Journal of Transport & Health xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Journal of Transport & Health

journal homepage: www.elsevier.com/locate/jth

Towards a comprehensive safety evaluation of cycling infrastructure including objective and subjective measures

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ARTICLE INFO

Keywords:
Infrastructure evaluation
effectiveness
conflict analysis
video
passing distance
perceived safety

ABSTRACT

Cycling infrastructure has been implemented worldwide to promote bicycle use and to minimize injury risk. A comprehensive evaluation of such infrastructure is required to assess its success. In terms of safety, assessments ideally focus on both objective and subjective parameters. This study explores the application of a combined objective-subjective safety assessment approach in a pre-post analysis of a left-turning bicycle box in Zurich, Switzerland. A computer-based video technology was used to objectively measure passing distance between bicycles turning left and continuing motor vehicles passing on the right. In an in-situ survey perceived safety while crossing the intersection and a photo-based assessment of the intersection were collected as indicators of subjective safety. Median passing distance between bicycles and motor vehicles did not significantly change after the implementation of the bicycle box, but the shortest distances were increased. Perceived safety while crossing the intersection was significantly higher after marking the bicycle box, which is consistent with safety expectations expressed based on photos with and without left-turning box. Gender and general perception of traffic safety within the city are significant determinants of expected and perceived intersection safety. Women expect greater safety gains from the left-turning box (photo based), but its effect on perceived safety when actually crossing the intersection does not differ between genders. While the applied video technology is not yet practice-ready, it shows great potential to complement cycling safety evaluations, in combination with self-reported perceived safety indicators.

1. Introduction

The promotion of bicycling as a mode of transportation is pursued by cities worldwide for a host of benefits, such as being free of emissions, space-efficient, and healthy. Although health impact assessments of cycling indicate that benefits from increased physical activity outweigh injury risks (Doorley et al., 2015; Mueller et al., 2015) lack of safety in mixed-traffic remains a key issue in cycling promotion. Its negative effect is two-fold: for one, crash victims can suffer severe injuries or worse, second, the (perceived) risk of crashing deters people from cycling more, or from cycling at all (Götschi et al., 2016). Both, objective and perceived traffic safety,

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https://doi.org/10.1016/j.jth.2017.12.003

Please cite this article as: Götschi, T., Journal of Transport & Health (2017), https://doi.org/10.1016/j.jth.2017.12.003

which are not necessarily correlated (Elvik and Bjørnskau, 2005), have been identified as crucial determinants of the decision to bike (Jacobsen et al., 2009; Sanders, 2015). Equally, road and cycling infrastructure are linked to safety (Reynolds et al., 2009) and bicycle use (Rietveld and Daniel, 2004; Winters et al., 2010).

To allow decision makers to strategically invest in infrastructure to achieve maximum return on investment, the effects of different infrastructure types need to be better understood. Research investigating the effectiveness of measures to increase cycling is growing (Brand et al., 2014; Forsyth and Krizek, 2010; Ogilvie et al., 2004; Yang et al., 2010), but remains challenging. Studies that investigate the safety effects of specific infrastructure are scarce (Dill et al., 2012; Loskorn et al., 2013; Teschke et al., 2012; Zangenehpour et al., 2016, 2013).

Safety assessments of specific (small scale) cycling infrastructure face a set of challenges: a) the outcomes of interest, i.e. safety relevant incidents, are generally rare, b) common outcomes are less relevant than rare ones, e.g. light injuries vs. fatalities, and c) common outcomes, e.g. light injuries and falls, are harder to measure than rare ones. Quantitative safety assessment therefore first of all face a challenging trade-off between focusing on *accurate measures of highly relevant but extremely rare events* vs. *crude measures of less safety relevant proxy-measures that are sufficiently common* to be statistically analyzed. As such, what traffic safety research refers to as the low mean problem (Lord, 2006), is particularly aggravated for cycling. This highlights the importance of alternative methods that are based on surrogate safety and behavioral measures.

A range of indicators can be considered when assessing objective safety of cycling, such as the crude number of crashes, injuries or fatalities; or expressed as rates per inhabitant, trip, distance or time travelled. Each of these indicators has its pros and cons concerning reliability and accuracy (Götschi et al., 2016). Thus, existing data on traffic crashes, in particular minor crashes or injuries and those that do not involve vehicles, might not be accurate enough (Götschi et al., 2016). Hospital and police records often do not completely correspond to each other due to underreporting (Agran et al., 1990; Aptel et al., 1999; Juhra et al., 2012). Both underestimate actual crashes. In contrast, data on fatalities or severe injuries can be more accurate but they lack statistical reliability due to the limited sample size of such rare events. When assessing cycling safety for a specific infrastructure, as compared to a whole city or country, this problem is aggravated because of the low number of crashes. The same challenge applies to determining denominators to derive risk estimates, i.e. crash rates. For large areas, population data or travel surveys can provide denominators to be combined with crash statistics, but for a specific infrastructure project, exposure data is not readily available.

In order to avoid the issue of low numbers of actual crashes, analyses based on conflicts provide an alternative. Surrogate measures of safety such as vehicle speed, distance between conflict-involved vehicles, post encroachment time or time to collision are examples of indicators used in conflict analyses (Gettman and Head, 2003; St-Aubin et al., 2014; Tarko et al., 2008).

Some data required for conflict analysis can be collected by means of manual traffic inspection of video recordings (e.g. Phillips et al., 2011), but this technique is time and resource consuming. In order to improve efficiency computer-based video technologies that automatically recognize road users, classify them by transportation modes (motor vehicle, bicycle and pedestrian), track their paths, and measure conflict indicators have been developed and applied (Zaki and Sayed, 2013; Zangenehpour et al., 2016, 2015). As such, computer-based video technology is promising both with regards to objectively and accurately measuring safety indicators and with regards to capturing sufficiently large samples.

