2= .81$, and from section 3 to 4, $F(1,24)= 7.4$, $p= .01$, $\eta^2= .23$. The average speed of defensive cyclists was lowest with 5 m/s, while offensive cyclists were 1.5m/s faster, and the neither nor group travelled with an average speed of 6.2 m/s (see Figure 71).

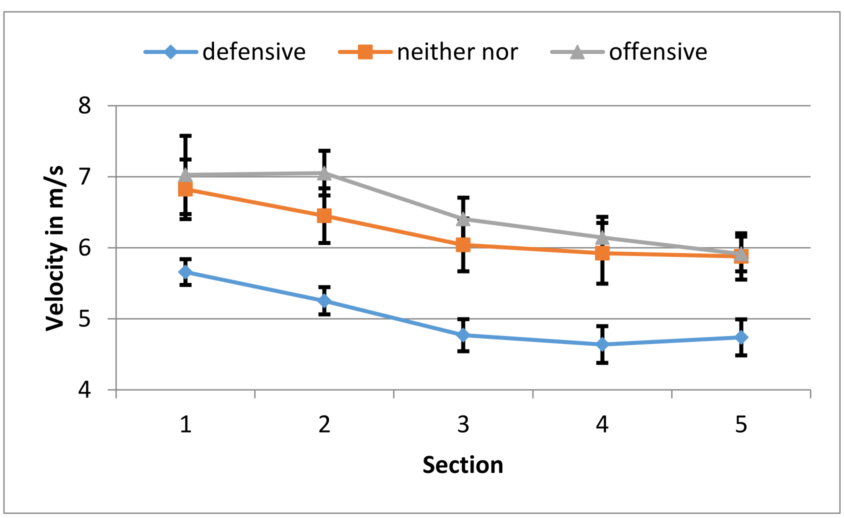


Figure 71: Mean velocity values of non-critical baseline and experimental trials grouped by cycling style and section. Error bars represent the standard error.

3.3.4 On-bike focus group study

3.3.5 Method

3.3.5.1 Recruitment and procedure

We conducted one focus group to attain a deeper understanding of the in-truck and on-bike XCYCLE systems from the cyclists´ perspective. Out of ten participants, 4 were females and 6 males aged between 24 and 54 years (M=30.8), and all of them were bicycle users. Seven participants were university students, 3 were workers. The focus group took place in Cesena (Italy) and was moderated by a trained student. The participants were students of the University of Bologna and were recruited following a snowball strategy, where each participant who agreed to take part in the focus group recommended other potential participants. The focus group took place in the University of Bologna campus of Cesena, Italy.

At the beginning of the session, all cyclists signed an informed consent form. Participants were shown a presentation of the XCYCLE systems and a video recording of the use case scenario. The presented use case scenario depicts a traffic situation in which a truck is about to turn right on an intersection while a cyclist is approaching on the right side of the truck. When the cyclist is in range of the system, it signals the risk of collision both to the cyclist and the truck driver. The latter stops, lets the cyclists pass, and after turning right continues his journey. The cyclists watched the scenario both from cyclist's and driver's perspective. The moderator then followed an interview grid formulated beforehand to elicit responses from the group.

3.3.6 Topics in the Focus Group Interviews

The following topics were discussed with the cyclists:

1. The cyclists' experiences of similar critical traffic situations
2. What makes the situation critical
3. Cyclists' general opinions about the on-bike warning system
4. Cyclists' trust in the warning system
5. Risks associated with the warning system
6. Pros and cons of the warning system
7. Recommendations for further improvements of the warning system

3.3.6.1 Analysis

Recorded interviews were reported using a verbatim transcription style. For the analysis of the contents of the interviews the University of Bologna used a coding scheme provided by VTI which was used in Sweden to analyze the content of the focus groups with truck drivers and cyclists as well. The codes were grouped and sorted into different categories, and the final ones are the headings which make up the results section. The main emphasis of the analysis was to describe general thoughts and the common opinion from the focus group sessions, rather than to focus on single statement from all individuals. However, when individuals expressed things that was considered of special interest and relevance for the study, this was included in the analysis.

3.3.7 Results

3.3.7.1.1 Experiences of similar critical situations

Cyclists reported that they are familiar with the critical situation taken in account. It is an everyday situation for those who cycle. Cyclists considered themselves as vulnerable road users and underlined their need of adequate cycling infrastructure; in fact, safety concerns were commonly considered as the primary barrier to cycling. The traffic scenario in which the cyclist and the truck driver stop at the same time was mentioned and described as "ambiguous".

> *The important element is that the truck driver was warned about the incoming bicycle.*

3.3.7.1.2 Cyclists' opinions about the XCYCLE on-bike warning system

Participants expressed their perception about the system and described it as useful, even considering potential limitations, such as possible malfunction or false alarms. Some cyclists reported that the system would be useful for buses as well, since they are more frequent than trucks in urban areas.

> *Yes, it could be useful, even considering the possible malfunction of the system. Everything that makes the road safer for cyclists is useful.*

Furthermore, cyclists reported that they might not be able to hear the acoustic warning of the on-bike system because of the traffic noise.

> I don't know if the cyclist would be able to hear the alarm when travelling in traffic.

3.3.7.1.3 Possible effects of the usage of the system

<u>Risk</u>

Two main risks connected to the usage of the on-bike systems were identified by participants. The first is related to the possibility of the system of being stolen and used to deceive truck drivers. The second refers to the possibility of the system to be accidentally activated in the cyclist's bag (or elsewhere), hence causing false positive alarms in passing trucks even with the user not using a bicycle. The second risk identified becomes relevant only in case of a portable/removable version of the system.

> If the on-bike system were portable, people could forget it in their purses or bags causing false positives to truck driver's system.

<u>Trust</u>

Participants stated that they would trust the system. The on-bike system was described as reliable and not subject to interference. However, participants would not trust the system blindly in traffic. Over-reliance on the system was mentioned as a risk for both truck drivers and cyclists, in fact truck drivers might be prone to ignore the mirrors, while cyclists might tend to ignore traffic laws.

> I would trust the system signalling my presence to truck drivers, but I would always look at the road for incoming vehicles.

3.3.7.1.4 Improvements of the system proposed by cyclists

Portability was recommended as a feature for the on-bike system. Cyclists should be able to take the system with them. The system should also be able to detect vehicles approaching from the rear side of the bicycle. One participant stated that the in-truck system should be also available for cars and that the on-bike system should be able to detect cars as well. Lastly, participants agreed that the system should work between vehicles of different brands.

> I'd prefer to have the system installed on the outside of the bicycle, so I would be able to take it with me when parking my bike.

> The system should be installed on cars too and the on-bike systems should be able to detect cars.

The system should work between different brands. An in-vehicle system developed by a specific manufacturer should be able to identify a bike with a system from a different brand.

3.3.8 Discussion and conclusion

The aim of the semi-controlled field study was to evaluate the on-bike system with participants assessing their acceptance of and trust in the warning system as well as investigating effects of the warning system on behavioural changes. Altogether, 15 participants crossed the AIM research intersection 4 x 13 times (3 times without the system activated and 10 with the system activated). After each crossing, participants rated their perceived safety and criticality of the crossing situation. When the system was activated they also indicated the status of the on-bike system and the adequacy of the warning. At the end of each experimental block, participants indicated their trust in and acceptance of the system. In addition to the subjective data, trajectory and video data was recorded for each of the intersection crossing.

The aim of the focus group study was instead to gather qualitative data and give space to end users for open comments, suggestions and feedbacks. Videos showing the functioning of the system in right-turn scenarios were displayed to participants which then had to discuss and comment them following the interviewers' grid.

In the semi-controlled study, the analysis of the acceptance and trust rating showed that, overall, ratings decreased with experience. Participants rated the idea of the on-bike system positive, but the ratings decreased after using and experiencing the system. At the same time, the results of the adequacy analysis also showed that in more than half of the cases, participants did not agree with the status of the warning system, meaning that the on-bike system warned in situations when it was not necessary and also did not warn in situation when it would have been necessary. Even though the evaluation of the HMI was not part of the study, the design of the on-bike system may have also influenced the ratings. It was prominently mounted on the handle bar of the bicycle and not easily fitted to every handle bar. Lighting conditions may have also interfered with perceiving the warning.

The analysis of the safety and criticality ratings did not reveal any effect of the manipulation (i.e., on-bike system activated vs. deactivated) on the perception of the situation. Cycling style, on the other hand, may affect the ratings. Cyclists who indicated to be defensive felt the safest while crossing the intersection and also rated the situation as at least critical. The analysis of the number of critical situations showed that defensive cyclists had fewer critical situations than offensive cyclists, but not as the neither nor group. At the same time, this group felt the least safe and rated situation more critical than the other cyclists. Safety ratings also did not increase over time. This indicates that participants did not start to feel safer riding with the system.

Contrary to the assumption, behavioural changes over time due to the manipulation could also not be observed. Participants changed their intersection approach behaviour due to the on-bike system. Results in the literature (Sagberg, Fosser & Sætermo, 1997; Hoedemaeker & Brookhuis, 1998; Wilde, 2013) suggested that, over time, participants would adapt their approach speed, meaning that they would cycle faster and riskier. Those effects could not be revealed analysing the approach speed. Cycling style, on the other hand, appeared to affect the way participants approached the intersection.

Overall, the on-bike system was tested in a setting in which the cyclists had priority over the motorists. It may be that cyclists need not see the necessity of the warning system in this particular situation as motorists needed to give way to cyclists. The system may be tested again in a scenario where neither motorists nor cyclists have priority.

Results from the focus groups highlighted positive ratings of participants regarding trust and usefulness when evaluating the system without actually using it, which is in line with the semi-controlled field study results. Furthermore, the focus group study has been useful to highlight end users' concerns, which are mainly related to security reasons (e.g. theft and malicious use of the system) and shed light on users' wishes for further design improvement, which revealed to be feasible (e.g. portability, possibility to detect cars).

3.4 Truck system

3.4.1 Introduction

In urban traffic, cyclists run a relatively high risk as they are highly vulnerable due to the lack of protections. Even though there has been a reduction of accidents and fatalities in traffic in total, cyclists account for a stable or growing share of persons injured in traffic accidents. Around 2000 cyclists are killed in traffic accidents with motorized vehicles every year in Europe and a significant proportion of the accidents take place at crossings.

Situations with trucks and cyclists are specifically difficult and risky. The truck drivers have limited field of view of their vicinity, especially on the truck's inside, i.e. the right-hand side of the truck (left-hand side in countries driving on the left side, for example the UK and Japan), also called the "blind spot", and, therefore may not see cyclists close to the truck. Cyclists close to the truck are not able to see the truck driver in order to seek contact, to signal his/her presence or to anticipate the truck drivers' intentions and actions. A specifically dangerous situation is at crossings when the truck is turning right and there is a cyclist in the blind spot next to the truck. The cyclist may be overrun by the truck or trailer when the truck is turning right.

In the XCYCLE project an in-vehicle warning system was developed, giving the truck driver a warning about cyclists close on the truck's inside. The in-vehicle warning provides visual and acoustic messages to draw the truck driver's attention to cyclists in the blind-spot and, thus alerts the driver not to turn right until the area is clear and safe (see Figure 5).

3.4.2 Purpose

In this study the warning system was evaluated in focus group interviews with truck drivers as well as with cyclists. The purpose of the study was:

- To gather the participants' descriptions of their experiences from critical traffic situations (trucks and cyclists in crossings)
- To evaluate the warning system from a user perspective (truck drivers and cyclists) based on the participants' perceived usefulness, trust and risks of the system, its benefits and drawbacks etc.
- To collect the participants' comments and suggestions for further improvements of the warning system

3.4.3 Method

Below, the recruitment, running and the analysis of the focus group studies are described. It should be noted that focus groups were conducted both in Sweden and Italy, and the recruitment and demonstration differed slightly between the two locations (see below).

3.4.3.1 Recruitment and procedure

Sweden
In total, six focus groups were recruited, four with truck drivers and two with cyclists. The groups consisted of four to six participants each.

The truck drivers were recruited from a database that VTI holds for its simulator studies. Hence, the truck drivers were ordinary drivers, holding a variety of different jobs within truck driving, who at some point had participated in a simulator study. All of them lived and worked in or around Gothenburg. The cyclists were recruited using an advert in social media. All that clicked on the advert, appearing as "Cyclists wanted for participation in a focus group study", were asked to fill in a short screening questionnaire. In the recruitment, cyclists who used their cycle in some extend for transport purposes (e.g. not only or training purposes etc) were sought for. The rationale for this was that we wanted participants that had some experience with biking in urban areas where interaction with other road users (e.g. trucks) naturally occurred. Otherwise an even distribution between gender and age were sought for in the recruitment of the groups.

After welcoming the participants that were going to participate in the focus group discussion, they were given information about the study as well as ethical principles. They were also given possibilities to ask questions and signed an informed consent to participate. The participants were told that the interview would be recorded, that their participation was completely voluntary and that they could leave at any time without motivating why.

After the introduction, the situation and the XCYCLE truck system was demonstrated using a virtual reality (VR) environment. The urban scenario was built with the game engine Unity 2017 and the participants wore an HTC Vive Headset to experience the scenario. The demonstration was a pure demonstration; i.e. no interaction was either required or possible by the participants.

Figure 72: Participant in VR demonstration

For the truck drivers, the demonstration implied they were placed behind the wheel, inside a virtual Volvo truck cabin, with the XCYCLE system mounted in the VR-cabin. The placement of the warning lights was in in the middle of the cabin, on the dashboard as suggested in WP3, and the warning sound was a bicycle bell. The participants representing the cyclists were instead positioned on a bicycle, in a bicycle lane, adjacent of the truck, to the right. Hence, both the truck drivers and the cyclists experienced the situation from their "natural" perspective as they would have done in real traffic. However, nor the truck drivers or the cyclists were active in a sense that they did any physical movement in order to accelerate, turn the steering wheel, pedaling etc. Instead they passively followed the scenario but could look around in the VR environment by turning their head as they would have done in the real world.

The situation demonstrated was a truck coming towards an intersection with the intention to turn right. At the same time a cyclist appeared from behind, just to the right of the truck but in a designated bicycle lane, with the intention of continuing straight in the intersection. The truck drivers experienced this situation several times each, sometimes with the XCYCLE system switched off, and sometimes with it switched on, giving a warning by light and sound. The cyclists experienced the situation in two different ways; one where the truck stopped and let them by, and one where it turned in front of them, thus forcing them to stop.

Italy

In total four focus groups were conducted, three with truck drivers and one with cyclists. A total of nine truck drivers and ten cyclists participated to the focus groups.

To recruit truck drivers to participate in the focus groups we contacted, by phone, more than 15 private organizations as well as regional transport associations. After establishing the first contact, we sent more detailed information to those who showed interest in the project, on the activity we wanted to pursue and on the system itself. Then, the date, the place, and the number of participants to the focus group were agreed. The Cyclists were recruited in an informal way following the snowball strategy, where each participant who agreed to take part in the focus group recommended other potential participants.

At the beginning of each session, all participants signed an informed consent form. Participants were shown a presentation of the XCYCLE systems with a brochure and a video, provided by VTI and VOLVO, of the use case scenario from a previously recorded VR experience and from a real-life simulation. The use case scenario depicted a traffic situation in which a truck is about to turn right in an intersection while a cyclist is approaching on the right side of the truck. When the cyclist is in range, the system signals the risk of collision to the truck driver. The latter stops, lets the cyclist pass, and after turning right continues his journey. The moderator then followed a set of guiding questions formulated beforehand to elicit responses from the group.

Figure 50: Moderator showing the in-truck system functioning to participants

3.4.3.2 Topics in the Focus Group Interviews

To address the aim of the study, the following topics were discussed in the focus group interviews with the cyclists and the trucks drivers, respectively.

Truck drivers:

- The truck drivers' experiences from similar critical traffic situations
- What makes the situation critical
- The truck drivers' opinions in general about the in-vehicle warning system in the truck
- Trust in the warning system
- Risks associated with the warning system

- The truck drivers' opinions and impressions of the interfaces; the visual and the sound (character, placement, design, intensity etc.)
- Pros and cons of the warning system
- Recommendations for further improvements of the warning system

Cyclists:

- The cyclists' experiences from critical traffic situations
- What makes the situation critical
- The cyclists' opinions in general about the in-vehicle warning system in the truck
- Trust in the warning system
- Risks associated with the warning system
- Pros and cons with the warning system
- Recommendations for further improvements of the warning system

3.4.3.3 Analysis

The analysis was based on a content analysis approach (Kvale, 1997; Patton, 2002) on verbatim transcriptions of all interviews. In the first stage of the analysis, all interviews where read though several times to get a holistic overview of the dataset. Then followed an initial coding process, where meaningful statements where sought for that where connected to the aim and research questions of the study. These statements where, at this stage assigned, different codes. The codes were then gone through and similar codes were merged, hence the number of codes where reduced at this stage. Then the codes were grouped and sorted into different categories. The final categories are the headings which make up the results section. The main emphasis of the analysis was to describe "the general, common voice" from the focus group sessions, rather than to focus on single statement from individuals. However, when individuals expressed things that was considered of special interest and relevance for the study, this was included in the analysis.

3.4.4 Results

Below the results from the focus groups with the truck drivers and cyclists respectively are presented.

3.4.4.1 Truck Drivers

3.4.4.1.1 Common to have experiences of the critical situation

All drivers state that they recognize the critical situation very well. It is a situation that everyone has experience of as truck drivers. Those who drive in urban areas daily, express that it is a situation which they encounter every day. Hence, according to the drivers, the more driving in populated areas, the more common the situation is experienced.

> It happens every day. And it requires you to be alert because you can't take for granted that they will stop.

In the quote above the driver states that one must be alert all the time, and that counting on that cyclists will stop when turning is nothing you can do. Drivers also point out that encounters are more common in the morning and the afternoons, which correlates diurnal traffic peaks.

The situation is experienced as critical by the drivers for a number of different reasons. The driver is often seated relatively high up, with no rear side-windows to glance through as in a car, and with mirrors that have wide blind spots, which make it harder to see cyclists compared to e.g. being seated in a car. According to drivers, the most difficult position to discover a bicyclist in is when he or she is positioned adjacent to the front wheel of the truck and forward towards the bumper:

> If they are right in front. There it's very hard to discover them. They can be alongside the front and with the mirrors, you don't see the cycle there.

