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The relationship between cycle track width and the lateral position of cyclists, and implications for the required cycle track width

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A B S T R A C T

Introduction: Sufficient cycle track width is important to prevent single-bicycle crashes and collisions between cyclists. The assumptions on which the minimum width is based in guidelines is founded on only a few studies. The aim of the present study is to investigate the relationship between cycle track width and lateral position of cyclists. *Method:* We conducted an experiment to evaluate the lateral position of cyclists along cycle tracks with different widths (Study 1). Participants cycled on an instrumented bicycle with a LIDAR to measure their lateral position. Five conditions were defined: cycle track width of 100 cm, 150 cm and 200 cm without interaction, and cycle track width of 150 cm and 200 cm with an oncoming cyclist simulated by a parked bicycle. The cross-sectional Study 2 is based on the collected lateral position measurements at cycle tracks with varying width reported in Dutch studies since 2010. *Results:* The experimental Study 1 with 24 participants shows that an increase in cycle track width causes cyclists to ride further away from the verge and keep more distance from an oncoming cyclist. The cross-sectional Study 2 was based on lateral position measured at 33 real-life Dutch cycle tracks. Study 2 yielded similar results, indicating that doubling pavement width increases lateral position by some 50%. Study 2 shows that, compared with a solo cyclist without interaction, a right-hand cyclist of a duo and a cyclist meeting an oncoming cyclist ride around 30% closer to the verge. *Conclusions:* The wider the cycle track, the more distance cyclists maintain from the verge. Cyclists ride closer to the verge due to oncoming cyclists. *Practical applications:* Given a cyclists' lateral position while meeting, common variations between cyclists' steering behavior, and vehicle width and circumstances, a cycle track width of 250 cm is needed for safe meeting maneuvers.

1. Introduction

Cycling contributes to public health because it requires physical effort (Oja et al., 2011) and offers economic and environmental advantages over motorized transport (Fishman et al., 2015). However, 41,000 cyclists die every year in traffic crashes, 3% of the total number of traffic deaths worldwide (WHO, 2020). Most fatal bicycle crashes are collisions with motor vehicles. The majority of severe injuries among cyclists and an increasing share of fatal crashes, however, are due to single bicycle crashes (Aarts et al., 2021; Boufous et al., 2013; Schepers et al., 2017a). An international review showed that the share of hospitalized casualties due to single-bicycle crashes varied from 52% to 95% (Schepers et al., 2015; Utriainen et al., 2022).

While the presence of a cycle track is important to prevent bicycle-motor vehicle crashes (Thomas & DeRobertis, 2013; Van Petegem et al., 2021), sufficient cycle track width is important to prevent collisions between cyclists as well as single-bicycle crashes such as riding off the pavement (Boele-Vos et al., 2017; Olesen et al., 2021; Schepers, 2013). In a crash study, Hoogendoorn (2017) found that increasing cycle track width by one meter, reduced the odds of riding off a cycle track and falling (OR = 0.43; CI = 0.19–0.96). As it is difficult to derive cycle track

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width requirements from these studies, guidelines look at cyclists' steering behavior assuming that steering behavior contributes to bicycle crashes. Requirements on the minimum width of a two-way cycle track in several design guidelines are specified to be 75 cm for the space occupied by cyclists (an assumed 55 cm cyclist body and 20 cm lateral deviation from a straight line) combined with two *buffer zones* (Parkin, 2018; Schröter et al., 2021) as depicted in Fig. 1:

a) a buffer between the cyclist and verge, in this study called 'lateral position' (buffer a in Fig. 1).
b) a buffer between cyclists for meeting and overtaking (buffer b in Fig. 1).

The Dutch design manual for cycle traffic recommends a minimum of 150 cm for standalone bidirectional cycle tracks where mopeds are not allowed and with well-designed verges such as in in Fig. 1 (ANWB, 1966; CROW, 2016). The width of 150 cm is based on three 25 cm buffer zones plus the lateral space of cyclists' physical contours towards the center of the cycle track (75 cm). Buffer a is not necessarily equal to half the physical contour of a cyclist because a cyclist may move partially across the shoulder.