A second objective of comprehensive safety evaluations of cycling infrastructure is to understand the role of (lack of) safety on cycling behavior. Many cyclists are reluctant to cycle on a particular infrastructure or across an intersection if they perceive it as dangerous (Lawson et al., 2013). Therefore, understanding subjective measures of safety plays an important role in cycling promotion. Surveys of infrastructure users are the method of choice to capture safety perceptions. Household surveys have been used for the assessment of traffic safety perception in large areas (e.g. Rissel, et al., 2010), but for the evaluation of specific infrastructures, in-situ surveys promise more accurate information.

Evaluation of cycling safety infrastructure considering a combination of both objective and subjective parameters is rare and is mainly based on injury data and household surveys (Cho et al., 2009; e.g. Winters et al., 2012). The aim of this study was to apply a comprehensive approach to safety analysis of a specific cycling infrastructure. The pre-post evaluation combines objective safety indicators automatically derived by video analysis technology and subjective indicators collected through an in-situ survey. To investigate the feasibility of the suggested approach, it was applied to a left-turning bicycle box in Zurich, Switzerland, marked specifically to increase passing distance between left turning cyclists and motor vehicles on the right (Fig. 1).

The specific research questions addressed were:

- What are the expectations of cyclists with regards to safety improvements due to the bicycle box?
- What is the effect of the bicycle box on the perceived safety of cyclists crossing the intersection?
- What is the effect of the bicycle box on the passing distance between cyclists and motor vehicles?

2. Methodology

2.1. Study setting

The site for the case study was chosen in collaboration with the City of Zurich, based on three criteria: 1) high traffic density of cyclists and motor vehicles, 2) traffic flows potentially leading to conflicts between both types of road users, and 3) feasibility to mark a left-turning box. As a result, the non-signalized intersection of Sonneggstrasse and Universitätstrasse was selected (Fig. 1). This site is located close to the Swiss Federal Institute of Technology and the University of Zurich, which implies a large number of students riding by bicycle. The left-turn maneuver can be challenging for cyclist in light of crossing tram tracks with frequent tram passings

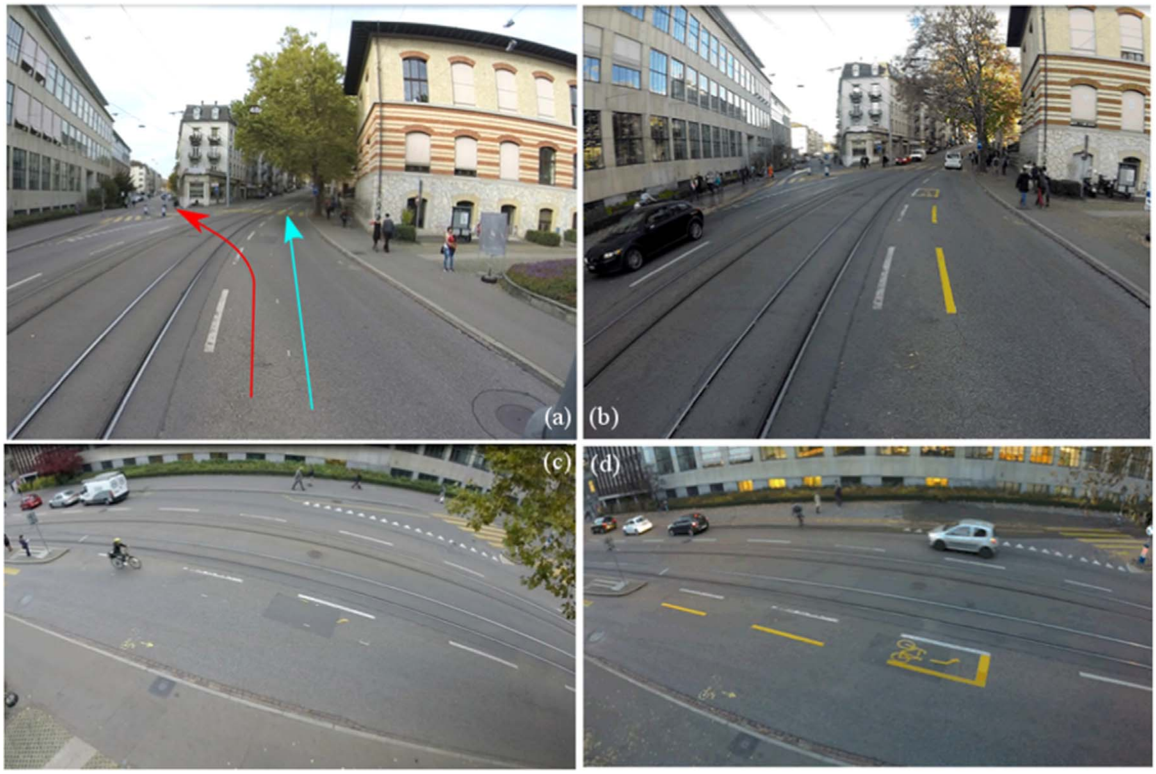

Fig. 1. Site of the case study before (a, c) and after (b, d) marking of the left-turning bicycle box. Video footage used included ground perspective from camera 1 (a, b) and bird's eye view from camera 2 (c, d). The red arrow shows the trajectory of left-turning bicycles and the blue arrow shows the trajectory of motor vehicles passing them on the right (a).

approx. every 2 min, and often heavy car traffic. A left-turning bicycle box was marked halfway through the project (24th October 2015) by the City of Zurich with the intention to increase passing distance between bicycles turning left (red arrow in Fig. 1a) and motor vehicles passing them on the right going straight (blue arrow in Fig. 1a).