In this area, the seating position and the mirror configuration of a truck make it difficult to discover a bicyclist, the drivers point out. Some drivers also mention that rainy conditions and darkness make it more difficult to spot bicyclists, especially as some of them don't have lights and/or reflectors. In terms of the characteristics of the infrastructure, the most difficult configuration is experienced to be when there is a bicycle lane in shared space with the motorized traffic, or bicycles in the same space without a designated lane. In that situation the truck and the bike are close to each other, which for the truck driver, make the bicyclist difficult to detect. The drivers also add that detecting a bike is harder when approaching an intersection, with the intention of turning right, when there is a green light and they roll forward, compared to when first have stopped for a red light and then passing the intersection. In the latter they point out that, the time standing still gives the them some extra situational awareness of what is going on, as well as longer time to complete the turn:

> If you're standing still and waiting for the light to turn green you have a chance to see him or her. The cyclist. But if you come rolling you have feel that you have less control.

Another aspect that the drivers talk a lot about throughout the interviews is the lack of knowledge and respect they experience that cyclists have in traffic. According to the drivers, cyclists often continue straight out in an intersection without looking, not following traffic rules or behaves recklessly in general. This finding is further reported under 0.

3.4.4.1.2 In general, positive attitudes towards the XCYCLE in-truck warning system

The drivers expressed positive attitudes to the system in general. As the use case is regarded as a critical situation, a system helping them in detecting bicyclists, and thus have the potential in reducing injuries and fatalities, is seen as helpful and much welcome.

> As a support system that helps to detect it would be accepted and welcomed among drivers.

The bicycle bell warning sound was put forward as nice and intuitive. However, a few drivers expressed concerns that all the technology packed into today's trucks posts a risk that the driver might be "overloaded" with all sorts of sounds and LEDs flashing. They also moved forward that that there could be a risk that drivers start trusting the system too much and thereby not scanning the intersection as rigorously as before. All drivers still thought that the pros with the having the system, would overweigh the cons by far.

> Of course! There is enough with one life saved for the system to have paid itself off.

Visual interface – nice and intuitive or somewhat misplaced

The visual warning signal composed by LEDs was considered both appropriately positioned, intuitive, and easy to see, as well as difficult to observe and too far from the truck's steering wheel. The drivers that held the latter opinion, suggested to move the LED system closer to their line of sight to make it easier to notice and also to make it slightly bigger. Some participants were also somehow concerned about the LEDs visibility during daylight, and about its brightness in the night, with the risk of being blinded while looking at it.

> The LED should be closer to the driver because even if we're not looking directly at the system it would be in our line of sight.

Audio interface – bicycle bell very intuitive

The auditory warning, the sound of the bicycle bell, was highly appreciated by the truck drivers since it would allow drivers to quickly recognize the incoming danger. Furthermore, participants expressed very positive attitudes towards the system's directional sound when detecting incoming bicycles. However, one participant stated that the type of sound wouldn't be relevant in the long run; any sound would fit the system as long as the driver learns to recognize its meaning.

> The ring bell as warning sound is amazing.

3.4.4.1.3 Possible effects of the usage of the system

Risks

Guided by their experience, truck drivers detected various risks connected to the use of the system. Participants reported that truck drivers may over rely on the system and pay less attention to the road. This phenomenon, named by participants as "habituation effect", was reported as a possible risk connected to the use of the system. As truck drivers, cyclists may rely too much on the in-vehicle system to prevent collisions and may behave recklessly. Also, truck drivers were concerned about false positive alarms. The majority of truck drivers reported that the best way to counteract the negative behaviours of cyclists would be to oblige them by law to have the system installed on their bicycles. Also, it would be of great importance to extend the use of the system to every truck other than to every bicycle. Maybe, the only risk connected to the system is to make a habit to totally rely on it.

Trust

All participants, regardless of how much they did liked the system, reported that they would not blindly trust it. This trust issue was not specific for the XCYCLE system, in fact truck drivers reported that they would never totally rely on a technological system when driving. It would only be a support for the driver and not a substitute. Participants stated that they would always check truck's mirrors before turning or performing any other manoeuvre, even if the system signals that there are no risks.

> You can't just rely on the system, you have to check the road yourself before turning. Anyway, the system would be with no doubts helpful to drivers.

> I won't trust it completely. I can't rely on it completely. Everyone and everything can do mistakes, even the system

3.4.4.1.4 Improvements of the system proposed by the truck drivers

One topic that was discussed during the interviews was what recommendations, as drivers, that they wanted to give to the developers of the XCYCLE in-truck system. A few recommendations emerged during this part of the discussion (even though they thought it was somewhat difficult without having driven with the system for some time). One was that there should be a warning light indicating if the system for some reason become faulty, so that the driver knows this when driving. Another was to not make the system possible to switch off for the drivers. If possible to switch off, they foreseen that some drivers would do so and thus possible positive effects with the system would be lost for those drivers. A third recommendation was to, in the future, integrate the system’s user interface with the head-up display that new trucks increasingly will be equipped with.

During this topic, a question was discussed whether the system should intervene and automatically brake the truck, or not, in a situation where if no action was taken by the driver would lead to a collision with a cyclist. The drivers had different thoughts on this. Some thought it should stay as a warning system and not intervene. Reasons for this was for example that harsh stops could risk that vehicles behind could run into the truck, or risks related to movements of the cargo loaded on the truck. However, most of the drivers held the opinion that the system should brake automatically, as a last resort, to prevent the cyclist from being injured or killed. They pointed out that drivers are responsible for securing the cargo well so that it does not move around in case of braking, and that vehicles behind should keep a safe distance by law. The dominant thought among the drivers was thus that the system should auto brake as a last resort, even though some were somewhat sceptical.

3.4.4.2 Cyclists

3.4.4.2.1 Experiences as cyclists in similar critical situations

The participants in the cyclist groups described the situation in urban traffic as increasingly demanding and described experiences from many critical situations – not only with other cars and trucks, but also with cyclists and pedestrians. The participants also said that cyclists often neglect to have lamps and reflectors, which makes it difficult to see them in darkness. The participants also had experiences from cyclists that take chances and put them self in danger.

> In fact, many people don’t use a bicycle because they’re afraid of the traffic

> If the person on the pavement will suddenly step out into the road, or if that cyclist will stop unexpectedly

> They do not (always) follow the traffic rules

A recurrent matter in the interviews with the cyclists was the importance of direct eye-contact with the truck driver in order to anticipate his/her actions. However, direct eye-contact was experienced as very difficult to get. Truck drivers cannot see much of their vicinity due to their position high up from the ground and it is impossible to call for their attention. A strategy to handle this problem mentioned by the participants is to consider oneself as invisible. When driving close to trucks it is also important that you as a cyclist keep an eye on the turning indicators. If you can’t see them, you may find yourself in a dangerous situation if the truck turns. This situation is especially dangerous if the truck has a trailer which cuts the corner when the truck turns.

Another critical situation can happen even a truck stops and let the cyclist pass before turning, but there are other vehicles behind the truck that drive right in front of you

The participants also mentioned an upcoming critical situation with the increased popularity with electric bicycles. These bikes are often much faster than regular bicycles and, therefore, approach trucks very fast, resulting in less time for the truck driver to detect the cyclist who is suddenly next to the truck.

3.4.4.2.2 Cyclists' opinions about the in-vehicle warning system

Overall, the participants thought the in-vehicle warning system was useful and that it could contribute to increased safety and fewer accidents. They thought the advantages with the system overruled the disadvantages, considering the many critical and dangerous situations cyclists encounter daily in urban environments and at crossings. The participants also thought the warning system could support truck drivers in situations where they have limited field of view. The participants' main concerns, though, were about the warning system's reliability and capability.

> Any system that can increase traffic safety is good.
>
> What if there is a malfunction in the system?
>
> If the driver doesn't stop, will the truck stop anyway?
>
> The system signals my presence, but the truck driver could be distracted and ignores the warning.

3.4.4.2.3 Possible effects of the usage of the system

Risk

The participants were also concerned about risks with this kind of warning system. For example, a mix of trucks with and without the warning system could cause critical situations: if a truck does not have the warning system, but the cyclist thinks it has the cyclist may behave in a less cautious way. The cyclists' lack of knowledge of the warning system's capabilities and limitations could also be a risk. The participants also mentioned over-reliance of the warning system as a risk for both for cyclists and truck drivers. For example, cyclists may drive straight forward, because the they think the truck driver will be warned and stop, while truck drivers may think they can turn right (and not look in the mirrors), because the warning system has not given any warning. False alarms could also make the truck drivers less attentive to real warnings. In addition, the warning system could be malfunctioning due to technical problems, bad weather, dirt on the sensors etc. and not warn the truck drivers.

Trust

The participants mentioned that they don't trust drivers (car and truck) in general, e.g. some don't use the turning signal, they ignore you or that they have a careless driving behavior towards cyclists. The participants also said they don't always trust technical solutions, especially when their life is dependent on it.

The risks associated with the system are also related to the sense of trust in the warning system. As a cyclist you need to know how the warning system works; its capabilities, what it can do, what it cannot do, what the truck drivers must do etc. As a cyclist you also need to know if the system has detected you. This means that the system should provide some kind of feedback to the cyclists. However, some participants seemed to have a different opinion:

> I want a receipt that the system and the truck driver have seen me and will stop and not run over me.

> It might be best not to know if the trucks have the system or no in order to stay cautious when driving in traffic

> I would trust the system signaling my presence to truck drivers, but I would always look at the road for incoming vehicles.

3.4.4.2.4 Improvements of the warning system proposed by the cyclists

The participants proposed several ideas about how to improve the warning system, i.e. that the warning system should also include external communication/warnings to the cyclists in addition to the in-vehicle warnings to the truck drivers. Their ideas referred to two main areas:

1. *Communication*
    a. System's capability:
        i. The system warns the truck driver
        ii. The system intervenes if the truck driver does not stop/brake
    b. The truck driver's intention, e.g. stop, turn, drive straight
    c. That the cyclist is in the "blind-spot" and cannot be seen by the truck driver
2. *Confirmation*
    a. The system confirms to the cyclists that it has detected the cyclist
    b. Truck driver has noted the cyclist and will act/stop

Suggestions proposed by the cyclists *How to realize the ideas*:

- A lamp or strip of lamps placed on the side of the truck, which has red light as default and changes to green light to communicate that that the truck has stop and you can drive/pass with your bicycle. Or smileys that communicate the same messages.
- A device on the bicycle that communicates with the truck's warning system and that gives you information stop/pass etc.
- Red lights or other devices that are seen only when you as a cyclist is standing in the blind-spot.
- A camera mounted on the truck that covers the Blind-spot and a monitor in the cab
- Automatic emergency brake if the driver doesn't stop

3.4.4.3 Non-warning system related factors

3.4.4.3.1 Attitudes

Drivers vs Cyclists and vice versa

In all focus groups (both in Sweden and Italy), when the drivers discussed experiences from the critical situation, relatively strong negative attitudes towards cyclists were expressed. The drivers depicted cyclists as irrational and unpredictable who lacks common sense on how to behave in traffic. According to the drivers they often cycle against red light, cycle just in front of the truck, use their mobile phones whilst cycling, and believes that they have right of way all the time. They were also described, by the drivers, to have poor understanding of heavy vehicles, and in need of education or training (which should be mandatory) to behave better in traffic. It should be noted that not every driver expressed those attitudes. They were, however, strikingly common in the groups.

Similar attitudes were recorded in the groups with the cyclists, who blamed the truck drivers for "owning" the street and ignoring the cyclists.

> They just drive straight on …we (cyclists) have also rights in traffic… why can't they just use the turning indicator – can't be that difficult…

These kind conflicts between truck drivers and cyclists can trigger irritation at both parties and may fuel the attitude of *Us and Them*, meaning that "They" are the main cause to the critical situations and that "They" should change their behavior. Both truck drivers and cyclists stated that they manage to handle critical situations thanks their sense of preservation.

Some cyclists also expressed understanding of the truck drivers' situation, though, e.g. that the truck drivers have difficulties to see what is next to the truck due to their elevated position and their limited field of view.

> They are just ordinary people who don't want to run over anyone.

Although a deeper analysis of this finding falls outside the scope of this report, a few things are worth mentioning. The findings described above can, on a basic level of analysis, be interpreted as there is a lack of understanding of "the others'" perspective in traffic. One reason for this can be that there is a lack of experience from being "the other". Many truck drivers did not cycle in urban areas for themselves, and the cyclists did not drive trucks for themselves. This lack of understanding of the different needs the other has is also held back because of the type of communication that is possible between truck drivers and cyclists in traffic. The type of communication possible is scarce and (in most cases) non-verbal and limited to indicators, signals and sometimes facial expressions. As a ground for establishing mutual understanding the premise is thus weak. Another way to understand how these attitudes arise is related to the design of the infrastructure. For conflicts to arise in the first place, there must be something that serves as a ground for them, i.e. that generates them. Here, the actual design of the infrastructure can be one part of this ground. For example, poor designs that make it ambiguous on how to behave as cyclists or drivers, badly placed and/or not synchronized traffic signals and no or bad separation principles between cyclists and motor vehicles. Such cases can be seen as a rational starting point for conflicts to arise which are then facilitated by lack of mutual understanding and poor communication possibilities between drives and cyclists.

Technical solutions

New and innovative technical solutions were generally seen as positive and useful by participants, mostly in the automotive field. Some expressed sceptical views though criticising the general trend to incorporate more devices in the truck. Truck drivers reported to appreciate new technologies, especially if they're capable to reduce risks and dangerous situations. Given their work, participants were well informed on technical solutions regarding trucks and cars, and usually had positive attitudes about them. Participants reported that they always try to have the best technology available installed on their truck, and even if some truck drivers reported to dislike or usually don't use certain technical solutions they all prefer to have it installed on the truck than not be equipped with it.

> Without technology there are more risks.

3.4.4.3.2 Knowledge of traffic rules

In the interviews some participants (cyclists as well as truck drivers) it became clear that not all were sure about the traffic rules. For example, in the cyclist groups some of the participants were not sure about:

- Who should give way to whom in the different situations
- If truck drivers have to use the turning signal
- If cyclists have to indicate before turning
- If the rule giving way for vehicles coming from the right also applied for cyclists etc.

Other cyclists stated that knowing the traffic rules is key for everybody's safety.

> Don´t break the law, don't drive on red lights and use the turning signal when you turn. If people drive in a predictable manner, the safety risks will decrease considerably.

3.4.4.3.3 Infrastructure

Some critical situations were according to the interviewees caused by the lack of development and maintenance of the traffic infrastructures. The network of bicycle lanes is often limited and the cyclists have to drive on the roads. The bicycle lanes are often rather narrow and not separated from other users such as pedestrians, baby strollers, mopeds etc. Moreover, the maintenance is often insufficient, e.g. there is a lot of gravel on the lanes, especially in spring (gravel is used to prevent slippery surfaces in winter) which can cause punctures, but also long braking distances and risks of falling due to the rolling gravel.

The cyclists said they would like to have cycle lanes separated from the roads, which would increase the distance to the truck and provide more room and time for the cyclists to see the driver and to avoid dangerous situation when the truck turns right at a crossing. Traffic lights would also make the situation safer.

3.4.5 Discussion

The focus groups with truck drivers and cyclists provided valuable information about how to improve the XCYCLE in-truck system. Apart from learning about the perceptions on the presented system and about the traffic situation described in the use case scenario, we gained valuable insights about issues not considered previously (e. g. the needs for manoeuvring of trucks or the suitability of urban roads for them). Finally, the perceptions that the truck drivers have of the cyclists is a valuable knowledge for understanding the relation between truck drivers and cyclists as groups of road users. This will help guiding efforts aimed at improving road safety not only by enhancing the promotion strategy of the XCYCLE system, but also by facilitating mutual recognition and respect of needs of these two social groups.

From the described experiences and perceptions of the participants emerged that the use case scenario taken into consideration is quite common. The perception of cyclists as vulnerable road users is widespread among truck drivers and cyclists, and the situation described as use case scenario is commonly recognized as dangerous. The XCYCLE in-truck system was viewed as useful for increasing traffic safety and cyclists agree that they would trust it in traffic. Despite these opinions, cyclists stated that their cycling behaviour would not change if they were using the system.

Truck drivers perceived cyclists as dangerous road users due to their lack of respect for the road rules. The majority of truck drivers appreciates the system's functioning and its characteristics, even though some risks and doubts connected with its use were identified. Also, participants suggested to move the LED closer to the steering wheel and to add a camera and a video to the system. Safety improvement was considered to be of crucial importance and appears to be a strong factor which may influence truck drivers' decisions to install and use the XCYCLE system. Even if the majority of them reported that they would not blindly trust the system they would still prefer to have it installed on their trucks.

3.4.5.1 Methods discussion

According to Lincoln and Guba (1985) the trustworthiness and quality of qualitative research need to be judged by other criteria than quantitative studies. They have proposed *credibility*, *dependability*, *confirmability* and *transferability* as useful concepts to discuss and establish a study's quality. Without describing these concepts in detail, the following have been done to establish trustworthiness in this study:

We conducted several focus groups with truck drivers and cyclists in two different countries (Sweden and Italy). The focus groups were made relatively heterogeneous in terms of age and gender, apart from the truck drivers where the majority were men. The truck drivers represent a broad spectrum of experience as truck drivers, as well as different trades. The cyclists also represent a broad spectrum, although limited to those who use their bike for transport in urban environment.

In total, eight focus groups where conducted, six with truck drivers and two with cyclists, in both Sweden and Italy. For the truck drivers, saturation was achieved, meaning that no new data of interest came out towards the end of the data collection. However, one limitation is that only one focus group with truck drivers were held in Italy. Still, the data from this matched the ones in Sweden very well. The number of focus groups with cyclists were three in total, two in Sweden and one in Italy. Even though the groups contributed with much valuable data for the study, saturation was probably not achieved. Hence, there cannot be ruled out that if more focus groups had been conducted, more data would have come out. This obviously has to do with cyclists being a diverse group in general.