Many scientific studies examined lateral position of cars, buses, or parked cars relative to cyclists (De Ceunynck et al., 2017; Dozza et al., 2016; Duthie et al., 2010; Llorca et al., 2017; Schramm & Rakotonirainy, 2010), but few studies examined lateral position of cyclists on physically separated cycle tracks to substantiate the assumed dimensions in guidelines such as those in Fig. 1. An exception is a study published in 1980 by Godthelp and Wouters (1980) that led to the above mentioned 20 cm space for course deviation that is still the starting point in Dutch guidelines (CROW, 2016). Zamanov (2010) studied how much distance cyclists kept from each other when meeting on 15 cycle tracks of varying width in Vienna. The wider the cycle track, the more distance cyclists kept from each other. Since 2010, lateral position was examined in a number of Dutch observational studies. However, these studies were mostly reported in grey literature and are not yet considered in evaluating the relationship between pavement width and lateral position to inform guidelines (Janssen, 2017; Jelijs et al., 2020).

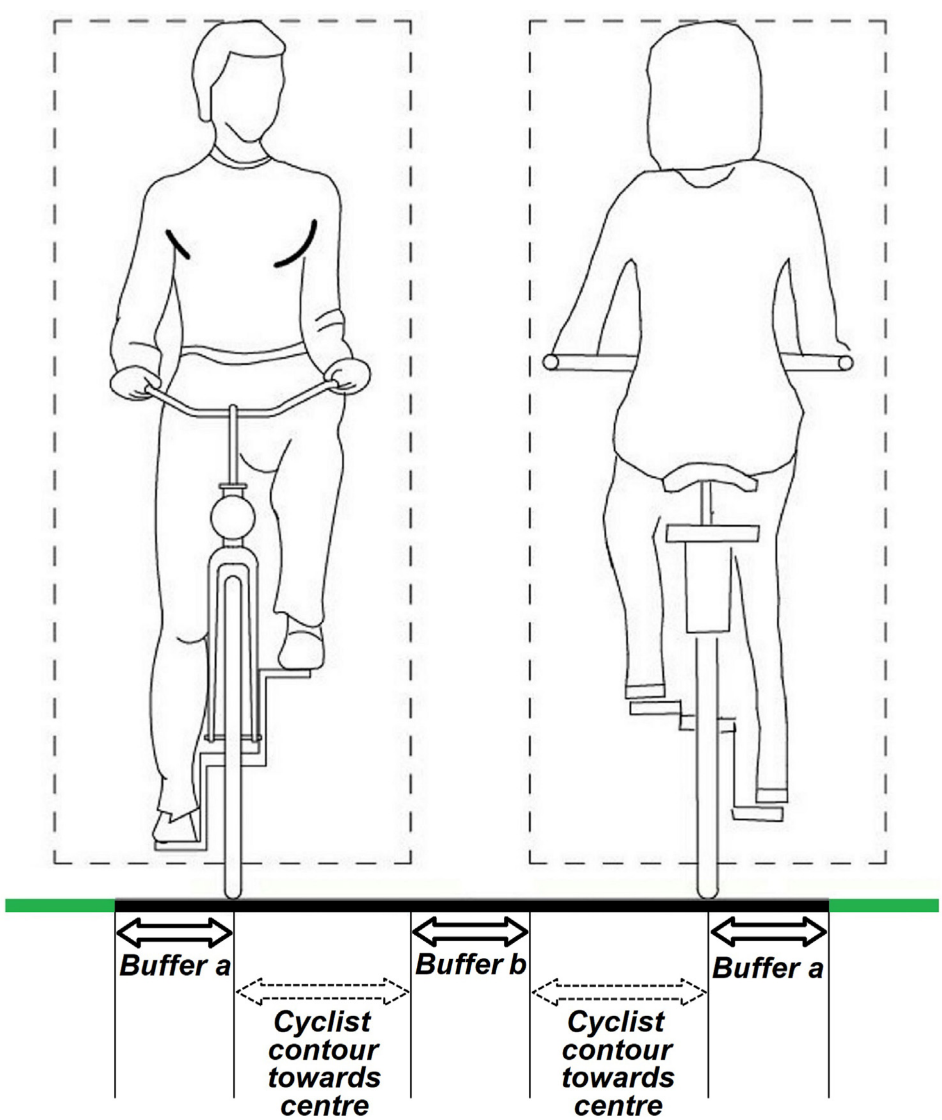

Fig. 1. Lateral space required for cycling.