2.2. *Computer-based video technology*

Objective safety was assessed using computer-based video analysis, which applied an algorithm developed by Zangenehpour et al. (2015). To optimize and adapt the use of this technology to local settings, field tests were carried out at two different sites, evaluating the effects of red painted bike lanes, intended to alert drivers of crossing-maneuvers with cyclists (see Appendix A). The tests revealed that camera position, battery status, time of day, and weather conditions can affect the reliability of the results. These insights from the field tests were taken into account when developing the study protocol for the evaluation of the left-turning box.

The site of the case study was filmed before (3rd, 8th and 20th October 2015) and after (10th and 19th November 2015) the implementation of the bicycle box. Two GoPro Hero 3+ Silver cameras were used to film the intersection. Before choosing the final camera angles six alternatives were tested by inspect short video sequences of a few minutes for possible inconveniencies and potential problems. Finally, the intersection was filmed from two different angles (Fig. 1): Camera 1 was installed on an existing tramway signposting about 2.5 m above ground to provide a ground perspective that enabled the measurement of distances between road users. Camera 2 was fixed to a 10 m high ad-hoc telescopic stick and provided a bird's eye perspective that enabled the identification of trajectories of road users.

To yield a large number of interactions between motor vehicles and cyclists, the intersection was filmed for a considerably longer period of time than in the field tests (about 17.5 recording hours, more than 3 h each day), exclusively during well-frequented hours in the afternoon (between 14:00 and 18:00) and decent weather conditions. Battery discharge times were assessed prior and exchange procedures were timed to minimize recording gaps. Cloudy sky was considered optimal to film, since it does not cause sunbeams that blur images, or shadows that can be challenging for the shape recognition algorithm.

The distance between left-turning bicycles and passing motor vehicles was selected as the surrogate indicator of objective safety. The algorithm of the video technology was calibrated with the involved road directions to recognize relevant road users and conflicts. It was initially planned that footage from camera 2 would be processed by the algorithm to a) identify road users in these directions, b) to track their trajectories and c) to classify road users as bicycles or as motor vehicles based on their speed, appearance and movement patterns. Footage from camera 1 would be used to measure distances. However, the automatic recognition of road users

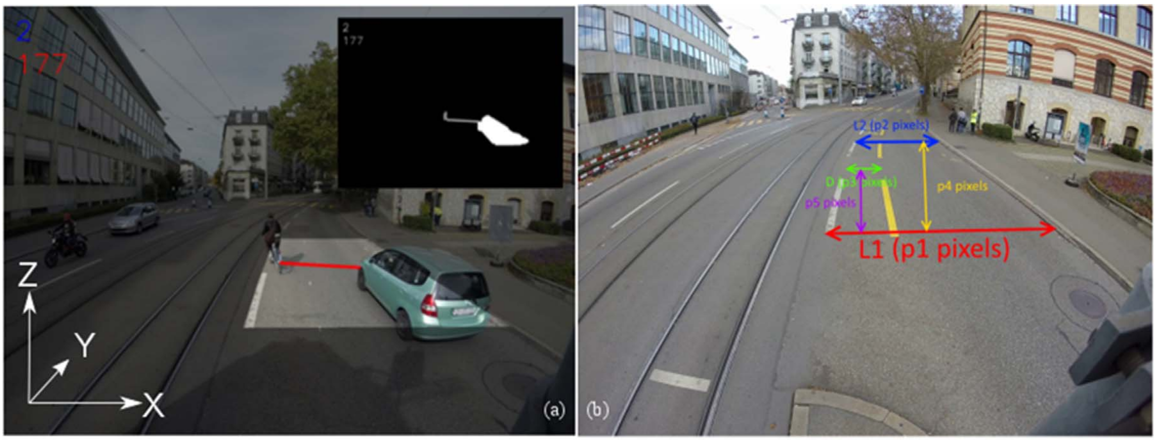

Fig. 2. Example of distance measurement including the light square where the algorithm measure distances and the black background showing the object shapes computed by the algorithm (a) as well as correction of foreground-background deviation (b).

was unsatisfactory with the input from camera 2. Only about 10% of the actual number of left turning bicycles was identified correctly. As a result, the original plan had to be modified as follows: a) the automatic road user and conflict recognition from camera 2 was dropped. b) a new algorithm was developed instead, which identified potential conflicts as two road users passing next to each other and measured their closest distance, using footage from camera 1 (Fig. 2). c) these cases were manually classified by vehicle type to select the relevant interactions, such as bicycles turning left when motor vehicles pass them on the right. d) Finally, these distances were manually validated, selecting only those that captured distances perpendicular to the road users and parallel to the ground.

For every conflict the algorithm captured 15 frames per second and provided the corresponding distances. Distances were initially measured in pixels and in a later step transformed into meters. The algorithm automatically measured the horizontal distances (axis X in Fig. 2a), allowing for a vertical deviation of ± 5 pixels tolerance (axis Z). To avoid a deviation that underestimates distances of situations located far away from the camera (axis Y) the following linear correction was applied, which accounted for the angled perspective:

$$Corrected\ \ D = L_2 * \left[\left(\frac{p_5}{p_4}\right) * \left(\frac{p_3}{p_2}\right)\right] + L_1 * \left[\left(1 - \left\{\frac{p_5}{p_4}\right\}\right) * \left(\frac{p_3}{p_1}\right)\right];$$

where L_1 and L_2 were distances measured and p_3 was calculated by the algorithm that was introduced in the formula to obtain the corrected distance (Fig. 2b).