When it comes to judge whether a qualitative study could be considered valid outside the context it was collected in, Lincoln and Guba (1985) speak about transferability. According to them, the degree of transferability of a qualitative study is a direct function of the similarities between the context in which the study was made, and the context that one wishes to transfer the study to. The hypothesis is that there is a high degree of transferability to a context that matches the one in which the study was made in. The question for the present study is therefore which contexts in reality that match the context in which this study was made. Considering that we got saturation of the data, and that the data collected in Italy, with a different culture compared to Sweden, was similar, we believe that this study has a relatively high transferability in general. The fact that the groups in Sweden and Italy matched each other well, gives support for that its results can also be transferred to other parts of Europe; hence its results should be applicable in other European contexts. However, there cannot be ruled out that the results will have less transferability to some contexts. Differences in cultures among truck drivers and cyclists for sure exist in other countries, and what implications this might have is difficult to judge. Nevertheless, we believe that a good starting point is that there are aspects in this study that is applicable and should be taken into consideration when deploying the XCYXLE in-truck system across Europe.

3.4.6 Conclusions

The following conclusions can be drawn from the focus group study of the truck system.

Truck drivers:

- The truck drivers considered the warning system as useful and helpful. The pros were estimated to over-weight the cons; truck drivers would like to have the system installed on their vehicle.
- Cyclists' lack of knowledge of trucks' needs on the road and their disrespect for traffic laws were mentioned by the majority of truck drivers as a main problem while driving.
- The truck drivers identified various risks related to the in-vehicle warning system, for example:
    - Habituation effect, or over-reliance, may lead to risky behavior. Both truck drivers and cyclists may pay less attention to the road due to the over confidence in the system.
    - False positive alarms may lead truck drivers to ignore the system in case of true alarms
    - Possible technical malfunction could interfere with the warning system efficiency
- The truck drivers reported that the warning system could make them more careful on the road, anyway their driving behavior would not be modified by the system. Anyhow, they thought that truck drivers in general may be influenced by the system.
- The truck drivers reported that they would install the in-vehicle system, but they wouldn't blindly trust it since even machines can make mistakes. This trust issue regards every technological system in the automotive field, not only the XCYCLE system.

Cyclists:

- The cyclists were generally positive towards the warning system. Aanything that can make the situation safer is good. The pros were thought to overweight the cons.
- The lack of communication between the truck drivers and the cyclists was mentioned as a main problem in situations where trucks and cyclists co-exist.
- The cyclists mentioned several risks associated with the in-vehicle warning system, for example:

  - Over-reliance of the system could make truck drivers as well as cyclists less attentive and less careful in similar situations as presented in the focus group interviews
  - False alarms to the truck driver could make him/her less attentive and, at worst case, ignore true alarms.
  - Technical malfunctions (blocked sensors etc.) could degrade and shut down the warning system
- The cyclists thought the warning system would probably not lead to changes in their cycling behavior, for example being less careful (..., *but some might be*, according to some participants)
- The cyclists thought the traffic infrastructure is an important factor to prevent accidents and it needs to be better designed, for example separated bicycles lanes, and better maintained.
- The cyclists' trust in the warning system seemed depended on factors such as knowledge about how the warning system works; its capabilities and to get information about that the system has detected the cyclist.

1 Cost-benefit analysis (T6.4)

1.1 Methodological Approach

Cost-benefit analysis (CBA) allows us to produce an overall assessment of the socio-economic impacts of the XCYCLE systems. We use CBA to measure and value the benefits and costs of the intervention, and we do this essentially in line with the approach recommended by the EU FESTA Handbook (Barnard et al., 2017), and in a similar form to recent CBAs of other road user support systems (e.g. 'ecoDriver' - Jonkers et al, 2018). The methodological approach here is tailored to the context of XCYCLE, focusing on cycle-vehicle collisions at intersections. In particular, the willingness-to-pay (WTP) experiments described in Section 2 were used to understand the perceived benefit of the systems as a whole - which is important because the systems are new, and because they have multiple effects on cyclists which may interact, so a holistic measure is needed to capture the total impact.

The FESTA Handbook defines a Field Operational Test (FOT) as "A study undertaken to evaluate a function, or functions, under normal operating conditions in road traffic environments typically encountered by the participants using study design so as to identify real-world effects and benefits" (Barnard et al., 2017, p. 14). Its final section is dedicated to the conduct of CBA: the steps are to first perform case-study scale analysis, and then to scale-up to the EU level using statistics or simulation modelling, comparing the scenario with the system in place to the scenario without the system. It is necessary to assume growth of market penetration over a period of years, and to approximate the costs of accidents and the system itself. Different future scenarios may be tested to assess the sensitivity of the results.

1.1.1 XCYCLE CBA Framework

The CBA is constructed as a 'stakeholder CBA': we identify the impacts on specific incidence groups before summing to the societal level (Table 24). This allows us to understand more about the attractiveness of the intervention to each group.

Table 24: CBA framework for XCYCLE

Incidence group	***Impacts***
Infrastructure Manager (IM) – the road authority	Costs of installing, maintaining and operating infrastructure components (additional costs)
	Transfers from Government (to fund additional costs)
Cyclists	Costs of purchasing, maintaining and operating on-cycle components (additional costs)
	Individual benefits of accident reduction
	Benefits of time, effort and discomfort saved
Drivers (or owners) of motorised vehicles	Costs of installing, maintaining and operating vehicle components (additional costs)
	Benefits of accident reduction
Industry - OEMS	Revenues
	Costs of installing vehicle components (additional costs)
Government	Healthcare and other cost savings
	Transfers to fund infrastructure changes

The overall societal impact will be measured using a Net Present Value (NPV) and Benefit:Cost Ratio (BCR), which provide an *absolute* and a *relative* measure of the value created by the systems respectively. The NPV is simply the sum over time of the discounted benefits minus the discounted costs, whilst the BCR takes the benefits and divides these by the costs of delivering the system, so that a 'value for money' measure emerges.

$$NPV = \sum_{t=0}^{T} \frac{\sum_i B_{ti} - C_{ti}}{(1+r)^t}$$

where t is the year, starting from the base year, until the final year of the appraisal period;

B_{ti} and C_{ti} are the benefits and costs of the system in year t, to group i ;

i include cyclists, other road users, industry and government;

r is the discount rate - the values of this and all other parameters are set out in the following section.

$$BCR = \frac{\sum_{t,i} B_{ti}/(1+r)^t}{\sum_{t,i} C_{ti}/(1+r)^t}$$

In this case, the *i* may be focused on a particular group. The BCR is particularly useful in measuring the success of these systems for each of the stakeholders, so we will report the BCR where appropriate for cyclists, truck operators, industry and government.

1.1.2 CBA Parameters

This section sets out the general parameters and assumptions which were used in the CBA for XCYCLE. Wherever possible, these were grounded in EU guidelines on cost-benefit analysis, to maximise comparability with other EU research, and studies in traffic safety and intelligent transport systems.

The discount rate was set at 3% (real), the same rate as recommended by the FESTA Handbook (Barnard et al., 2017). This is a consensus rate that has been the default in European CBA of transport systems through Bickel et al. (2006) and Ricardo-AEA et al. (2014). The official EU Impact Assessment Guidelines (European Commission, 2009) set a different rate of 4% (real) for all impact assessments of policies, however since 2009, some of the drivers of social discount rates have changed, in particular economic growth and expectations of future real growth have declined, and interest rates (not a direct determinant of social discount rates but a comparator) have fallen markedly. Looking ahead to a possible future scenario where economic growth strengthens, and interest rates begin to rise again, we opted to use 4% as a sensitivity test to the 3% social discount rate.

2015 was chosen as the base year for prices and discounting in the CBA. A recent year for which full data is available is usually chosen as the base year - 2015 fits this requirement. Any data that was based in other price years was converted to 2015 prices using the Consumer Price Index (CPI) which was sourced from Eurostat. The index was forecast up to 2020 based on applying the average change in the CPI from 2002 to 2017 of 1.8% per annum. Real GDP growth up to 2017 was also sourced from Eurostat and forecast values up to 2020 were calculated based on applying the moving average of the growth in the three preceding years.

Cost inflation was estimated by comparing the CPI and the Construction Production Price Index from Eurostat. Comparing the two indices from 2002 to 2017 showed that the real increase in construction production costs was 0.35% per annum. This value was used to forecast the real cost change of installation and operating and maintenance (O&M) costs over the appraisal period for each scheme.

The marginal value of time used for the calculation of travel time savings was €12.50/hour for 2015 in 2015 prices, which is the value for non-business trips in the EU Guidance (Ricardo-AEA, 2014). It was assumed that the value of time would increase in real terms by 2% per annum, reflecting expected GDP growth. To check the suitability of these values for the cycling context, comparisons were drawn with other values, in particular from Borjesson and Eliasson (2012) and Van Ginkel (2014) who conducted choice experiments focusing on cyclists' values of travel time saving. Borjesson and Eliasson found a value of €15.9/hour on street in Sweden, and €10.5/hour on cycle paths, based on respondents in Stockholm. Van Ginkel found €13.43/hour for commuting on standard cycle routes in the Netherlands, and €10.26 for other non-work trips again under standard cycling conditions. These values provide support for the chosen CBA value of €12.50/hour across commuting and other non-work trips. Other marginal values, where needed, are based on Ricardo-AEA (2014), or the specific cycling studies mentioned (Borjesson & Eliasson, 2012, and Van Ginkel, 2014).

The time period for the CBA is based on expected life-cycles of relevant ITS equipment and vehicles: of particular relevance are bicycles, detection and computing equipment, and trucks. 15 years is used as the default, and 10 years as sensitivity test. 13.6 years was the average economic life of a truck measured in the ecoDriver project (Jonkers et al., 2018); 15 years is a typical expected economic life for VMS electronics and electrical components (RMS, 2014); consumer electronics typically have a shorter life of 13-14 years or less (Prakash et al. 2015); while the economic life of a bicycle is under-reported, bicycle frames have a long life (~20-30 years) however electronics mounted on the bike may have much shorter lives. Oguchi et al. (2010) give 14.7 years as the average service lifespan of a bike. There is a risk that any technology offered for XCYCLE systems - even infrastructure-based systems - is quickly made obsolete by a subsequent generation of technology: the 10-year sensitivity test addresses this risk. For comparability, all systems are appraised over the period 2021-2035 (or 2021-30 in the sensitivity test) for operations. It was assumed that the equipment for each scheme will be constructed and installed in 2020 and the schemes will become operational at the start of 2021.

1.2 Inputs to the CBA

1.2.1 Green Wave

For GreenWave, data was provided by RUG for a set of variables including: numbers of cyclists using the intersection during specified time periods; rates of red-light negation (violation); numbers passing through green without waiting; waiting time at red; and arrival time headway. Additional data was provided by VTI on stopping behaviour, speeds and acceptance in a semi-controlled study. DINNIQ provided further information on traffic control optimisation and system costs.

It was assumed that the system would require the installation of four sensors and two variable message signs (VMS) at each signalised intersection. Cost data from the ITS Cost Database (US DoT, 2018) was used to identify a lower range for the capital and installation costs and the upper end of the range was based on Dynniq's estimates for implementing the system at one intersection in Groningen. For the appraisal a mid-point value in this range was used giving a cost per intersection of €8,000 for sensors and processing and €5,000 for signage.

It was assumed that the equipment would be installed at all signalised intersections in urban areas in the EU28. This was calculated by applying the proportion of people who live in urban areas in the EU28 which is 72% (PBL Netherlands Environmental Assessment Agency, 2016) to the total number of signalised intersections in the EU28 (180,000) to give 129,600. The operating and maintenance (O&M) costs of the scheme were assumed to be 5% of capital and installation costs.

1.2.2 On Bike and Amber Light Systems

For the On-Bike system, the willingness-to-pay (WTP) evidence from the two WTP experiments (Section 2 above) was crucial in establishing the benefit to users, and users' demand response to the new product. Data was also provided by DLR for a set of variables including post encroachment time (PET), speed and acceptance.

Amber Light was also covered by the DLR data relating to post encroachment time (PET), speed and acceptance, however Amber Light was not included in the WTP experiments.

Based on a review of costs in the ITS Cost Database (US DoT, 2018) and market price data for analogous systems, it was assumed that the purchase price of the On-Bike system would be €30 per bicycle - this necessarily assumes mass-production of the system and a simple design focusing on the key functionality: production in small numbers would elevate the costs a long way above willingness-to-pay. It was assumed that infrastructure would also be required at each intersection, including equipment to communicate with the on-bike system. In total €11,000 per intersection is included in the CBA for capital and installation costs (less than Green Wave as no electronic sign infrastructure is required). Amber Light would be expected to be in the same region of cost as Green Wave, since it includes sign infrastructure. Operating and maintenance costs are set at 5% of capital & installation costs, per annum.

1.2.3 Truck-Based System

Data on the Truck-Based System was obtained from the research by Volvo and ITS Leeds and supplemented by literature-based sources on system costs and accident prevention. Focus group results from work by VTI (Section 3.4 above) were also taken into account.

Costs were taken from published sources. The cost of installing one extra sensor on each truck was assumed to be at the midpoint of the estimated range of €186-243 from Siedl et al. (2017) at €214.50 per truck. It was assumed that all of the approximately 6,250,000 trucks in the EU over 3.5 tonnes (ACEA, 2017) would install the system. The number of trucks over 3.5 tonnes was forecast to grow over the appraisal period at approximately 1% per annum based on the moving average of the number of trucks in the previous three years.

1.2.4 All systems

Important generic data for the scaling-up stage was brought together from a number of sources. The annual number of cycle km in the EU28 was assumed to be 134,231,025,984 (European Cyclists' Federation, 2016) and the total number of cyclists in the EU was assumed to be 200 million (European Cyclists' Federation, 2018). It was assumed that both the number of cycles and cycle km would increase by 1% per annum over the appraisal period. The number of cycle km was converted into cycle hours using an average cycling speed of 15.5km/h (City of Copenhagen, 2012).

The forecast annual number of cyclist fatalities and injuries are shown in Table 25 which were sourced from Silla et al. (2015). They are based on the forecast trends in Hancox et al. (2015) which were estimated based on applying the trend for changes in the number of fatalities and injuries between 2002 and 2012 forward to future years.

Table 25: Forecast Annual Number of Cyclist Fatalities and Injuries in EU28.

	2012	2020	2030
Single cyclist fatalities	277	185	116
Cyclist-vehicle fatalities	1,917	1,282	801

Single cyclist injuries	28,635	27,490	26,320
Cyclist-vehicle injuries	149,660	142,218	134,699
All road fatalities	28,126	16,555	8833
All road injuries	1,429,888	1,055,760	748,317

The number of signalised intersections in the EU28 was assumed to be 180,000 based on data from the Navteq database (DRIVEC2X, 2014).

1.3 Analysis

1.3.1 Green Wave

The Green Wave system was found to produce improvements in the cycling experience which users found useful and satisfying, although with potential for further improvement. On the van der Laan acceptance scale (-2 to +2), the system was rated +1.46 (±0.49) for usefulness and +1.19 (±0.61) for satisfaction (see Section 3.1.5). In the CBA, in order to measure the benefits of the current Green Wave system to users, a number of scenarios were considered, based on the evidence gathered through the observational study (3.1.4) and semi-controlled field study (3.1.5), supplemented by evidence from literature sources where necessary.

The XCYCLE field studies found evidence of both a reduced frequency of stopping by cyclists and savings in time spent stopped at red lights - this would give an increase in comfort, as described in Section 3.1.5.2. The findings of the observational and semi-controlled studies differ somewhat: the following scenarios aim to capture the range of time savings and comfort benefits indicated by the studies.

1. The first scenario focuses on stopping behaviour. In the literature on measures of cycling 'comfort', the *frequency of stops* is a key variable (e.g. Dufour, 2010; ECF, 2002), and this is supported by the economic valuation literature (e.g. Börjesson and Eliasson, 2012). Based on the RUG data, there is approximately a 5% reduction in the % of cyclists having to stop at the Green Wave intersection. We assume that these are due to the cyclist slowing down to avoid stopping - instead pedalling or coasting towards the intersection.

The equivalent measure from the semi-controlled study was a 3% reduction in stopping (non-significant), however each participant only cycled through the section four times in the baseline and four times in the treatment condition. It is possible this did not allow for learning and familiarisation to feed through fully into behaviour. Further research could address this aspect.

The value for the 'disutility of stopping' for those cyclists would have stopped in the baseline scenario but no longer would in the treatment scenario, was based on the research by Börjesson and Eliasson (2012). The result is a benefit of 1.1 Euro cents per cyclist per intersection on average across all cyclists.

2. The second scenario is included for comparison - this is a sense check based on a very simple calculation of benefit using only *overall cycle travel times* through the section, with and without the Green Wave system in place. The difference is, on average, a saving of only ~1 second with the system in place. The evidence on this is from the semi-controlled study (saving 0.7 seconds, though not significant); and by calculation from the combined evidence of the observational data and the semi-controlled study data, which produced a saving of 1.55 seconds (again on average across all cyclists). Again, the difference between the pure semi-controlled evidence and the wider evidence may be due to the limited time for learning in the former study, and also because the former study was undertaken during 'quiet' periods when the observational data shows the time savings are reduced.

Using the value of travel time savings for cyclists (as above) and applying the multiplier of 2.0 for delay time - which applies to cycling (Börjesson and Eliasson, 2012) and is found on other modes as well - this indicates a benefit of 0.7 Euro cents per cyclist passing through the intersection. This is a small benefit per incidence, but when aggregated over all cyclists and all intersections the benefit is still substantial.

3. The third scenario focuses on the *overall comfort of cycling*. Previous research studies have produced WTP-based values for cycling under comfortable versus less comfortable conditions, notably van Ginkel (2014), which we benchmarked against Börjesson and Eliasson (2012). Van Ginkel defines a comfortable cycle route as a "non-stop, comfortable and safe route where cyclists have priority on crossings and experience a pleasant ride" - by contrast an uncomfortable route is characterised by cyclists having little priority and being required to stop many times. The study obtains a WTP value for time spent cycling in comfortable versus 'standard' conditions. This needs to be adjusted to a 2015 basis and weighted for commuting versus other trip purposes (the commuting value is higher, as expected). Hence, we obtain an indicative value of €2.88/hour for 'comfortable' versus 'standard' conditions, and by extrapolation double that for 'comfortable' versus 'uncomfortable' conditions, €5.75/hour. We have to scale this down to the route section (123m long), and we assume a standard cycling speed of 15.5kph as above. The result is a benefit of 2.3 Euro cents per cyclist using the intersection, if the Green Wave system is able to improve this section from 'standard' to 'comfortable', or from 'uncomfortable' to 'standard'. (The benefit of 4.6 Euro cents shown in parentheses in Table 26 would be the maximum achievable - the benefit per cyclist of improving the section from the lowest level, 'uncomfortable', to the highest, 'comfortable').