The aim of this study is to investigate the relationship between cycle track width and lateral position of cyclists, in order to inform guidelines on the minimal cycle track width needed for safe cycling. An experimental study is carried out where the cycle track width is manipulated and lateral position of cyclists is recorded (Study 1). An experiment has a good internal validity but the realism with which conditions are manipulated may compromise external validity. To be able to judge and discuss the external validity of the results, a cross-sectional Study 2 was conducted: cycle track width and lateral position reported in studies since 2010 were collected in one database to examine their relationship.

2. Materials and methods

2.1. Study 1: Experiment

2.1.1. Participants

Participants were recruited via word of mouth among students at the Delft University of Technology (TU Delft). Participants indicated their availability through an online form. All participants were assigned a timeslot on December 8 or 9, 2020. All participants signed an informed consent form. They were informed of the design and duration of the experiment and the data that would be collected.

2.1.2. Set-up and equipment

The experimental set-up used an instrumented bicycle, and five scenarios: cycle track width of 100 cm, 150 cm and 200 cm without interaction, and cycle track width of 150 cm and 200 cm with a simulated oncoming cyclist. A 100 cm wide track with oncoming cyclist was considered too risky because guidelines recommend a minimum of 150 cm for a bidirectional cycle track. The bicycle was instrumented with a LIDAR and GPS. The experiment took place along a 300 cm wide standalone cycle track at the TU Delft campus that was fenced off from other traffic (see Fig. 2). The location was chosen because the negligible height difference between the pavement and the verge would allow cyclists to swerve safely over the verge if needed. To change the width, cycle tracks were marked using movable white band on the cyclists' left-hand side while keeping the real verge at the right-hand side. The oncoming cyclist was simulated using a parked bicycle. The middle of the parked bicycle was located 44 cm away from the track's edge as Janssen (2017) found this lateral position as average while riding abreast in an observational study. Compared to an oncoming cyclist, the parked bicycle had the advantage that it was placed in a fixed lateral position, but the disadvantage that the oncoming cyclist is less realistic.

On the first day it was dry and almost windless, which allowed to attach the white band to the pavement using duct tape. On the second day it was foggy and there was some wind, which made duct tape inadequate. As shown in Fig. 3 orange pylons were instead used to hold the band in place. The pylons may affect lateral position but this is unlikely to affect the conclusions about the effect of width on lateral position owing to the within-subject design in which participants were exposed to the same pylons in each condition on day 2.

After a training trial to get used to the instrumented bicycle, participants rode each of the five conditions (100 cm, 150 cm with and without parked bicycle, and 200 cm with and without parked bicycle) three times. The order of the conditions was changed for each participant to avoid bias due to order effects. Study 1 used an instrumented bicycle that had been previously developed at Delft University of Technology and was modified to a limited extent for this experiment. The instrumented bicycle shown left in Fig. 4 was used to measure lateral position by a LIDAR (Laser Imaging Detection And Ranging) and speed by GPS. A Data Acquisition System (DAS) was placed in a small watertight box, attached to the luggage carrier. An Arduino board was used to control and collect data from a GPS antenna and LIDAR at 100 Hz, both being stored in the same file. The LIDAR (LIDAR-Lite v3) was attached to the back of the bicycle and positioned low to the ground with an extension to aim transverse to the axis of the cycle track at the barrier on the right verge. The 80 m long and 30 cm high barrier at the right side of Fig. 4 was placed on a fixed 100 cm distance from the cycle track to allow the LIDAR to measure the distance between the rear wheel and barrier (i.e., lateral position). One of the researchers checked whether participants crossed the right or left edge, which could later be verified on the footage of a camera that had the entire track in view from the roof of a van. The parked bicycle is put on the cycle track in the right picture of Fig. 4.