The manual validation of distances involved a selection of the best available measurement for each conflict out of the available frames, inspecting the distance measurement between vehicle and bicycle (red line in Fig. 2a) with regards to level height above ground (i.e. perpendicular to axis Z) and equal distance from the camera (perpendicular to axis Y). Moderate deviations from these criteria were considered acceptable. During this process several identified conflicts had to be discarded because no measurement was considered sufficiently valid (see Discussion).

2.3. *In-situ survey*

Simultaneously to the video recordings, before and after the implementation of the left-turning bicycle box, in-situ surveys were carried out to assess subjective safety indicators. A signpost alerted cyclists that had just turned left about the survey. Two uniformed policemen assisted the survey asking cyclists to pull over and take part in the survey. The survey itself was conducted by two interviewers employed by University of Zurich. The questionnaire (see Appendix B) was administrated using SurveyGizmo and filled out on a Smartphone or Tablet. The survey participants received a set of bicycle lights as acknowledgement.

Survey participants were first asked to rate how they experienced crossing the intersection (perceived safety) on a scale from 1–10. After some questions regarding possible improvements, participants were asked to rate the counterfactual situation based on a picture (expected safety). Before the bicycle box marking, respondents were shown an altered picture showing the future bicycle box, while after the actual marking they were shown a picture of the intersection without the bicycle box. In addition, participants were asked about a number of potentially safety relevant factors, such as their assessment of general cycling safety in the city of Zurich, demographic aspects such as gender, age group, and nationality, whether they grew up in rural or urban areas, about their cycling skills (frequency and years cycled), helmet use and type of bicycle (e-bike or standard).

The influence of these co-variables on perceived and expected safety was modeled in multivariate linear regressions. Variables were selected based on their significance, magnitude of effects, and influence on other coefficients as well as based on a priori considerations. Three models are presented to illustrate the most relevant findings.

Data were analyzed using STATA 13 statistical software (www.stata.com).

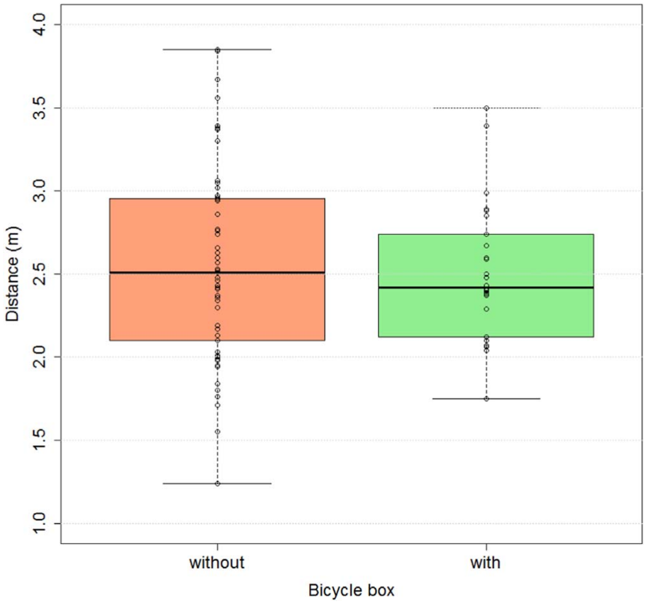

Fig. 3. Passing distance between motor vehicles and left-turning bicycles without and with bicycle box.

3. Results

3.1. Objective safety assessment

Within the 17.5 recording hours of this project the video algorithm identified 521 *potential conflicts*, i.e. two road users passing each other. The subsequentmanual validation extracted 110 *relevant interactions*, i.e. bicycles turning left, passed by a motor vehicle on the right. 21 cases were discarded due to invalid measurements (see Discussion). As a result, a remaining sample of 89 valid cases (59 before and 30 after the implementation of the bicycle box) was used for the analysis of passing distance (objective safety).

Fig. 3 shows the resulting distance quartiles without and with left-turning bicycle box. The median distances between bicycles turning left and passing motor vehicles before (2.51 m) and after (2.42 m) implementing the bicycle box were not statistically different (Wilcoxon p-value = 0.77). However, shortest distances were noticeably larger with the left-turning bike box than without.

3.2. Subjective safety assessment

277 cyclists that just turned left at the studied intersection took part in the in-situ survey, 178 persons before (pre-survey) and 99 after the implementation (post-survey). Average survey duration was 4.5 min. Thanks to the uniformed policemen there was a very high participation rate. Non-participation only happened when fieldworkers were overwhelmed with interviewing, and as such occurred randomly. There were no refusals to participate once stopped by the police.

The survey results (Table 1) reveal that perceived safety increased significantly after implementing the bicycle box. On a scale from 0 (very unsafe) to 10 (very safe) respondents assessed cycling safety at the intersection without bicycle box with a mean score of 5.17, and 5.84 with the bicycle box. Based on a picture showing a recreation of the bicycle box before the implementation respondents in the pre-survey expected higher safety scores (6.84), while after the implementation respondents in the post-survey rated a picture without the bicycle box significantly lower (4.10). The difference between expected and perceived safety was consistent between the pre and post participants, despite the inverse constellation of the actual vs. counterfactual situation, i.e. + 1.67 expected improvment in the pre survey, vs. − 1.74 expected reduction in safety in the post survey. Both groups (pre and post) rated general safety conditions for cycling in the city of Zurich similarly (5.82 in the pre-survey and 5.75 in the post-survey).

Looking at the respondent profiles no significant differences were found between the pre and post groups in terms of cycling frequency as well as country and area of upbringing. Around 95% of respondents used the bicycle every day or almost every day, about three quarters grew up in Switzerland and more than half in urban areas. However, some differences were found in terms of gender, age, cycling experience as well as helmet and e-bike use. In the pre-survey the share of males (60%), and participants aged 21 to 30 (39%) was higher than in the post-survey (50% and 23%, respectively), while the share of ages of 41 and 60 was lower (23% versus 34%). Moreover, the share of respondents wearing helmet (58%), riding with an e-bike (6%), and having more than one year of cycling experience (56%) was lower in the pre-survey than in the post-survey (65%, 14% and 67% respectively).