Table 26: Summary of Green Wave user benefit scenarios.

Scenario	*User benefit estimate, per cyclist per intersection, Euro cents*
1. Comfort and time: reduction in stopping	1.1
2. Time savings-based comparator	0.7
3. Overall comfort: improvement from 'standard' to 'comfortable' (or 'uncomfortable' to 'comfortable')	2.3 (4.6)

Note: all benefits are measured as changes in generalised cost, before application of the rule-of-a-half.

The three results are a similar order of magnitude - which is encouraging. The result based on time savings only is the smallest - as expected since it is the narrowest and does not capture the specific behaviour of stopping. The result based on overall comfort changing from 'standard' to 'comfortable' is the largest, although we do not have specific information on the match between this and Green Wave. The first result, based on analysis of comfort impacts of the specific stopping behaviour, lies in the middle of the range and will be taken forward in the XCYCLE CBA.

The additional result for increasing comfort from 'uncomfortable' all the way to 'comfortable' (4.6 Euro cents), can be a useful benchmark, interpreted as an upper bound for what is achievable from cycling measures such as Green Wave. In practice it would probably be necessary to implement further improvements to achieve this, such as further increasing cycle priority at intersections.

The Green Wave system also has the potential to improve safety - by enhancing information to cyclists and allowing them to ride in a more comfortable and less stressed manner, leading to reduced red-light violations. However, the results of the observational study and the semi-controlled field study suggest that this potential has not yet been realised: there is no evidence of a reduction in red-light violations overall from the research. Therefore, for the moment, the Green Wave system is assumed to have no safety benefits in the CBA. The scope for safety benefits from XCYCLE systems in general can be seen clearly in the other systems, tested below. Green Wave can be seen as complementary to the other systems. For Green Wave in the CBA, we use the value 1.1 Euro cents per cyclist per intersection from Table 26, as a mid-range estimate of the system benefits, and this is based on the specific comfort benefits of the system.

Scaling-up to the EU level made use of the available data on total cycle km (as above), but also broke this down by cycling in urban vs rural areas (Table 27). For urban areas, there is evidence on the frequency of stopping (from Dufour, 2010; ECF, 2002), which allows us to estimate the impact of changes in stopping due to Green Wave.

Table 27: Green Wave: Scaling up across Urban and Rural cycling.

Area type	*Urban*	*Rural*
% of cycle km*	68.4%	31.6%
Frequency of enforced stops - e.g. due to red lights or other factors (baseline)	0.75/km	Very low: assume approx. zero

*Source: DfT (2018)

Assuming that the causes of enforced stops were split 0.5:0.25 between red lights at signalised intersections and other causes, and attributing plausible probabilities of being stopped at signalised intersections (0.67, which matches the semi-controlled study data - Section 3.1.5 above) and other obstructions (0.5), it can be inferred that there are 69 billion signalised intersection encounters by cyclists in urban areas, per annum (2015).

The implication is that the total benefit per annum obtainable from implementing Green Wave across signalised intersections on urban networks is approximately €900million (in 2021, at 2015 prices). The full CBA results are presented in Section 4.4.

1.3.2 On Bike and Amber Light Systems

The On-Bike and Amber Light systems are both designed to increase safety at intersections, focusing on cycle-vehicle collisions where the vehicle turns across the path of the cycle. Both involve communication to be alert for a potential collision: the On-Bike System communicates to the cyclist, whilst the Amber Light system communicates to the vehicle driver via an electronic road sign. The willingness-to-pay (WTP) experiment focused on the on-bike system, not the Amber Light, so we lack data on potential users' WTP for the latter.

This section is therefore mainly focused on the On-Bike system. The WTP experiment presented two versions of the On-Bike system: (i) an 'active' system which provides a warning to the cyclist if a collision is imminent; or (ii) a 'passive' RFID tag system which does not communicate to the cyclist. The WTP was found to be much larger for the 'active' system, and that system will be taken forward in the CBA.

In order to use the results from the six-country willingness to pay (WTP) experiment in the CBA, WTP values representing the EU were estimated by aggregating the values from the six surveyed countries based on a comparison of cycling rates and average incomes. The EU values were then adjusted for any differences in average income in the survey compared to national averages using an income elasticity of 1.18. This gave an EU28 WTP value of €82.10 in the scheme opening year of 2021 (in 2015 prices). It was assumed that this value would grow in line with real GDP over time (and in line with the change in the value of time over time) at 2% per annum.

The WTP values represent cyclists' valuation of the safety benefits of the system, and we also need to take into account the share of benefits to vehicle users (including car drivers and truck operators), and the share of benefits to government/society (depending on the healthcare funding model) from savings in healthcare costs in particular. These shares are based on the EU External Costs Handbook (Ricardo-AEA, 2014).

The usefulness and satisfaction data from DLR suggest that these systems are not quite as attractive to potential users as Green Wave. Usefulness of On-Bike was +0.51 (to cyclists) and Amber Light was +0.65 (to motorists); satisfaction was +0.23 and +0.18 respectively (all pre-experiment, on the van der Laan scale -2 to +2). For comparison, these scores were > +1 for Green Wave. This is matched by the WTP evidence, which (in the CBA below) indicates that cyclist user benefits are greater for Green Wave than for On-Bike. However, it should be noted that once the benefits to vehicle users and the savings in healthcare provision are added, the safety systems do in fact have greater total benefits at the societal level.

As noted in Sections 3.2 and 3.3 above, the usefulness and satisfaction scores increased for Amber Light but decreased for On-Bike after the experiment, indicating that the protypes exceeded expectations in the former case, and fell short in the latter case - the text in 3.3.3 explains the difficulties that the Braunschweig participants had with the prototype HMI for the On-Bike system. The earlier test in Bologna (Section 2.4) - and the WTP findings - show that the On-Bike system concept is valuable, even if the implementation requires some further refinement.

On the cost side, it was assumed that the system would only be installed in urban areas and so only cyclists living in urban areas would purchase the handlebar-mounted device. The number of potential purchasers of the system was calculated by multiplying the proportion of EU citizens living in urban areas (72%) by the number of cyclists in the EU. It was assumed that 50% of cyclists would purchase the system in the first year (2021), a further 20% each in 2022 and 2023 and the remaining 10% of cyclists would choose not to purchase the system (broadly reflecting the findings of the WTP studies in Section 2 above).

The analysis finds that the total benefit obtainable from implementing Green Wave across EU urban networks is approximately €13billion (at 2015 prices). The full CBA results are presented in Section 4.4.

1.3.3 Truck-Based System

The Truck-based system is also designed to improve safety at intersections, focusing specifically on truck-cycle collisions - a major contributor to cyclists' fatalities. The economics of the system - and the governance implications - are slightly different from the On-Bike (and Amber Light) systems, since the Truck-based system does not require any infrastructure changes.

In the evaluation study, the truck drivers considered the system useful, and most truck drivers stated they would like to have the system installed on their vehicle. We do not have a measure of WTP - that would require research with truck operators as well as drivers - however from the XCYCLE research we do have an understanding of effectiveness, which we were able to combine with standard values of accident reduction in the EU (Ricardo-AEA, 2014).

The number of cycle-vehicle accidents that the truck scheme would prevent was based on a combination of EU cycle casualty forecasts (see Table 11) and London data on accident types from Talbot et al. (2013). The latter showed that 32% of cycle accidents involve a 'left-hook' of the other vehicle across the path of the cyclist, and of the other vehicles involved 82% were HGVs. It was assumed that the system would work in 95% of incidences. Applying all these assumptions together meant that it was assumed that the installation of the truck scheme would prevent 24.9% of cycle fatalities and injuries per annum. Conservatively no increase in cycling was assumed as result - any increase in cycling the did occur would increase the Net Present Value in the CBA results.

The cost of installing one extra sensor on each truck was based on Siedl et al. (2017) as mentioned previously, and relatively modest at €214.50 per truck.

The analysis finds that the total benefit obtainable from implementing an On-Bike system across EU urban networks is approximately €7.4billion (at 2015 prices). The full CBA results are presented in Section 4.4.

1.4 CBA Results

1.4.1 Core Results

The core results are for a 15-year operating period (Table 28). In this test, all three types of XCYCLE systems are found to achieve a large positive Social Net Present Value (NPV), between €6.7bn and €30bn - i.e. they produce benefits at the societal level that exceed the costs by billions of Euros in each case.

Table 28: CBA of XCYCLE Systems (Core Results).

Social CBA	On-Bike System		Green Wave		Truck System	
	@3%	@4%	@3%	@4%	@3%	@4%
Net Present Value (NPV)	7,427	6,746	8,145	7,101	30,045	26,527
Benefit:Cost Ratio (BCR)	**9.8**	**9.7**	**4.5**	**4.3**	**Finance Positive**	**Finance Positive**

Stakeholder CBA
Stakeholder group:

	On-Bike System		Green Wave		Truck System	
Infrastructure Manager	@3%	@4%	@3%	@4%	@3%	@4%
Installation Cost	-1,230	-1,172	-1,453	-1,385	0	0
O&M Cost	-751	-666	-887	-787	0	0
Transfer from Government	1,981	1,838	2,341	2,172	0	0
NET PRESENT VALUE	0	0	0	0	0	0

	On-Bike System		Green Wave		Truck System	
Cyclists	@3%	@4%	@3%	@4%	@3%	@4%
Purchase Cost of Equipment	-4,188	-3,899	0	0	0	0
Running Costs of Equipment	-1,714	-1,514	0	0	0	0
Time & Comfort Benefits	0	0	10,486	9,273	0	0
Safety Benefits	10,097	9,143	0	0	22,321	19,787
NET PRESENT VALUE	4,195	3,731	10,486	9,273	22,321	19,787
Cyclist BCR	**1.7**	**1.7**				

	On-Bike System		Green Wave		Truck System	
Truck operators and car users	@3%	@4%	@3%	@4%	@3%	@4%
Safety Benefits	4,072	3,791	0	0	8,206	7,274
Costs - installation	0	0	0	0	-1,830	-1,729
Costs - O&M	0	0	0	0	-951	-842
NET PRESENT VALUE	4,072	3,791	0	0	5,426	4,704
Vehicle User BCR					**3.0**	**2.8**

	On-Bike System		Green Wave		Truck System	
Industry - OEMs	@3%	@4%	@3%	@4%	@3%	@4%
Revenues	4,188	3,899	0	0	1,830	1,729
Costs	-3,685	-3,431	0	0	-1,634	-1,544
Margin	-503	-468	0	0	-196	-185
NET PRESENT VALUE	0	0	0	0	0	0

	On-Bike System		Green Wave		Truck System	
Government	@3%	@4%	@3%	@4%	@3%	@4%
Transfer to IM	-1,981	-1,838	-2,341	-2,172	0	0
Healthcare & other savings	1,140	1,062	0	0	2,298	2,037
NET PRESENT VALUE	-840	-776	-2,341	-2,172	2,298	2,037

Costs are shown with a negative sign; benefits are shown with a positive sign.

Considering *value for money*, all systems would be classified as at least 'High' value for money based on their Social Benefit:Cost Ratio (BCR) - using a typical yardstick for public investment (BCR>2.0) (DfT, 2017). The BCR for Green Wave is 4.5 at a 3% discount rate (or 4.3 when we test sensitivity to a 4% discount rate). The BCR for the On-Bike System is 9.8 at 3% discount (9.7 at 4% discount), indicating very high value for money from the public investment required.

The Truck-Based System is financially positive for government - it leads to healthcare cost savings that will accrue at least in part to the government (depending on the healthcare funding model). This would place it in the highest category for value for money, from a government perspective.

From a *Stakeholder* perspective, the benefits of the On-Bike system to cyclists exceed the costs (BCR=1.7), although the design and performance of the particular system will be needing to be honed to achieve this. The benefits of the Truck Based System to truck operators show an even better BCR of approximately 3.0. Overall, there is no evidence from the CBA of any incentive problems for particular stakeholders.

1.4.2 Further Sensitivity Tests

The sensitivity of the results to a *reduced, 10-year operating period* was tested. Whilst there was some loss of Net Present Value to all the systems as expected (because the investment occurs before the stream of benefits from it), value for money remained robust: the Social BCR even for Green Wave only declined to 3.4 (at 3% discount) or 3.3 (at 4%) (see Table 29).

Another test was conducted to examine whether the NPV or BCR of the On-Bike System was highly dependent on the rather large demand stimulus reported in the WTP experiment (+16.5% in the amount of cycling when the On-Bike system is used). If instead the demand response was halved (to +8.25%), the BCR falls to 9.1 at 3% discount (9.0 at 4% discount), which is still very high: value for money was robust and would remain robust if zero demand growth was assumed.

As mentioned at the start of this Section, there was interest in testing the sensitivity to system costs. For Green Wave, a 100% increase in system costs from the estimates given could still produce a Social BCR of 1.7. For the Truck based system, doubling all costs (capital & installation, operating and maintenance) would reduce the BCR for truck operators to 1.6 (1.5 at 4% discount). In both cases, these are probably close to the limit at which the incentive to participate would be impacted (in the former case the city authority's incentive and in the latter case the truck manufacturer's and operator's incentive). For the On-Bike system, it is doubtful whether the economic case could withstand a 100% increase in costs (€60 for an On-Bike kit; and €22,000 per intersection for the infrastructure components; and a ten-fold reduction in the change in the level of cycling) - since Social BCR falls to 1.1 and the Cyclist BCR falls to 0.9. In addition, the assumptions about take-up would be seriously undermined.

Generally, the assumptions about take-up impact directly on the NPV and BCR. This is particularly an issue for On-Bike, where we have assumed a maximum take-up of 65% of cyclists, built-up over a period of three years after installation of the infrastructure equipment. Because the costs of the infrastructure are fixed relative to the number of cyclists actually using it, any shortfall in take-up is a problem for the social CBA. For example, if the level of take-up is only one-third of that (22%), built up over five years instead of three, then the Social BCR falls to 1.8 (or 1.7 under 4% discount or if we assume a (plausible) 10-year life for the handlebar mounted On-Bike system). That is approximately the level of BCR where the highway authority is likely to change its decision from a positive to a negative one on implementation.

Finally, we tested whether the On-Bike CBA can withstand a reduction of the WTP value by 50%, in the case where there is some uncertainty about the value emerging from the Stated Preference experiment (not necessarily the case in this study, but a general concern with Stated Preference-based values - that they may be biased upwards compared with values based on revealed preference data). The finding is that the

BCR for On-Bike falls to 1.1 in this case: therefore, it is important going forward that any the WTP evidence gathered in this study continues to be benchmarked against other evidence, checked for robustness, and care taken to avoid overstating WTP.

Table 29: CBA of XCYCLE Systems (Sensitivity to Reduced - 10 Year - Operating period).

10 Year Operating Period

Social CBA	On-Bike System		Green Wave		Truck System	
	@3%	@4%	@3%	@4%	@3%	@4%
Net Present Value (NPV)	6,296	5,795	5,077	4,522	20,722	18,688
Benefit:Cost Ratio (BCR)	**10.4**	**10.2**	**3.4**	**3.3**	**Finance Positive**	**Finance Positive**

Stakeholder CBA
Stakeholder group:

	On-Bike System		Green Wave		Truck System	
Infrastructure Manager	@3%	@4%	@3%	@4%	@3%	@4%
Installation Cost	-1,230	-1,172	-1,453	-1,385	0	0
O&M Cost	-532	-482	-629	-570	0	0
Transfer from Government	1,762	1,654	2,082	1,955	0	0
NET PRESENT VALUE	0	0	0	0	0	0

	On-Bike System		Green Wave		Truck System	
Cyclists	@3%	@4%	@3%	@4%	@3%	@4%
Purchase Cost of Equipment	-4,022	-3,760	0	0	0	0
Running Costs of Equipment	-1,170	-1,056	0	0	0	0
Time & Comfort Benefits	0	0	7,160	6,476	0	0
Safety Benefits	8,245	7,586	0	0	15,738	14,251
NET PRESENT VALUE	3,052	2,769	7,160	6,476	15,738	14,251
Cyclist BCR	**1.6**	**1.6**				

	On-Bike System		Green Wave		Truck System	
Truck operators and car users	@3%	@4%	@3%	@4%	@3%	@4%
Safety Benefits	3,911	3,656	0	0	5,786	5,239
Costs - installation	0	0	0	0	-1,764	-1,673
Costs - O&M	0	0	0	0	-659	-596
NET PRESENT VALUE	3,911	3,656	0	0	3,364	2,970
Vehicle User BCR					**2.4**	**2.3**

	On-Bike System		Green Wave		Truck System	
Industry - OEMs	@3%	@4%	@3%	@4%	@3%	@4%
Revenues	4,022	3,760	0	0	1,764	1,673
Costs	-3,540	-3,309	0	0	-1,575	-1,494
Margin	-483	-451	0	0	-189	-179
NET PRESENT VALUE	0	0	0	0	0	0

	On-Bike System		Green Wave		Truck System	
Government	@3%	@4%	@3%	@4%	@3%	@4%
Transfer to IM	-1,762	-1,654	-2,082	-1,955	0	0
Healthcare & other savings	1,095	1,024	0	0	1,620	1,467
NET PRESENT VALUE	-667	-630	-2,082	-1,955	1,620	1,467

Costs are shown with a negative sign; benefits are shown with a positive sign.

1.5 Scenarios and Discussion

The CBA indicates that there is a good economic case for all the XCYCLE systems, at this stage of assessment. The Truck-Based system is the best performer on an NPV test and it also scores most highly in a 'value for money' ranking, since it contributes positively to the public accounts. The Stakeholder BCR to users is also strong.

The results are very robust to reducing the appraisal period to 10 years' operating life, and to reducing the assumed demand stimulus to cycling. They are less robust to WTP being overstated; and whilst the Green Wave and Truck-Based systems can withstand system costs being increased by 50% or more, that is not the case for On-Bike which is more sensitive to costs.