While across both surveys expected safety was rated higher than perceived safety, the difference between perceived and expected safety was notably smaller in men (0.53), compared to women (1.26).

Table 2 shows the three most relevant multivariate regression models that predict both perceived and expected safety

Table 1
Results of the in-situ survey before and after the implementation of the left-turning bicycle box.

Variable	Survey answer	Before the bicycle box (N = 178)			After the bicycle box (N = 99)			t-test/ chi^2
		Value	Confidence interval (95%)	N	Value	Confidence interval (95%)	N	p-value
Perceived safety at the intersection	Score from 0 (very unsafe) to 10 (very safe)	(mean) 5.17	(4.83 – 5.51)	178	(mean) 5.84	(5.37 – 6.31)	99	0.02
Expected safety based on a picture (before = with; after = without bicycle box)	Score from 0 (very unsafe) to 10 (very safe)	(mean) 6.84	(6.59 – 7.09)	177	(mean) 4.10	(3.59 – 4.61)	99	0.00
Generally perceived safety in Zurich	Score from 0 (very unsafe) to 10 (very safe)	(mean) 5.82	(5.54 – 6.1)	178	(mean) 5.75	(5.35 – 6.15)	99	0.77
Gender				178			99	0.12
	Male	50%	(43% – 57%)	89	60%	(50% – 69%)	59	
	Female	50%	(43% – 57%)	89	40%	(31% – 50%)	40	
Age group				178			99	0.17
	0–20	9%	(6% – 14%)	16	10%	(5% – 18%)	10	
	21–30	39%	(35% – 43%)	69	27%	(22% – 34%)	27	
	31–40	27%	(23% – 31%)	48	24%	(19% – 31%)	24	
	41–60	23%	(19% – 28%)	41	34%	(29% – 41%)	34	
	> 60	2%	(0% – 14%)	4	4%	(1% – 17%)	4	
Cycling frequency				178			99	0.84
	1 to 3 times per day	6%	(3% – 10%)	11	5%	(2% – 12%)	5	
	Daily or almost daily	94%	(90% – 97%)	167	95%	(88% – 98%)	94	
Cycling experience				178			99	0.07
	< 1 year	44%	(37% – 52%)	78	33%	(25% – 43%)	33	
	> 1 year	56%	(48% – 63%)	100	67%	(57% – 75%)	66	
Country of upbringing				178			99	0.94
	Switzerland	74%	(67% – 80%)	132	74%	(64% – 82%)	73	
	Other	26%	(20% – 33%)	46	26%	(18% – 36%)	26	
Land use type of upbringing				178			99	0.77
	Urban area (> 20,000 inhabitants)	53%	(46% – 61%)	94	52%	(42% – 61%)	51	
	Rural area (< 20,000 inhabitants)	47%	(39% – 54%)	84	48%	(39% – 58%)	48	
Helmet				177			99	0.25
	Yes	58%	(50% – 65%)	103	65%	(55% – 74%)	64	
	No	42%	(35% – 50%)	74	35%	(26% – 45%)	35	
Bicycle type				176			99	0.03
	E-bike	6%	(3% – 11%)	11	14%	(9% – 23%)	14	
	Conventional bicycle	94%	(89% – 97%)	165	86%	(77% – 91%)	85	

respectively. Model 1 comprises, aside of the availability of the left-turning bicycle box, two basic control variables: gender and age. Model 2, in addition, included the assessment of general safety for cycling in Zurich and explained most of the variance (adjusted-R^2). Finally, Model 3 includes additional variables and assesses effect modification of the bicycle box by gender.

The regression analysis confirms that perceived cycling safety of survey participants significantly increases with the bicycle box (coefficient = 0.65 in Model 1p). Safety perception is lower among women (− 0.92 in Model 1p), while it is higher among persons that positively assess general cycling safety in the city of Zurich (0.43 in Model 2p). The above mentioned effects are significant and robust with regards to additional adjustments (Model 3p). Being young, cycling frequently and since a long time, growing up in a Swiss rural area, wearing no helmet, as well as riding a conventional non-electric bicycle seem to increase safety perception at the intersection, but these effects are not statistically significant. The effect of the left-turning bicycle box is the same for men and women (insignificant interaction term: − 0.12 in Model 3p).

In the assessment of expected safety based on a picture, the bicycle box increases expected safety by 2.73 (significant effect in Model 1e, adjusted for age and gender), which is considerably more than the perceived effect after actually crossing the intersection (0.65 in Model 1p).

The effects of other variables in the regression models for expected safety are similar to those for perceived safety: significant effects of gender and general safety perception of the city (− 0.83 in Model 1e and 0.29 in Model 2e, respectively), as well as no significant effects of age, cycling frequency and experience, country, land use type of upbringing, and helmet.

However, the interaction coefficient of bicycle box and female gender is significant (Model 3e), indicating that female cyclists

Table 2
Multivariate linear regression of expected and perceived safety of the studied intersection (95% confidence interval in brackets).

Predictor [category]	Expected safety based on a picture			Perceived safety at the intersection		
	Model 1e	Model 2e	Model 3e	Model 1p	Model 2p	Model 3p
Bicycle box [with]	2.73** (2.23 – 3.23)	2.70** (2.22 – 3.18)	1.91** (1.28 – 2.54)	0.65* (0.08 – 1.23)	0.70* (0.16 – 1.23)	0.77* (0.05 – 1.50)
Gender [woman]	− 0.83** (− 1.31 – − 0.35)	− 0.73** (− 1.19 – − 0.27)	− 1.81** (− 2.57 – − 1.05)	− 0.92** (− 1.47 – − 0.37)	− 0.76** (− 1.27 – − 0.24)	− 0.77* (− 1.42 – − 0.12)
Age group [21–30]	− 0.04 (− 0.91 – 0.83)	− 0.23 (− 1.07 – 0.61)	− 0.17 (− 1.00 – 0.66)	0.53 (− 0.47 – 1.53)	0.24 (− 0.69 – 1.18)	0.24 (− 0.72 – 1.20)
Age group [31–40]	− 0.30 (− 1.19 – 0.60)	− 0.35 (− 1.22 – 0.51)	− 0.14 (− 1.04 – 0.76)	0.31 (− 0.72 – 1.35)	0.22 (− 0.74 – 1.19)	0.13 (− 0.91 – 1.17)
Age group [41–60]	− 0.96* (− 1.85 – − 0.06)	− 1.11* (− 1.97 – − 0.25)	− 1.03* (− 1.93 – − 0.13)	− 0.27 (− 1.29 – 0.76)	− 0.49 (− 1.45 – 0.48)	− 0.68 (− 1.71 – 0.36)
Age group [60+]	0.75 (− 0.83 – 2.34)	0.50 (− 1.03 – 2.03)	0.57 (− 0.97 – 2.11)	1.53 (− 0.30 – 3.35)	1.15 (− 0.56 – 2.85)	0.97 (− 0.81 – 2.75)
Generally perceived safety in Zurich		0.29** (0.17 – 0.41)	0.28** (0.16 – 0.39)		0.43** (0.30 – 0.56)	0.43** (0.30 – 0.57)
Cycling frequency [daily or almost daily]			0.28 (− 0.74 – 1.30)			0.23 (− 0.91 – 1.36)
Cycling experience [> 1year]			0.20 (− 0.32 – 0.71)			0.43 (− 0.17 – 1.02)
Country of upbringing [foreign country]			− 0.38 (− 0.91 – 0.14)			− 0.14 (− 0.75 – 0.47)
Land use of upbringing [rural area]			− 0.03 (− 0.48 – 0.43)			0.10 (− 0.43 – 0.63)
Helmet [no]			0.12 (− 0.35 – 0.59)			− 0.29 (− 0.83 – 0.25)
Bicycle type [conventional bicycle vs. e-bike]			1.25** (0.44 – 2.06)			0.77 (− 0.17 – 1.70)
Interaction [bicycle box × woman]			1.58** (0.64 − 2.52)			− 0.12 (− 1.20 – 0.97)
Constant	4.82** (3.97 – 5.67)	3.26** (2.21 – 4.30)	2.26** (0.70 – 3.82)	5.37** (4.42 – 6.32)	2.96** (1.81 – 4.11)	1.96* (0.20 – 3.72)
Adjusted R^2	0.33	0.38	0.42	0.06	0.18	0.18
F-statistic	23.77	25.24	15.07	3.89	9.78	5.32
N	276	276	274	277	277	275

expect substantially higher safety improvements due to the bicycle box (+1.58 in Model 3e). Adjusted-R^2 values are noticeably higher in all models of expected safety than for perceived safety.

4. Discussion

This evaluation of a left-turning bicycle box revealed that cyclists' expectations are in line with planners' intentions to improve safety and that the bicycle box significantly increases perceived safety when crossing the intersection. However, a corresponding effect on the objective safety indicator "passing distance" could not be detected.

Our findings are in line with those of others who found safety-related improvements based on various indicators related to bike-boxes installed at signalized intersections, primarily to prevent right-hook situations between cyclists and right turning cars (Dill et al., 2012; Loskorn et al., 2013).

Expected safety contrasts based on rating the photo showing the counterfactual situation were considerably higher than actual improvements in perceived safety stated immediately after crossing the intersection. This difference is remarkably consistent between participants in the pre survey, such as rating expected gain in safety from adding the box, vs. participants in the post survey, rating expected loss in safety from removing it, respectively, indicating that the effect is not affected by the inverse constellation of the experiment between the two groups. The discrepancy between experienced and perceived safety is particularly strong in women, more than double of that in men. The effect of gender – women perceive safety at the intersection as lower – is of the same magnitude as the bicycle box improves safety, but the effect of the bicycle box on perceived safety does not differ by gender. This finding is in line with previous research that shows the higher risk aversion of women in general (Harris and Jenkins, 2006), when in traffic (Griffin and Haworth, 2015) and specifically when cycling (Emond et al., 2009; Garrard et al., 2012), although little is known about gender-specific effects of infrastructure.

Planners though are well-advised in considering safety needs, perceptions and expectations of female cyclists – and even more so potential future female cyclists, when designing cycling infrastructure. This clearly poses a challenge in low cycling regions, where female cyclists are a small minority, for exactly such safety related reasons.

Whether an improvement of perceived safety of around 0.7 points on scale of 1–10 is sufficient to justify the marking of a bicycle box may be the most relevant question this study raises. We would point out that in the case of road markings, like the bicycle box, costs are minimal. Further it should be taken into account that the value of 0.7 reflects an average, whereas the effect among those cyclists most concerned about safety, and hence in most need of safety improvements, is likely larger.