The systems are also complementary:

- The Green Wave system as currently defined delivers a benefit mainly in terms of cyclist comfort, as a result of reductions in the amount of stopping at signalised intersections;
- The other systems tested deliver a safety benefit: therefore, it may be attractive to adopt comfort & safety-improving systems together;
- Green Wave and Amber Light were both tested on, and found to be useful on, segregated cycleways - this raises the possibility of sharing sensors and supporting infrastructure in future, saving cost for the package as a whole. This might be an attractive solution for countries with high levels of segregated cycle infrastructure.
- The Truck Based (safety) system is effective when the cyclist is in the same roadway as the truck as they approach the intersection. Meanwhile On-Bike and Amber Light systems are effective with all vehicle types and potentially both are effective in segregated cycle lanes. Further research should focus on the optimal blend of these systems, including gathering the data on existing infrastructure needed to make such assessments, and widening the set of use cases tested in natural/controlled experiments.

The governance aspects of the Truck-based system are appealing, as well as the economic aspects: this does not require diverse local authorities to install suitable infrastructure - any truck equipped with the system can start saving casualties from the day it starts operating. The requirements for On-Bike are more complex, with both local authorities and cyclists required to take action to install systems and equipment (although in the longer term, getting away from costly infrastructure through fully networked and interconnected vehicles is also appealing, from the cost and governance perspectives, if it becomes feasible).

A concern with the Truck-based system is that it may need two sensors rather than the costed one, if it is to be used for driving on the left as well as the right (e.g. EU-UK traffic). As shown in the previous section, this would reduce the NPV and make the value for money case for truck operators marginal - therefore work could be undertaken to reduce the costs of supplying a pair of side sensors for trucks operating in this type of regime.

The CBA suggests that 'horses for courses' may apply (a range of solutions may be suitable for different cases found on the network). For some of the systems, particularly Green Wave and On-Bike, further development of the system could be useful, followed by further evaluation work. For Amber Light, a WTP study and/or some research around estimating the safety (collision) outcomes could be very helpful in strengthening the business case further in future.

2 Overall Discussion and conclusions

In this section the results of the willingness to pay studies, the on-site studies and the cost benefit analysis will be summarised, discussed and linked.

The aim of the present deliverable was to provide an in-depth evaluation of the effects of the technological innovations developed in the XCYCLE project, which are designated to detect, localize and prevent possible collision between cyclists and motorised vehicles, as well as increasing the cyclist's comfort in mixed traffic situations. Evaluations conducted in WP6 focused on assessing effects on users' willingness to pay, tactical behaviour, attitudes, trust and overall acceptance of the XCYCLE system. Furthermore, the cost benefit analysis contributed to assessing the effect of the XCYCLE innovations from a broader point of view, adopting a social and economic perspective

The willingness to pay studies focused on users' interactions with the XCYCLE on-bike system.

The first study, conducted using a field-test experimental design with a relatively modest sample, showed that most participants (84%) reported that they are willing to buy the on-bike system if available on the market. Participants were willing to spend on average 63.00€. The mean amount of money that participants were willing to accept for selling the system was 46.25€. The study highlighted that, in order to foster a fast and lasting introduction of the product in the market, the price should be kept relatively low, otherwise other incentives should be considered. Analysis showed non-significant correlations of the WTP and WTA with the behavioural intention to use the on-bike system, suggesting that participants may value the on-bike system but the intention to use does not increase as the value increases. Furthermore, the non-significant relationship between WTP and bicycle use could suggest that the system may be equally appealing by frequent and infrequent cyclists.

The second study consisted of a cross-sectional survey distributed through a large sample in six different European countries, using stated preference behavioural-choice based exercises. It allowed to get a deeper insight on which characteristics of the on-bike system are the most appealing for end-users and to understand how the usage of the system could influence peoples' cycling behaviour and perceived safety. Passive bike tag was the most popular among the respondents (68% would buy), followed by active system with audio-visual warning (68% willing buy), active system with handlebar vibration warning (65% willing buy) and active system with combined warning (66% willing buy). Analysis showed that, overall, respondents are willing to pay around 80% more for the active technology than for the passive technology. One of the most interesting results is that WTP values are almost half the UK values in Sweden and The Netherlands, whereas strikingly higher for Spain and Italy, reflecting that southern European users value the system more that northern European. WTP values being higher in the lower income countries suggests that the income differences are more offset than by other factors differing by countries, such as road conditions, cycling infrastructure and culture. However, overall, results indicate that the better the cycling infrastructure and/or the safer the underlying road conditions, the lower the WTP, reflecting a lower requirement for XCYCLE systems. Furthermore, females have 16% higher WTP values compared to males, and commuters 45% higher than non-commuters. Regarding effects on behaviour, the study highlighted that users' in UK and Spain are considerably more likely to change their cycling behaviour (60 and 66% respectfully) compared to other countries. This may reflect the lower baseline of cycling behaviour within both of these countries and therefore the potential to make more trips. Furthermore, the active technology appears to have a greater potential to change cycling behaviour as compared to passive technology, generating significantly more cycle trips. There is a strong likelihood that this reflects the active system's higher functionality and performance levels, leading to a greater trust in the system and therefore an increase in the propensity to cycle.

The green wave studies focused on assessing the effects of the innovative GLOSA (Green Light Optimal Speed Advisory) with adaptive control on traffic performances, waiting times, red-light violations, cycling comfort and increase in bicycle trips.

The green wave scale-up simulation study focused on assessing traffic performance in a road-network simulation where the XCYCLE green wave system is implemented in six consecutive intersections, comparing results with the baseline scenario of no system implemented. The simulation showed a clear success of the green wave system in reducing the number of stops of cyclists with a minimal impact on the overall traffic efficiency. Results also showed that consecutive intersections are more effective and very closely spaced intersections are less effective.

The green wave observational study goal was to assess the effects of the green wave system on cyclists' natural behaviour with respect to waiting times, stopping frequency, grouping of cyclists, route choice behaviour and anticipation of the green phase based on the predicted time displayed to the cyclists. These effects were compared to the standard traffic light system for cyclists in Groningen. No difference in the number of cyclists on the route was found, possibly because it takes a long time for people to change macro level behaviour, such as route choice. Fewer red-light violations were seen in the quiet period, although there is a slight increase in cyclists violating the red light during busy periods. The most safety critical violations where in the late phase of the red-light, where public transport could enter in conflict with cyclists. Researchers suggested that refinements of the control algorithm can solve this issue. Observed cyclists could adapt their behaviour to reduce their general number of stops and waiting times and specifically, the number of cyclists that can pedal through the intersection without stopping doubles from the busy baseline period to the busy effect period. The cyclists waiting time decreased by 30% from around 33 seconds to approximately 24 seconds. This is another indication that the system functioned as it was designed and therefore can help increase comfort for cyclists. Together with the reduction in number of stops, it can be concluded that those goals of the green wave system have been met.

The green wave semi-controlled field study allowed to obtain information on cyclist's tactical behaviour and reasoning in relation to the green wave system, specifically assessing efficiency, comfort, safety and acceptance. While the results for efficiency and comfort did not show any actual improvements in travel time or waiting time for the participants, they still had a positive opinion about the system in general. This may be explained by an increased feeling of control – if the cyclist knows about the remaining time to green, he or she can plan ahead. Other indicators like the distance from the intersection at the onset of the green light and the number of passages with amber light showed that cyclists understood and made use of the information provided by the sign. Information sampling was not affected by the presence of the XCYCLE sign, which indicates that the cyclists' attention was not captured inappropriately much. The study showed that cyclists did not neglect attending to the traffic light in the treatment phase despite the XCYCLE sign being present, and in an ideal world conveying the same, but augmented, information as the traffic light. This is an important finding and must be confirmed for better-functioning systems, as it is still the traffic light that delivers the legally reliable information. The most relevant suggestion gathered from participants is to integrate the count-down sign with the traffic light. The overall results of both studies show that the XCYCLE system improved cycling efficiency and quality, mainly in the busy periods, without negative effects on cyclist attention.

In order to warn motorists about dangerous interactions with cyclists, a flashing amber light system has been implemented at the AIM research intersection in Braunschweig. The system, communicating with the TraffiTower, is capable of sending warning messages to motorists using different levels of assessed criticality.

The effect of the amber light on motorist behaviour and road safety have been investigated in a five-week observational study. Obtained data were compare with baseline data gathered when the system was not yet in place, analysing a total of 2151 interactions between cyclists and motorists. The study highlighted positive effects on traffic safety and behavioural adaptation phenomena as well. Results showed that as a response to the amber light, the criticality of encounters between right turning motorists and crossing cyclists decreased and, at the same time, the analysis of the approach speed indicated an increase in speed of approximately 1.5 km/h, while PET increased by 0.3 s. Contrary to what has been expected, higher approach speed did not result in more safety-critical situations.

To gather further indications on the amber light's effects, subjective data were gathered in a second study, with more than 1200 road users responding to the survey. Results of the study are in line with results from the observational study, with cyclists reporting that motorists approached the intersection at lower speed and that they experienced fewer critical situations with them. Apparently, motorists looked for cyclists more often and stopped more frequently before crossing.

The on-bike system has been tested in a semi-controlled field study to investigate differences in subjective ratings (e.g. acceptance, trust, perceived safety and criticality) and changes in ratings over time. In addition, approach and crossing speed of cyclists was also measured to assess possible behavioural adaptation in response to the usage of the system. Results showed that acceptance and trust ratings decreased with experience. Participants rated the idea of the on-bike system positive, but the ratings decreased after using and experiencing the system. This can be related to the fact that in more than half of the cases, participants did not agree with the status of the warning system, meaning that the on-bike system warned in situations when it was not necessary, and did not warn in situation when it would have been necessary. In literature it has been extensively demonstrated that systems' false positives and false negatives have a detrimental effect on users' trust and acceptance. This suggests that to foster a large-scale adoption of the system, few improvements needs to be made both in terms of HMI design and risk assessment. It is also worth to mention that the on-bike system was tested in a setting where the cyclists had priority over the motorists which could have had an influence on participants ratings. In future evaluations the system could be tested again in a scenario where neither motorists nor cyclists have priority.

To gather deeper feedbacks and further suggestions by the end-users we *conducted a focus group with* cyclists evaluating the on-bike system. Results highlighted positive ratings of participants regarding trust and usefulness when evaluating the system without actually using it, which is in line with the semi-controlled field study results. Furthermore, the focus group study has been useful to highlight end users' concerns, which are mainly related to security reasons (e.g. theft and malicious use of the system) and shed light on users' wishes for further design improvement, which revealed to be feasible (e.g. portability, possibility to detect cars).

The XCYCLE in-truck warning system was evaluated through a focus group study, conducted in Sweden and Italy, with both truck drivers and cyclists. Interviews aimed to assess participants' perceived usefulness, trust, potential risks of the system, its benefits and drawbacks as well as collecting their comments and suggestions for further improvements. To let participants get a feeling of the system functioning, researchers used virtual reality headsets and video simulations along with videos of the technical testing of the system in real traffic environment. Regarding the right-turn use case, truck drivers stated that It is a very frequent dangerous situation and they agreed on its risk. The more driving in populated areas, the more common the situation is experienced. The risks are exacerbated by truck blind spots, rainy conditions and darkness. The drivers expressed positive attitudes to the system in general, deeming it helpful and much welcome. The bicycle bell warning sound was perceived as very nice and intuitive. The LED signal was by some suggested to be moved and dimmed, and by some regarded as well placed. Regarding concerns, some drivers expressed that due to the increasing number of driving assistance system installed in trucks they might be "overloaded" with sounds and LEDs flashing. They mentioned over-trust/over-reliance phenomena as possible as well. Still, all drivers thought that the pros of the system would overweigh the cons by far. Truck driver suggested some improvements for the system: adding a way to signal possible system's malfunctions; removing the possibility to switch it off; integrate the system in trucks' HUD or LCD screens. Mixed feelings were reported regarding the integration with autonomous braking. Cyclists expressed positive attitudes toward the system as well, maintaining concerns related to the system functioning and possible false positives or false negatives.

The cost benefit analysis allowed to assess the effect of the XCYCLE integrated system from a broader perspective, following the approach recommended by the EU FESTA Handbook (Barnard et al., 2017) and feeding from results of each system evaluation studies. The CBA adopted a so called "stakeholder CBA" framework, focusing at first on specific incidence groups (i.e., road authority, cyclists, drivers, industry/OEMs and the government) and then measuring the total impact on society using Net Present Value (NPV) and Benefit:Cost Ratio (BCR). Maximising CBA comparability with other EU research, and studies in traffic safety and intelligent transport systems was an important priority. Analysis revealed that there are feasible economic cases for each of the XCYCLE systems. The In-truck system resulted to be the most promising. Furthermore, results revealed to be robust enough to reduce the evaluation period from 15 to 10 years of operations.

The systems all together revealed to address the main aspect of cycling safety and comfort, as envisioned in XCYCLE, in a complementary way. While the Green Wave system delivers benefits mainly in term of comfort, the other systems proved to be effective in terms of increased safety. This suggests that adopting multiple solutions in a complementary way could allow to achieve greater results. The CBA highlighted that XCYCLE innovations could be arranged in different ways to provide the best solution for each specific scenario, thus maximizing benefits. Results suggested that for the Green Wave and the On-bike systems further developments could be useful.

2.1 Linking XCYCLE systems together for increased cycle safety and comfort

The systems developed in the XCYCLE project together aimed at addressing cycling safety and comfort in a complementary way. While the Green Wave system delivers benefits mainly in terms of comfort, the other systems are targeted at increased safety. The results from the XCYCLE project demonstrates that adopting multiple solutions in a complementary way has potential in improving overall conditions for cyclists, with increased cycling as a possible outcome.

The cost benefit analysis takes an overall view of the integrated system developed in the project. It highlighted that XCYCLE innovations could be arranged in different ways to provide the best solution for each specific scenario, thus maximizing the benefits. Results suggested the Green Wave and the On-bike systems further developments would be useful to improve its positive effects.

2.2 Suggestions for future improvements and research

Although the project has accomplished a wide range of useful and interesting results targeting increased bicycle safety, there is much left that can be done, both with improving and optimizing current systems as well as extending the scope of them.

Suggestions for improvements of the current systems are described in detail under each section above. Considering the possible extension of the scope of the systems, one way is to also target them towards pedestrian safety and comfort, thereby covering another group of vulnerable road users. For instance, the AIM research intersection already has the technical possibility of discriminating between different kinds of road users. Here, there is a good potential in addressing also pedestrian safety by the development of systems and risk assessments that in the end can result in injury risk reduction of this category. Moreover, the functionality of the on-bike system could have the potential of being integrated into smartphones, which a steadily increasing number of people carry nowadays. The possibility of also extending the bicycle detection system in the truck to pedestrian detection and driver warning is another example of what could be investigated further in the future. As the focus group study showed, any object positioned in the "dead" viewing angle of the truck, is hard to detect for the driver.

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Submitted:

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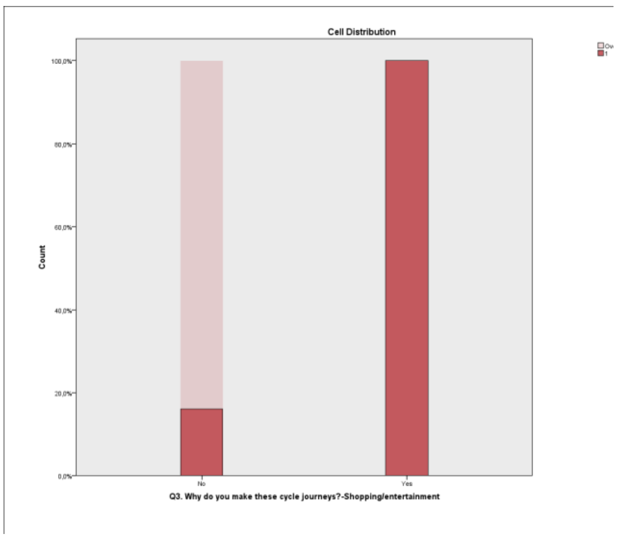
5 Annex

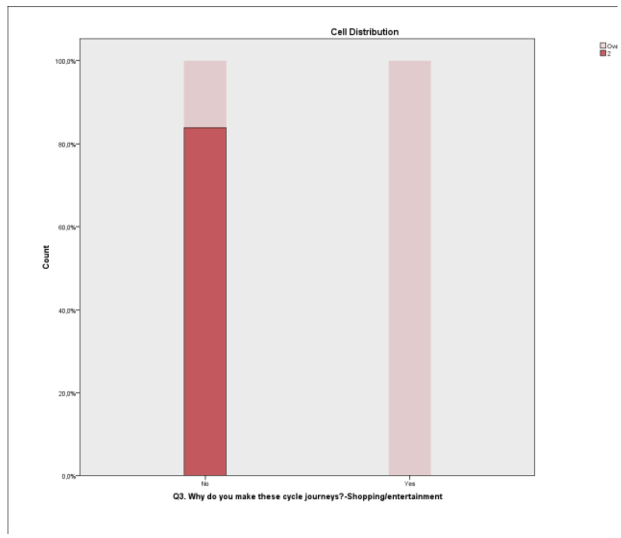
5.1 Annex 1

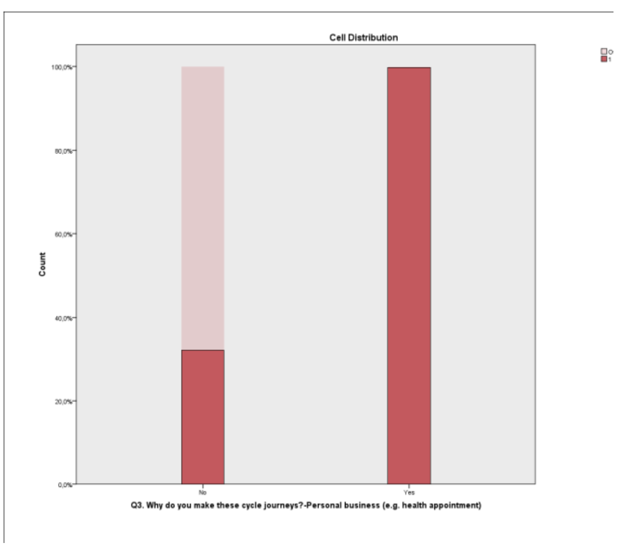
Segmentation: plots of the distribution of the data for each variable used as input sorted in descending order of overall importance