Our findings for subjective safety indicators are in line with economic research that shows an overestimation of value expectations in stated preferences (Murphy et al., 2005). An evaluation of buffered bike lanes has observed a similar difference between expected and perceived levels of comfort (McNeil et al., 2015). As such, assessments of expected safety by means of pictures likely overestimate effects that can be expected of cycling infrastructure. Similarly, higher adjusted-R^2 values found in the models for expected safety indicate that expectations towards new infrastructure might depend more on already formed and strong attitudes as well as long term experiences, while actual effects on perceived safety likely depend on various additional, individual or situational factors that could not be captured with our survey. Our findings clearly show that perceived safety is not solely a matter of site-specific factors. Perception of general safety conditions for cycling in the city correlate with the assessment of the studied intersection. City-wide perception of cycling safety explains almost half of the variation in perceived safety ratings at the intersection. These figures illustrate that promotion of cycling (through safety improvements) requires city-wide strategies. Patchwork improvements of isolated safety hot-spots, while desirable from a pure safety perspective, will do little to promote cycling, as long as general safety conditions for cycling in a larger area lag behind (Mekuria et al., 2012).

Using innovative computer-based video technology we were neither able to confirm nor refute the improvements in subjective cycling safety using passing distance as the objective safety indicator. The possibility that the bicycle box solely improves perceived safety without actual effect on objective safety cannot be excluded and calls for further research and development of objective methods. For example, cyclists might perceive higher safety levels just because they felt more protected in an exclusively marked area (Tilahun et al., 2007). However, there are several other possible explanations for these null findings. First of all, the methodology, while being continuously improved, currently still comes with numerous limitations, the most important ones are discussed further below. Secondly, a larger sample would have allowed conducting sub-analyses to tease out potential effects. Future studies should anticipate recording more extensive footage. Thirdly, the chosen safety indicator may conceptually not be adequate, which we discuss first.

For example, it is not obvious whether median passing distance, or only short passing distances are safety relevant. Our findings show a decrease in close passing maneuvers after marking of the bicycle box, but our sample is too small to evaluate this statistically. It is also quite plausible that the bicycle box led to an elimination of very large passing distances, which washed out any effect on short passing distances, when looking at median passing distance. On the other hand, the clear delianation by the bicycle box could increase comfort with short passing distances. Further, cyclists' safety perception may depend on a different objective parameter, for example speed. Even though passing distances may not have increased after implementing the bicycle box, passing speed of motor vehicles might have decreased due to a narrowing of the passing lane, which might explain the positive effect on perceived safety of cyclists.

Finally, to avoid over-interpretation of the objective safety findings, it is important to acknowledge some limitations of the video technology used. Application of computer-based video technology in mixed traffic settings is an innovative approach still under development (Brisk Synergies, 2016; Zangenehpour et al., 2015). Despite the field tests carried out in similar settings and substituting some core steps in the methodology, like bicycle recognition by manual assessments, several issues may have affected our objective results.

First of all, the sample size of potentially relevant conflicts was too low to conduct in depth analysis of subgroups of conflicts (e.g. passing distances shorter than a certain cut-off). Because the procedure required substantial manual efforts, the sample size could not be easily increased. Among likely reasons for the failure to reliably detect cyclists automatically are large motor vehicles partly hiding bicycles; similar trajectories, origins and destination zones of bicycles and motor vehicles, all of which are used by the algorithm to classify identified objects by mode; and inability of the algorithm to track trajectories interrupted by intermediate stops.

The algorithm for automatic distance measurements between passing vehicles required a substantial effort to exclude invalid measurements (Fig. 4). Especially during late recording times, vehicle and street lights as well as shadows were mistaken for objects. In some cases, automatic distance measurements were far from being horizontal (e.g. from car roof to bicycle wheel). Sometimes distances were measured when the motor vehicle was still behind the bicycle. Similarly, bicycle baskets, vehicle mirrors etc. introduce some inconsistency in the measurements. As such, the measurements of passing distance in the manually identified potential conflict situations may lack accuracy due to misrepresentation of the three dimensional space in the two dimensional footage. Although we corrected the measurements for distortions with increasing distance from the camera and manually assessed validity of the distance measure, inaccuracies likely remain due to start and end points of the distance measurements not aligning perfectly with

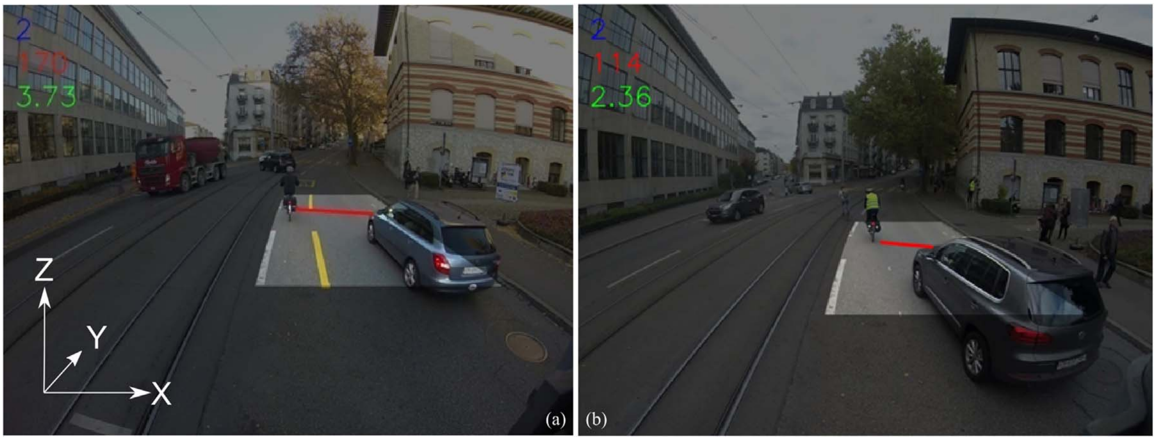

Fig. 4. Valid measurement with small deviation due to a bicycle bag (a) and discarded case due to a shadow and the position of the vehicle behind the bicycle (b).

regards to height above ground and distance from camera.