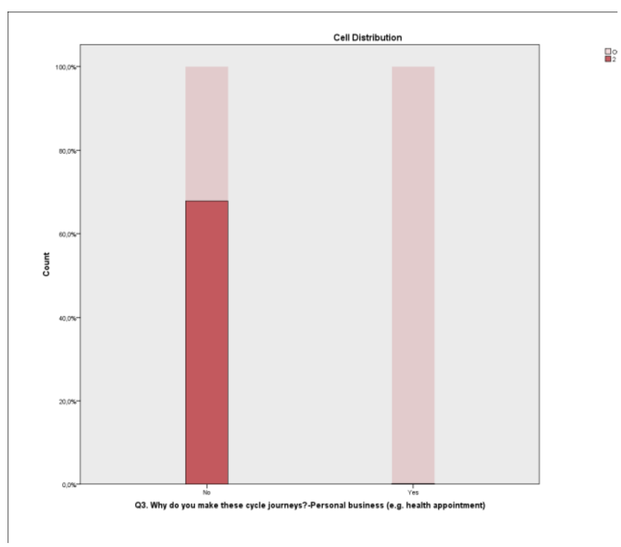
CLUSTER 1 - Everyday cyclists

CLUSTER 2 - Competitive/recreational cyclists



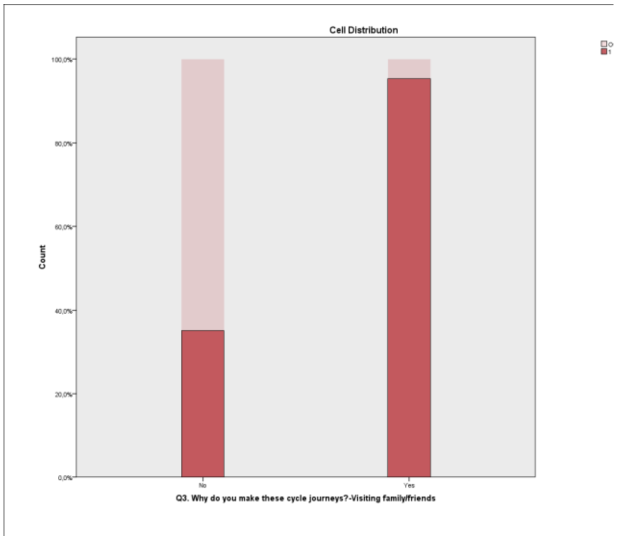


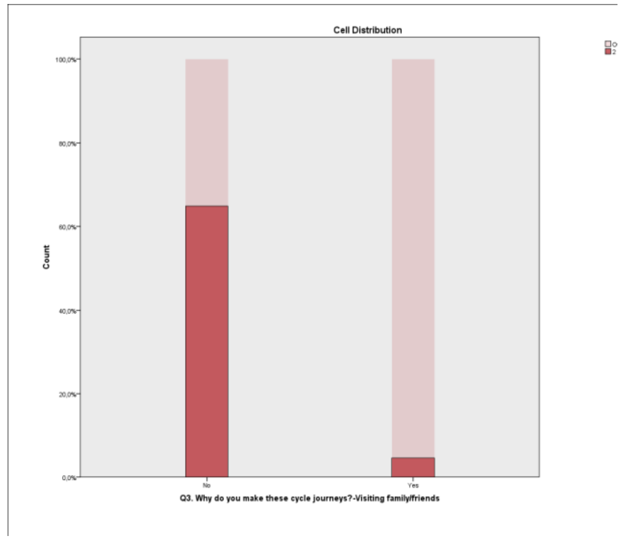


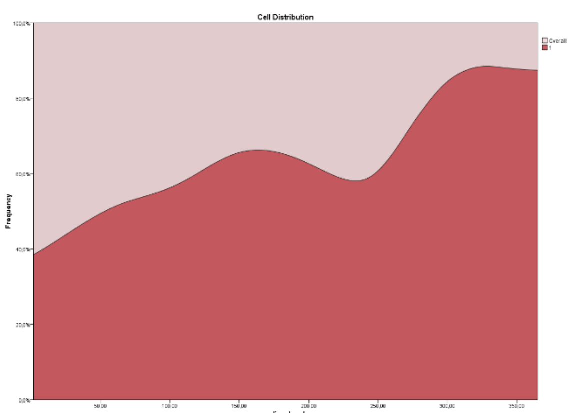


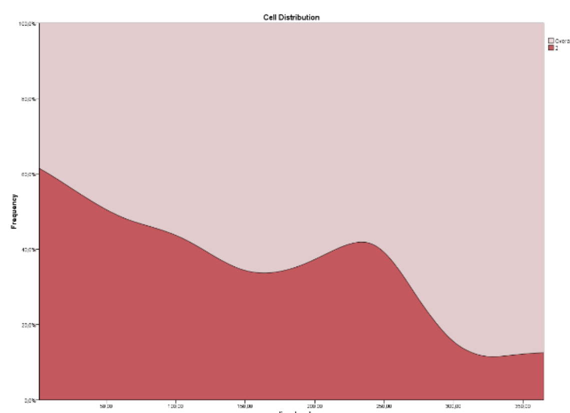
CLUSTER 1 - Everyday cyclists

CLUSTER 2 - Competitive/recreational cyclists



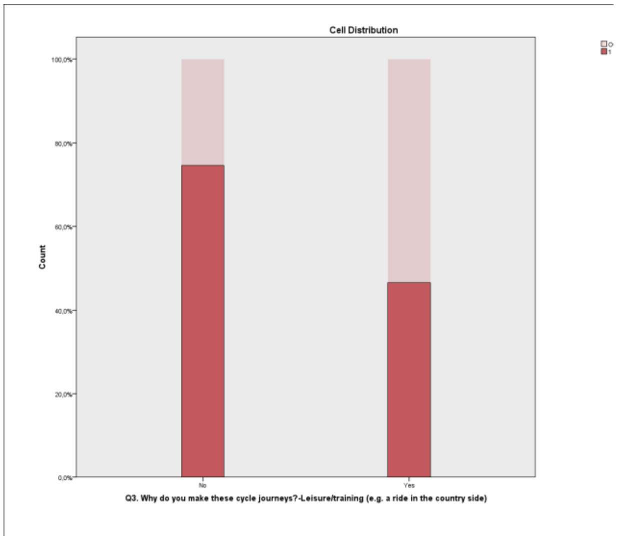


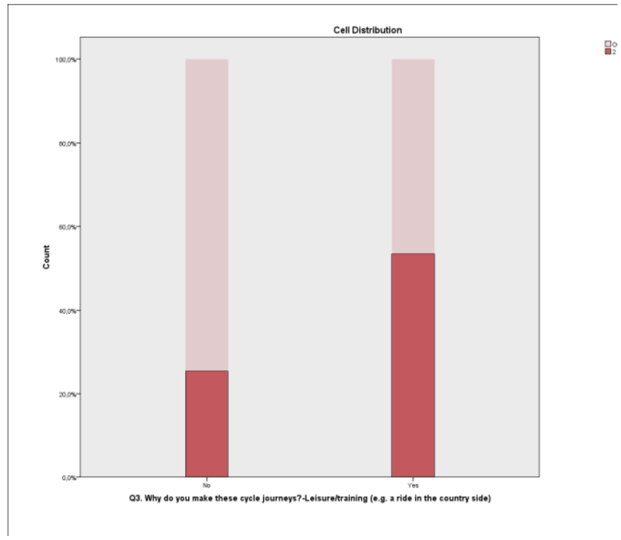


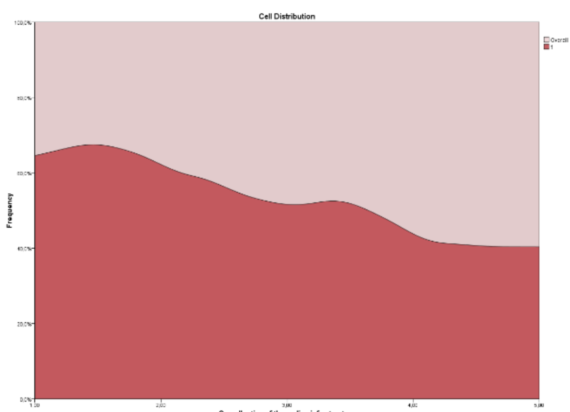


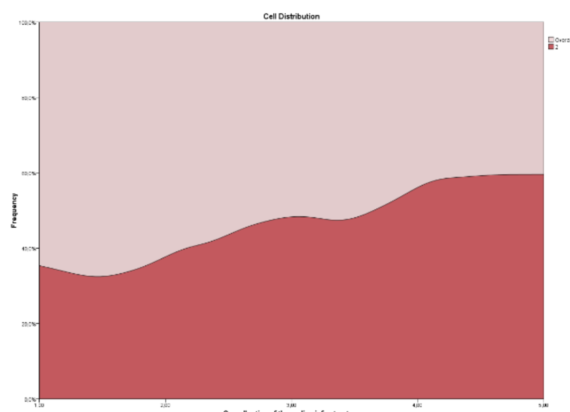
CLUSTER 1 - Everyday cyclists

CLUSTER 2 - Competitive/recreational cyclists



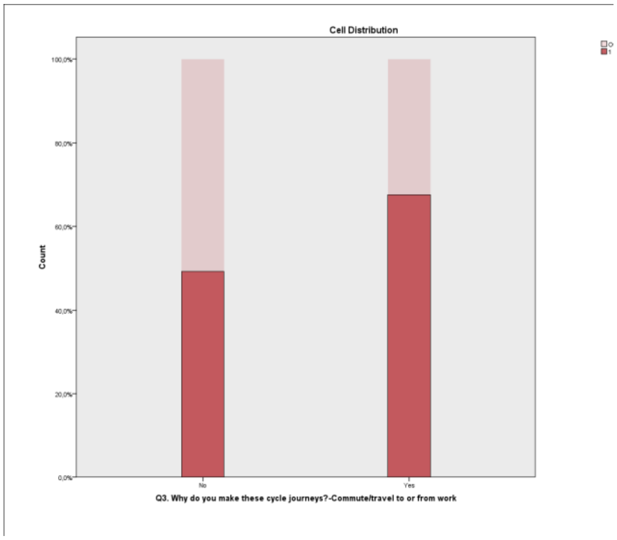


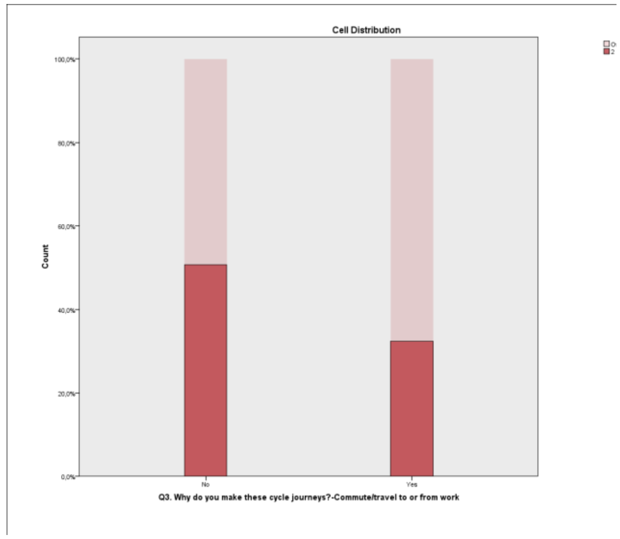


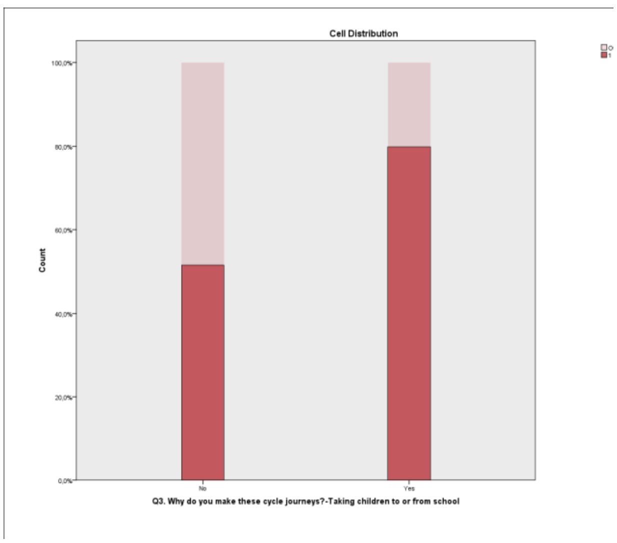


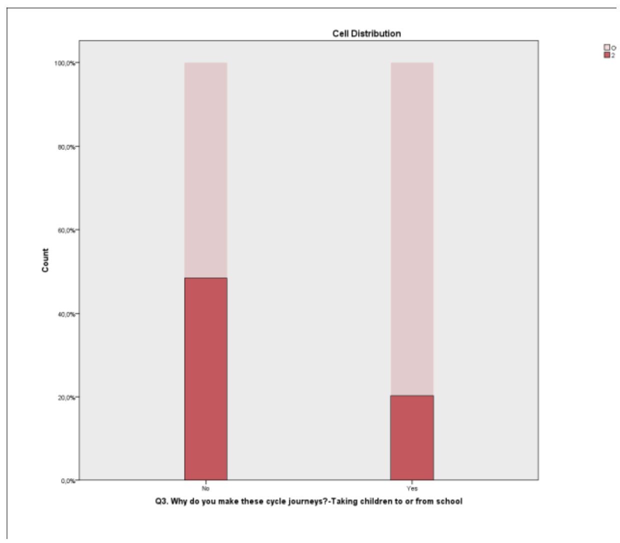
CLUSTER 1 - Everyday cyclists

CLUSTER 2 - Competitive/recreational cyclists



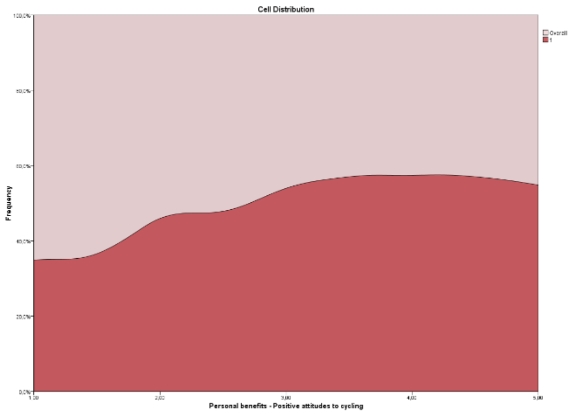


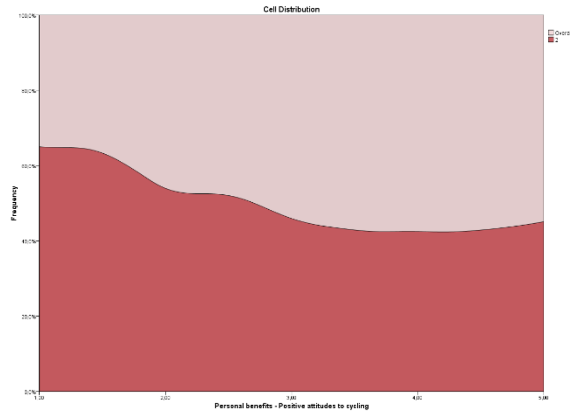


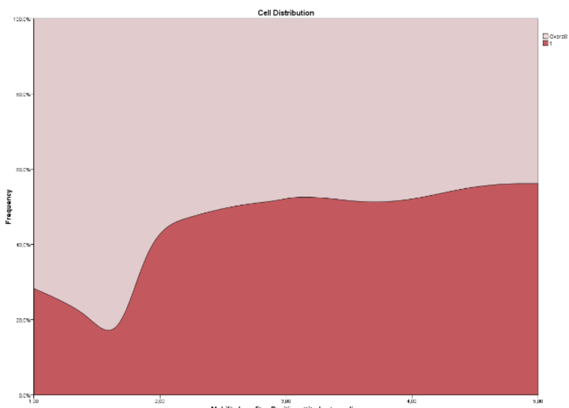


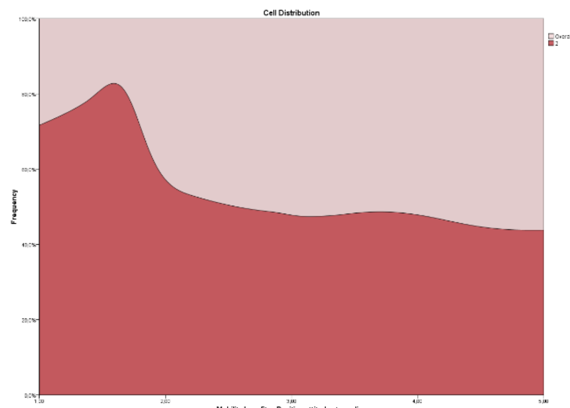
CLUSTER 1 - Everyday cyclists