In light of these limitations, the applied video technology is not practice-ready at this point. Nonetheless, its potential for use in evaluations of cycling safety is obvious and further investments in improving the technology are warranted. None of the identified issues appear insolvable in a day and age when driverless vehicles start mastering navigation in real world traffic settings. Aside from improved image detection algorithms we identify potential for improvement in camera placement and combination of multiple camera perspectives. However, the development of algorithms and other methodological aspects required to improve such applications was beyond the scope of this project.

5. Conclusions

Combining subjective and objective measures of safety in evaluations of cycling infrastructure provide a more complete picture than any one of these approaches alone. Collecting data on road user perspectives requires relatively little additional effort compared to the labor-intense objective safety assessment. Future developments and improvements of automatized approaches will clearly shift this balance in favor of more comprehensive studies, which are particularly warranted for cyclist and pedestrian projects, where in addition to safety improvements an increase in use is desired.

At this point the applied video technology cannot be considered practice ready for mixed-traffic applications under the investigated settings, but further development promises great potential to efficiently assess objective safety parameters. Our study supports the necessity to further invest in such methods to facilitate consideration of both objective and subjective perspectives to support evidence-based planning with regards to both safety improvements and cycling promotion.

Acknowledgements

The study was funded by Suva accident insurance and by AXA Foundation for Prevention.

We would like to express our thanks to W. Brucks and the police force of Zurich, C. Chung of Brisk Synergies, and G. Pestoni for their support in conducting this study.

Appendix A. Details of test sites

See Figs. A.1–A.2.

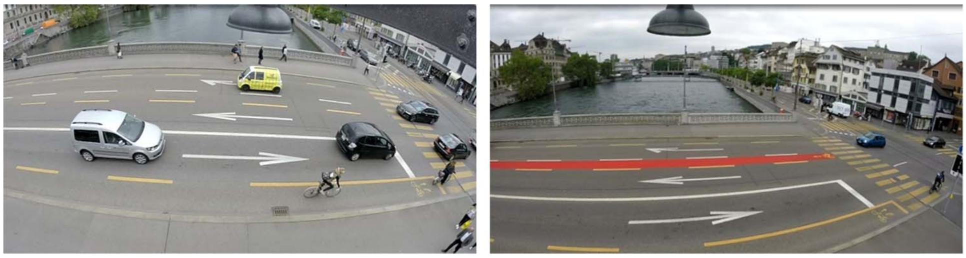

Fig. A.1. Test site 1 before (left) and after (right) the red painting on the bicycle lane at the bridge Rudolf-Brun-Brücke.

Fig. A.2. Test site 2 before (left) and after (right) the red painting on the bicycle lane at the intersection Werdstrasse and Birmensdorferstrasse.

Appendix B. In-situ survey

See Table B.1.

Table B.1
Questionnaire used in the on-situ survey (questions to be answered by the interviewer are showed between brackets).

Survey question	Answer options	Model variable
The University of Zurich carries out together with the SUVA and City of Zurich a research for cycling safety. Shall I make you some questions about it? The survey takes about 5 minutes.	Yes / No	
(Which is the sex of respondent?)	Male / Female	Gender
(Does the respondent wear a helmet?)	Yes / No	Helmet
(Does the respondent use a conventional bicycle or an e-bike?)	Bicycle / E-bike	Bicycle type
You just turned left. How safe did you feel in a scale from 0 (very unsafe) to 10 (very safe)?	1 / 2 / 3 / 4/ 5/ 6/ 7 / 8/ 9/ 10/ I do not know	Perceived safety at the intersection
Would you like to comment this score?	(Open answer)	
[a]Imagine that you advise the traffic planners of the City of Zurich. Which measure could increase, in your opinion, safety at the intersection? [Pictures are shown]	Car-free street / Bicycle lane / Sufficient street light / Traffic light / Traffic calming / Shared space / Others (open answer)	
[b]Imagine that you advise the traffic planners of the City of Zurich. Which measure could increase safety perception of unsure bicycle users at the intersection? [Pictures are shown]	Car-free street / Bicycle lane / Sufficient street light / Traffic light / Traffic calming /Shared space / Others (open answer)	
On the picture above you have seen the today's situation of the intersection that you just rated regarding safety. If this intersection would look like the picture below, how would you rate safety in a scale from 0 (very unsafe) to 10 (very safe)?	1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 / 10 / I do not know	Expected safety based on a picture
How appropriate do you think it is the suggested bicycle box?	Very appropriate / Rather appropriate / Neutral / Few appropriate / Not appropriate at all / No answer	
How often do you use your bicycle?	Daily or almost daily / 1–3 Times per week / 1–3 Times per month / Less than once per month / Never / I do not know	Cycling Frequency
Since how many months or years do you cycle in the city of Zurich?	0–3 Months / 4–6 Months / 6 Months – 1 year / 1–5 Years / > 5 Years / No answer	Cycling experience
In which country did you grown up?	(Open answer)	Country of upbringing
Did you grown up in an urban or in rural area?	Rural area (< 5,000 inhab.) / Small town (5,000–10,000 inhab.) / Medium-size city (20,000–100,000 inhab.) / Large city (> 100,000 inhab.) / No answer	Land use type of upbringing
How safe do you feel in general cycling in the city of Zurich in a scale from 0 (very unsafe) to 10 (very safe)?	1 / 2 / 3 / 4 / 5 / 6 / 7 / 8/ 9 / 10 / I do not know	Generally perceived safety in Zurich
What is your age group?	0–20 Years old / 21–40 Years old / 41–60 Years old / 61–80 Years old / > 80 Years old / No answer	Age group

[a] only asked of subjects who reported perceived safety of 7 or less.

[b] only asked of subjects who reported perceived safety of 8 or more.

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