CLUSTER 2 - Competitive/recreational cyclists



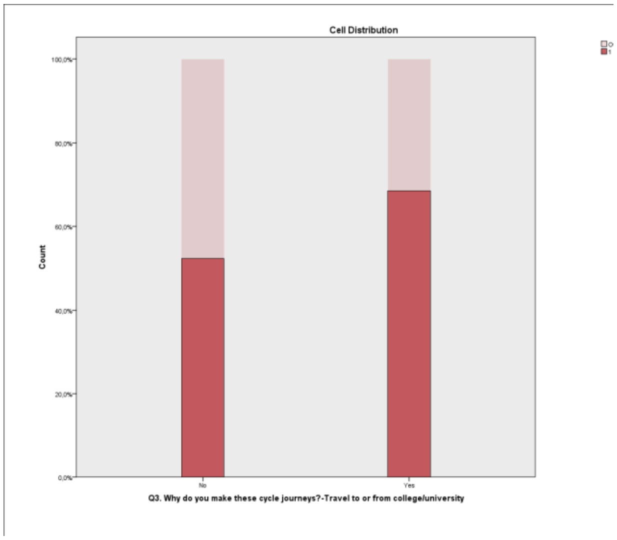


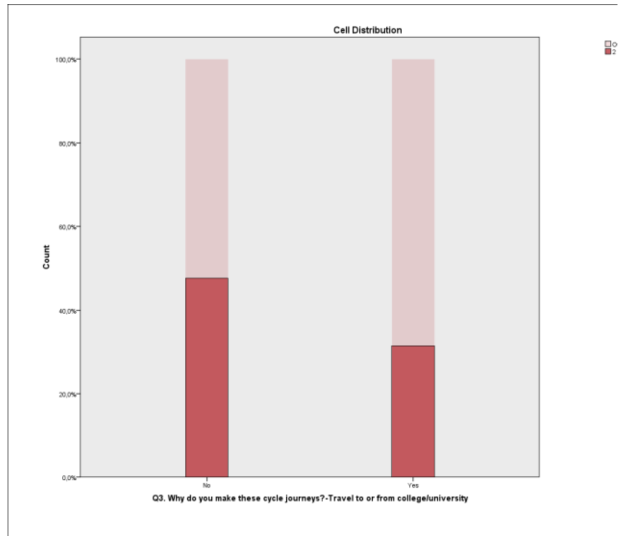


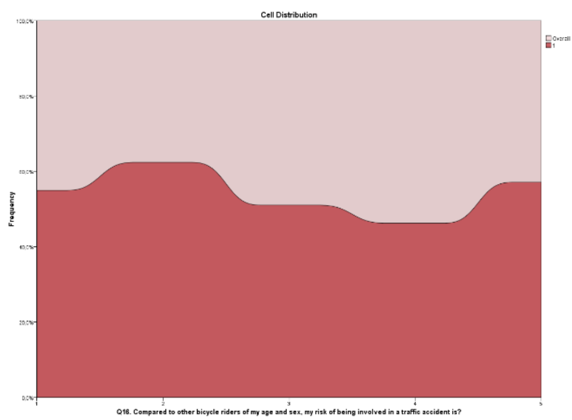


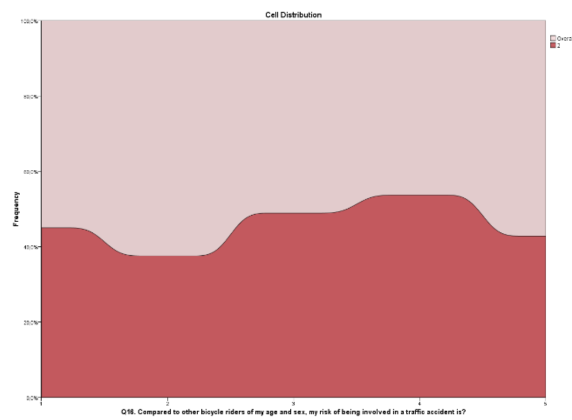
CLUSTER 1 - Everyday cyclists

CLUSTER 2 - Competitive/recreational cyclists

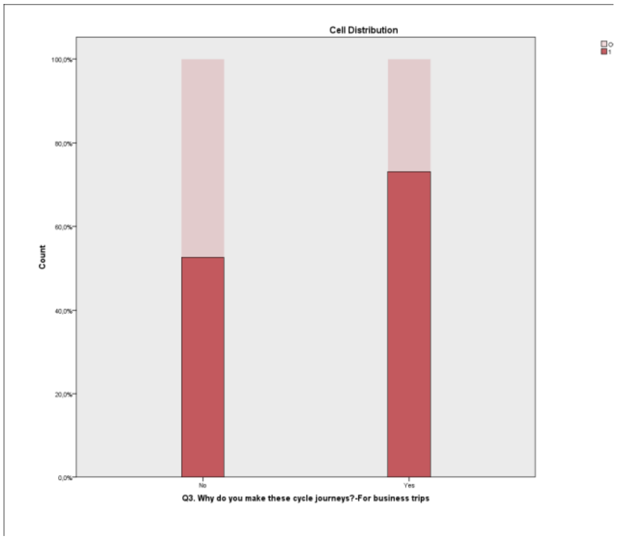




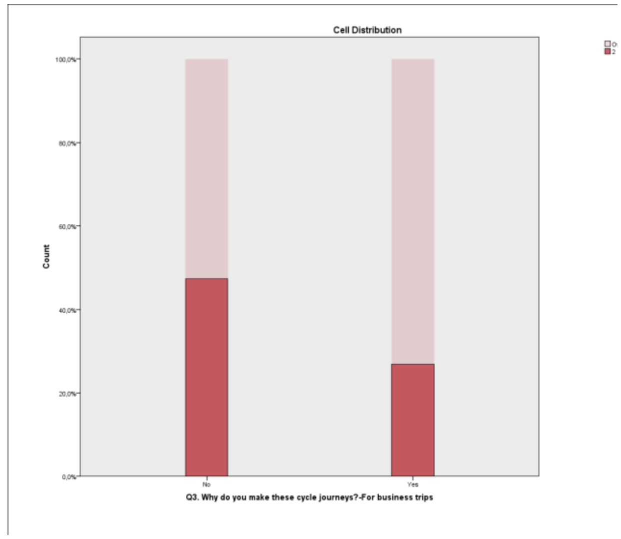


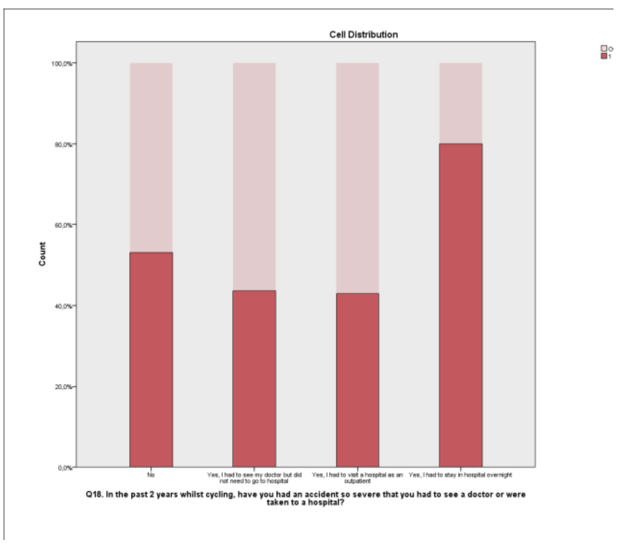


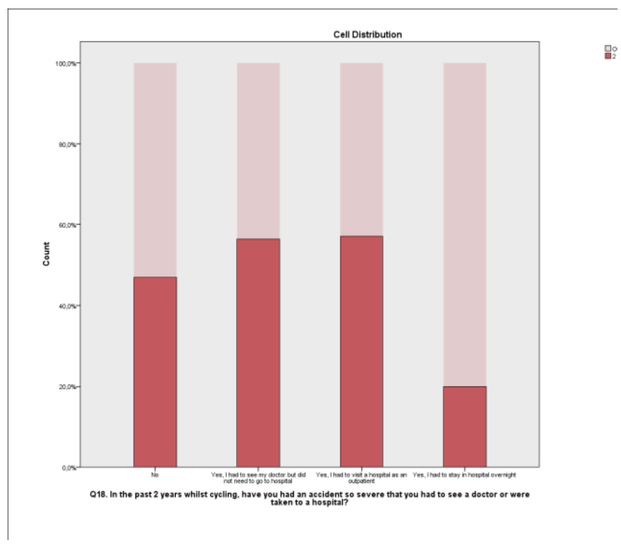
CLUSTER 1 - Everyday cyclists



CLUSTER 2 - Competitive/recreational cyclists

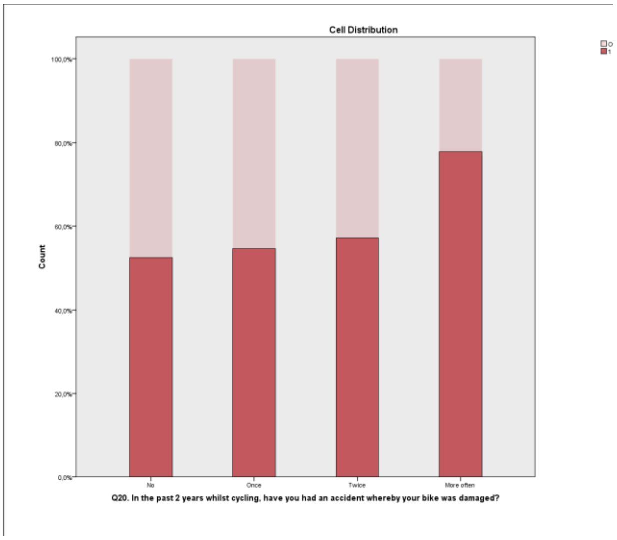


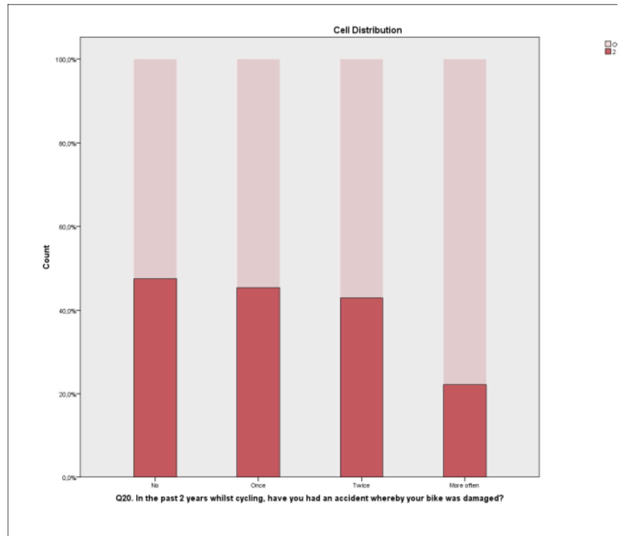


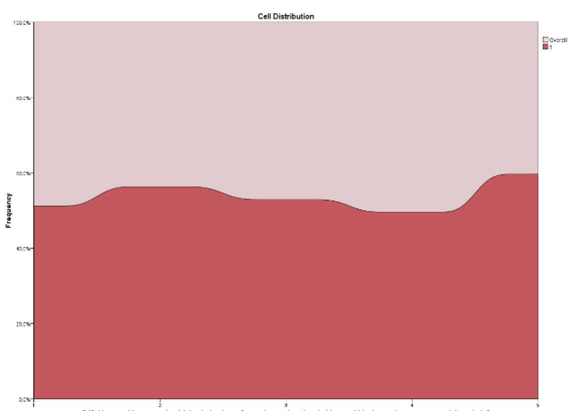


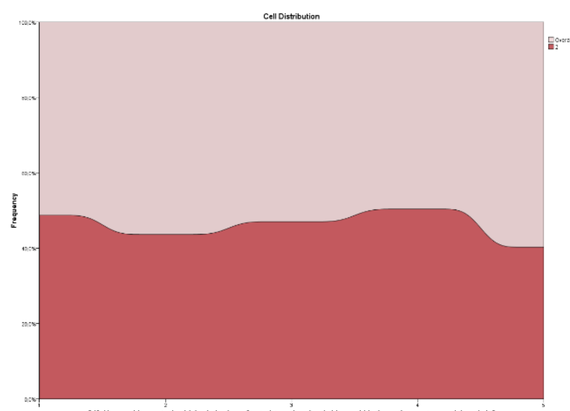
CLUSTER 1 - Everyday cyclists

CLUSTER 2 - Competitive/recreational cyclists



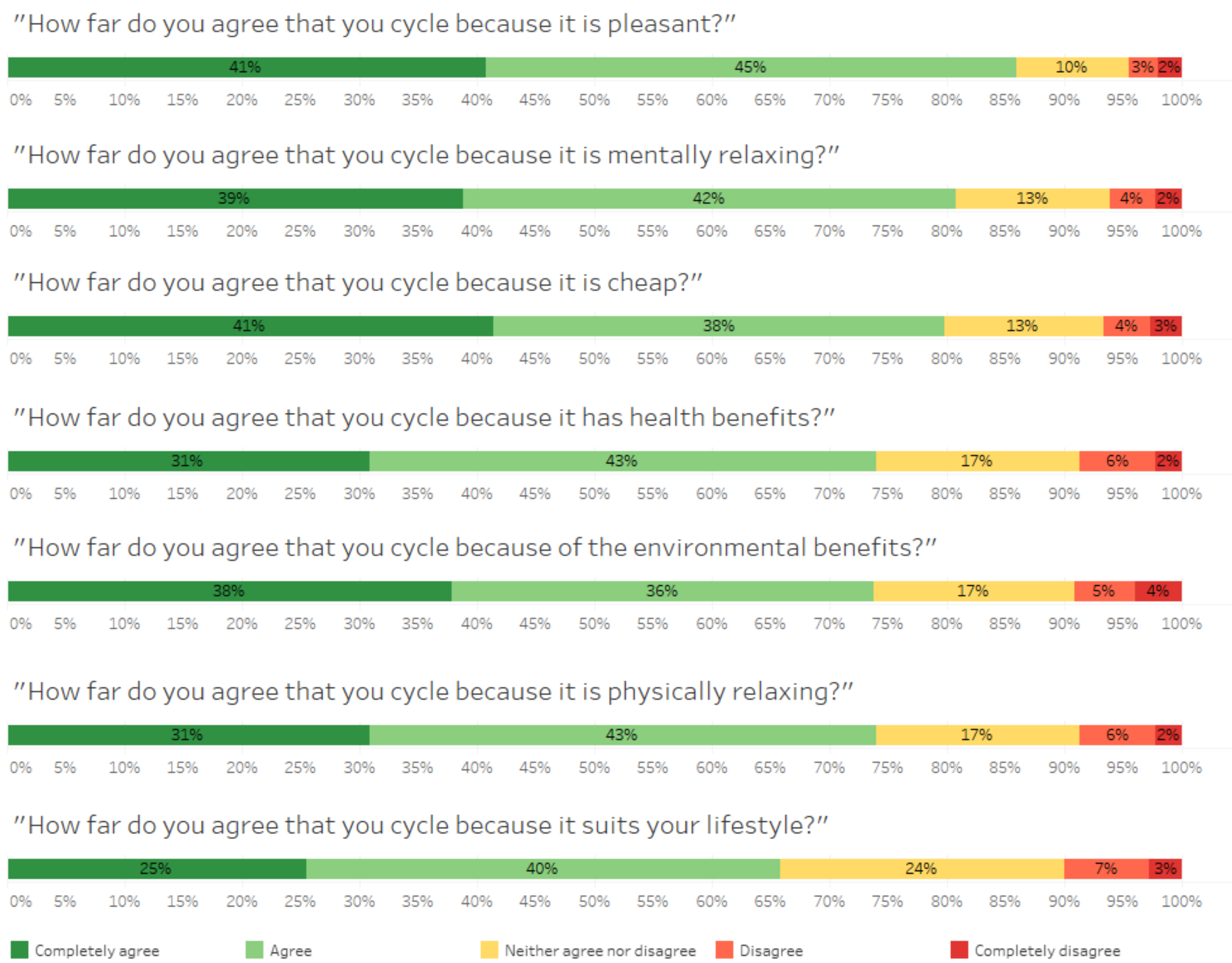




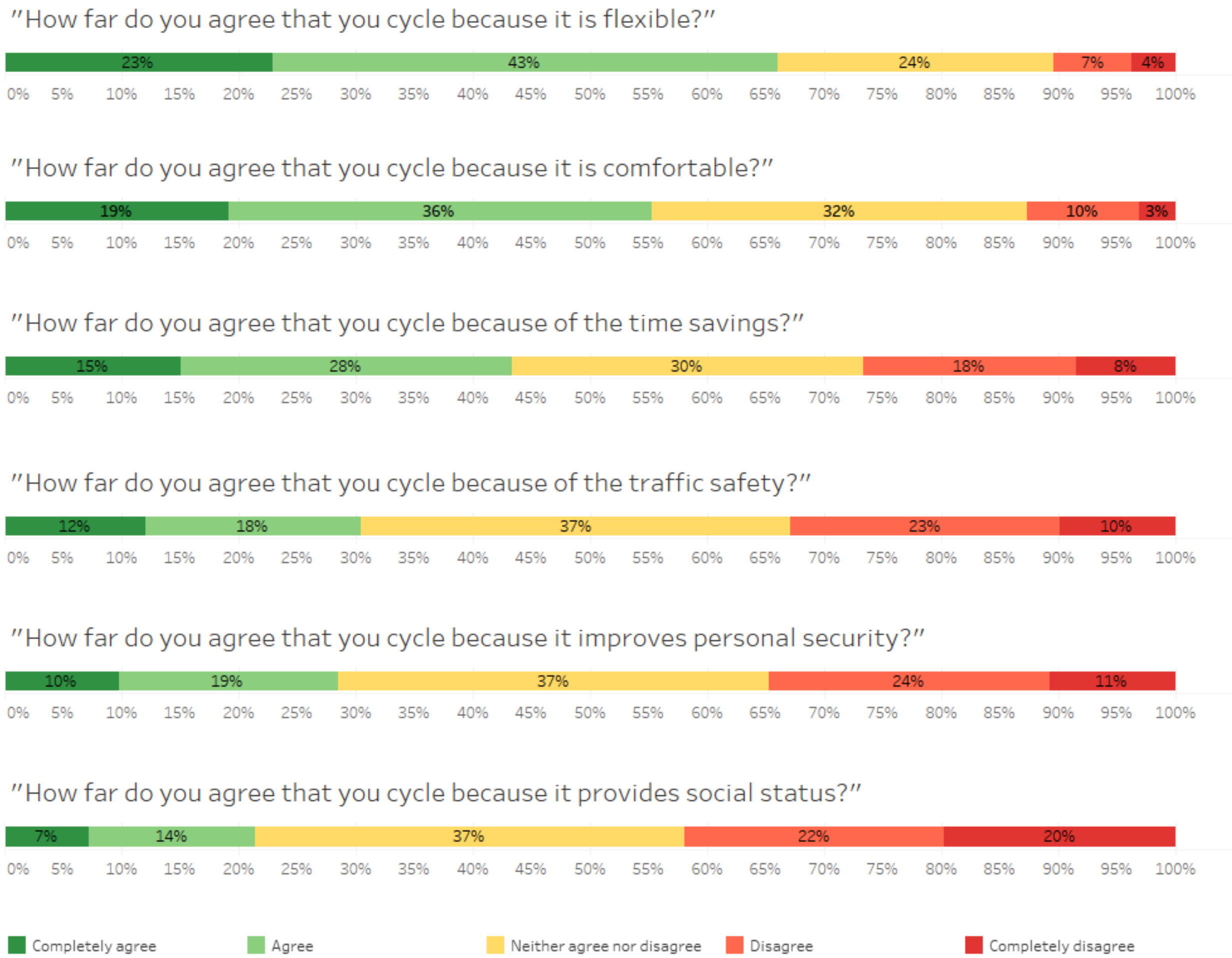


5.2 Annex 2

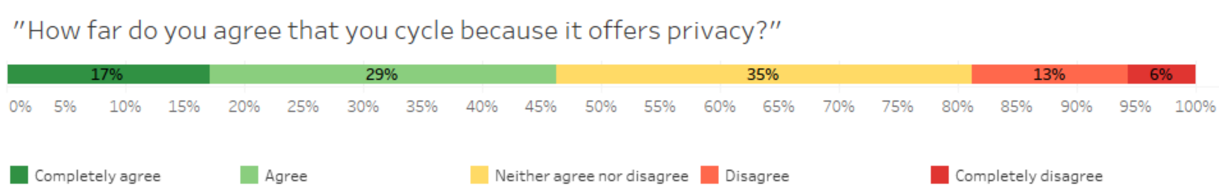
Agreement levels for cycling attitudes – *Factor 1: Personal benefits.* Note: Percentage values rounded.



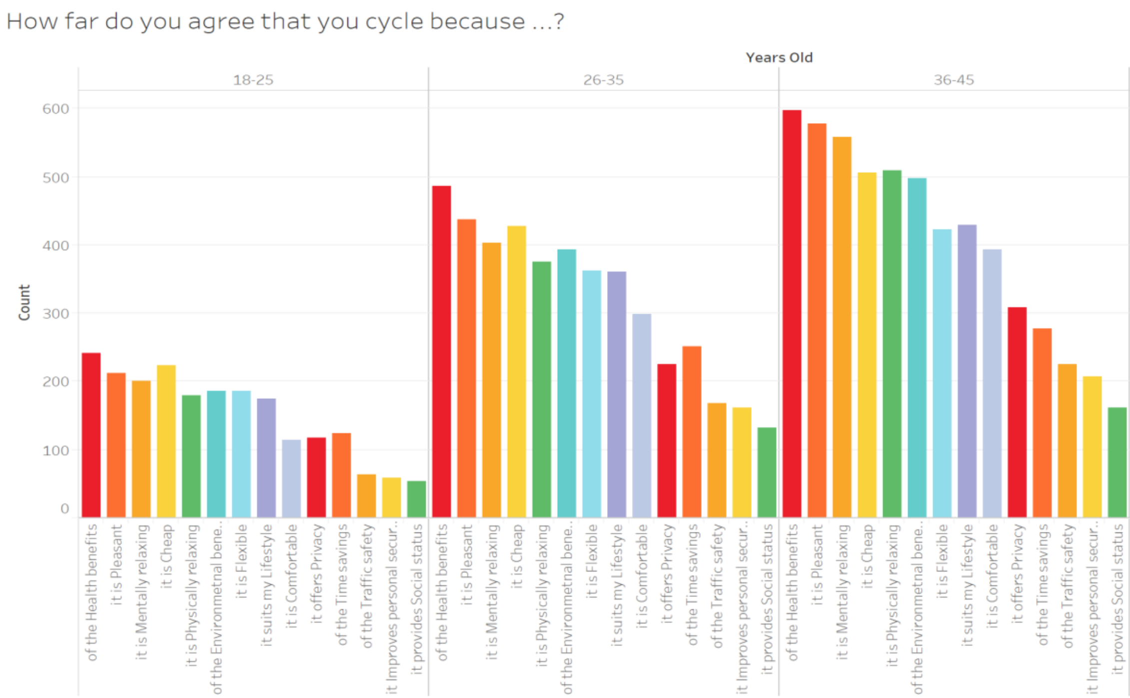
Agreement levels for cycling attitudes – *Factor 2: Benefits of cycling as a mean of transport*. Note: Percentage values rounded.



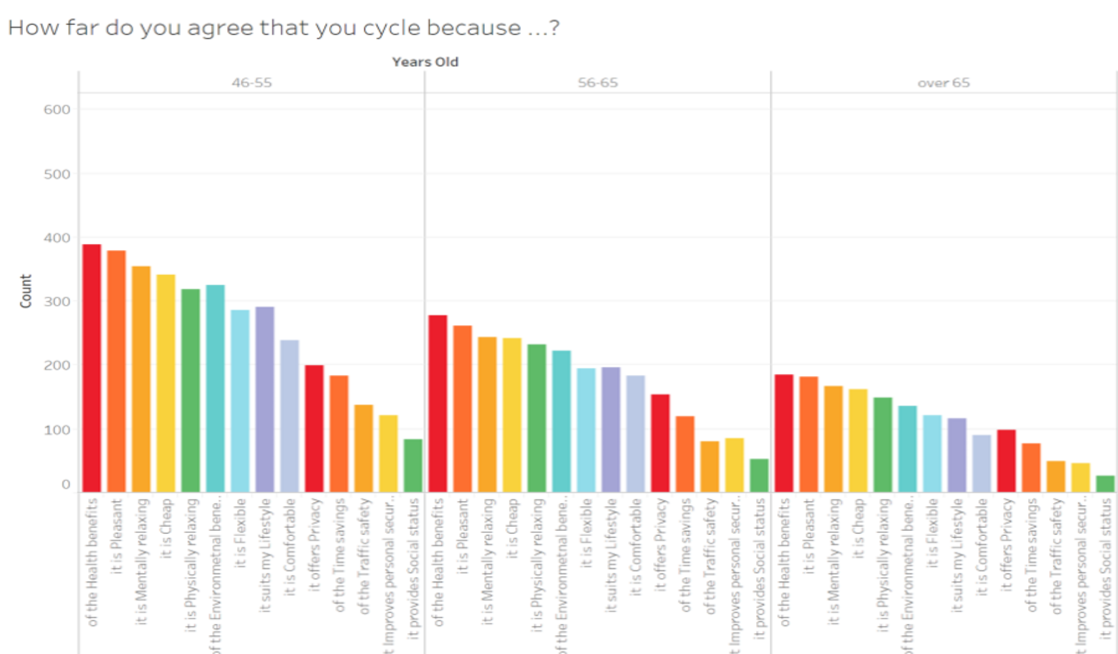
Agreement levels for cycling attitudes – *Outlier factor*. Note: Percentage values rounded.



Attitudes towards cycling agreement responses (“agree” or “strongly agree”) by age band (18-25yo, 26-35yo, 36-45yo)

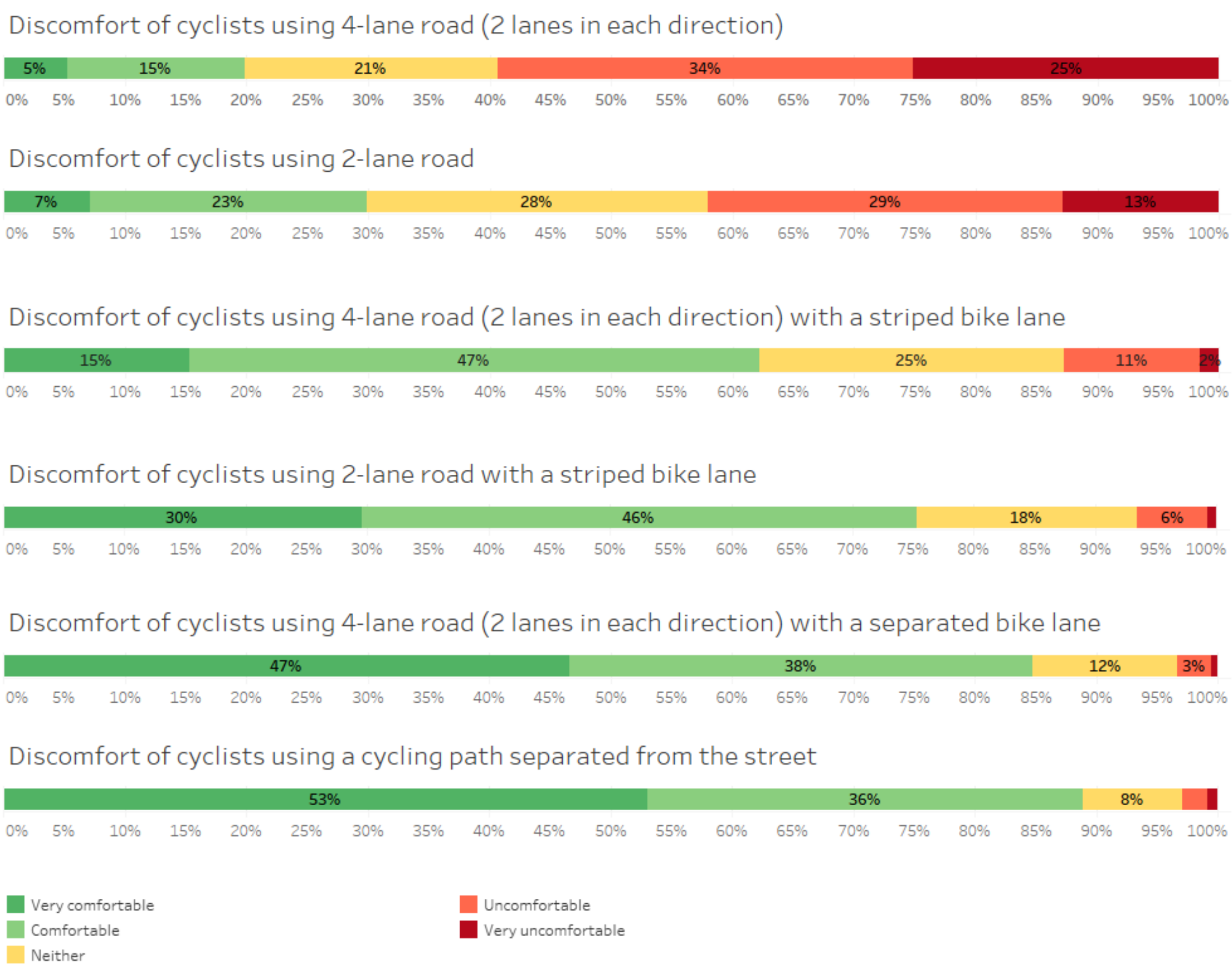


Attitudes towards cycling agreement responses (“agree” or “strongly agree”) by age band (18-25yo, 26-35yo, 36-45yo



5.3 Annex 3

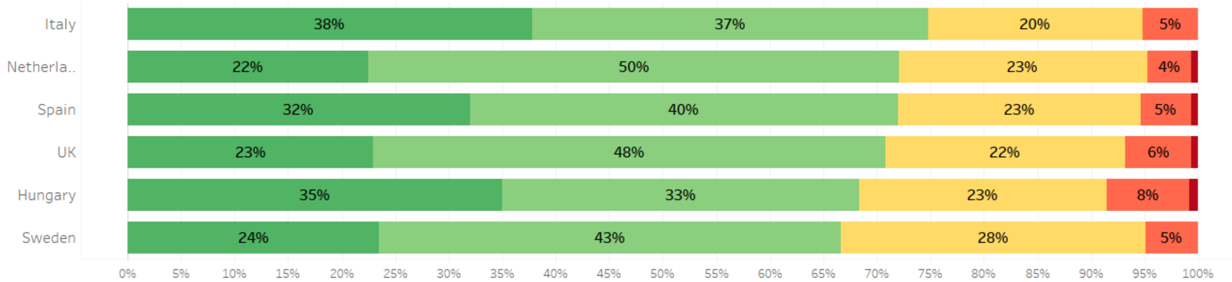
Perceived discomfort on different types of roads. Note: Values lower than 3% are not shown.



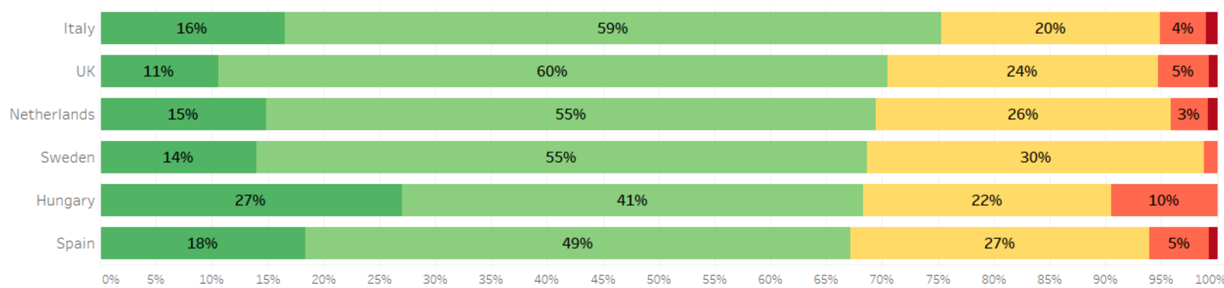
5.4 Annex 4

Change in perceived risk to be involved in a traffic accident due installation of the on-bike systems

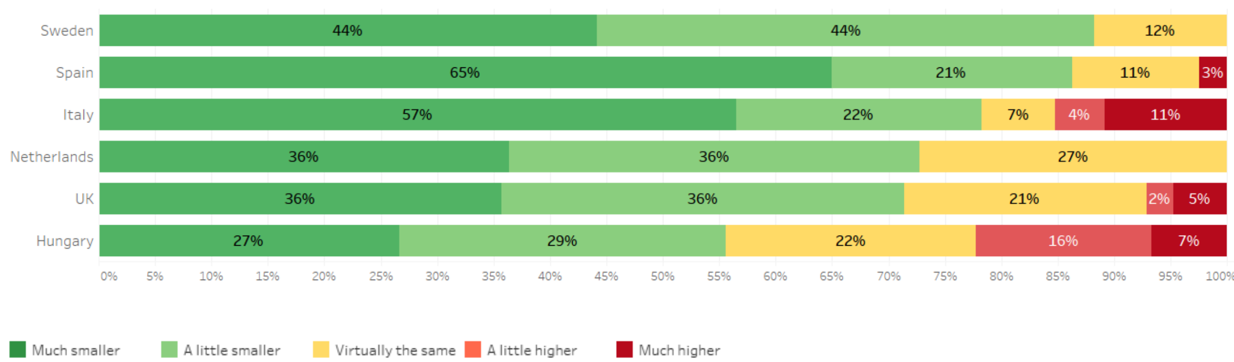
If your bike was fitted with active technology, would your risk, compared to other bicycle riders of your age and sex, of being infolved in a traffic accident be...



If your bike was fitted with passive technology, would your risk, compared to other bicycle riders of your age and sex, of being infolved in a traffic accident be...

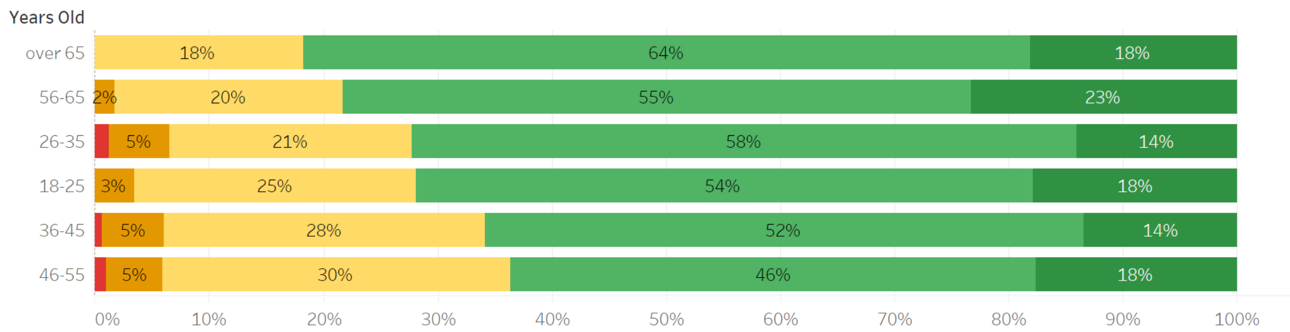


If your bike was fitted with both passive and active technology, would your risk, compared to other bicycle riders of your age and sex, of being infolved in a traffic accident be...

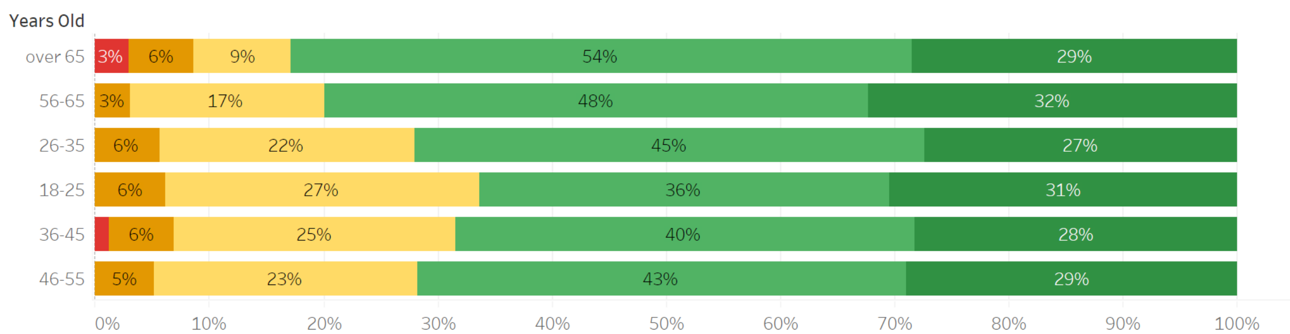


Change in perceived risk to be involved in a traffic accident due installation of the on-bike systems by age band

If your bike was fitted with passive technology, would your risk, compared to other bicycle riders of your age and sex, of being involved in a traffic accident be…



If your bike was fitted with active technology, would your risk, compared to other bicycle riders of your age and sex, of being involved in a traffic accident be…



If your bike was fitted with both passive and active technology, would your risk, compared to other bicycle riders of your age and sex, of being involved in a traffic accident be…