2.1.3. Data filtering

In the first step, all LIDAR values between 100 and 300 cm (corresponding with 0 to 200 cm from the right verge) and in the experimental riding direction according to the GPS were selected. The reason for this range was that the board to reflect the laser signal was placed 100 cm from the track edge and the maximum width of the experimental cycle track was 200 cm. Also, it was observed that no cyclists crossed the edges of the cycle track. As the automatic selection often yielded some measurements slightly before and after the trial (such as the values at the right side of the top graph in Fig. 5), these data points were excluded in a manual second step. The trials that could not be selected automatically, because GPS data were missing for these tracksm were selected manually from the dataset with only a filter on LIDAR values between 100 and 300. In the third step, the trial parts at a speed over 10 km/h were selected as low speeds cause increased course deviations (Godthelp & Wouters, 1980). Above 10 km/h the bicycle

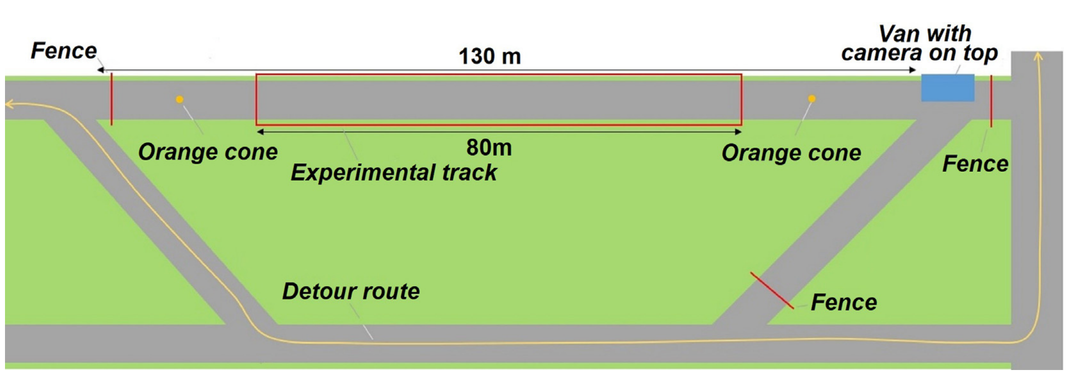

Fig. 2. Overview of experimental setup.

Fig. 3. Two methods used to attach the white band to pavement: first measurement day left and second measurement day right.

Fig. 4. The instrumented bicycle used for the experiment (left) and barrier for measuring lateral position by LIDAR (right).

becomes self-stabilizing, requiring little rider effort (Schwab, Meijaard, & Kooijman, 2012; Twisk et al., 2017). Some trials still contain outliers after filtering, for instance because the LIDAR signal went over the barrier and was reflected by a tree close by the track. As this corresponds to a higher measured value, most of the outliers are above the actual and true maximum lateral position. Note that a LIDAR value in Fig. 5 minus 100 cm is how far from the verge a participant was during the trial. For ease of reading, 100 cm was subtracted to report lateral position in Section 3.

2.1.4. Missing data

Due to the time required for a modified method of holding the white band as shown in Fig. 3, no usable data were collected from the first two participants on the second day. On both days the LIDAR failed during the trials of one participant, resulting in the loss of too much data to include in the analyses. From two participants during the first day, the LIDAR data were found to contain too much noise even after filtering, rendering their data unreliable. Of the remaining 18 participants all LIDAR data were available except one trial. The time needed for the GPS to receive enough satellite signals caused missing speed data in the first trials of half of the participants.

2.1.5. Variables

The cyclists' lateral position relative to the edge of the cycle track and speed were measured. The following lateral position variables were derived for each trial from the LIDAR data:

- Median lateral position: the median (separating the higher half from the lower half) was preferred over the average because it is less affected by outliers in LIDAR data such as those in the bottom of Fig. 5.
- 1st percentile lateral position: variable representing the closest distance to the edge of the cycle track. It was chosen instead of the actual minimum value to ignore outliers under the true minimum. Visual inspection of all tracks indicated less than 1% of the lowest LIDAR values represent noise.
- 95th percentile lateral position: variable representing the greatest distance from the edge of the cycle track. This variable ignores the 5% highest LIDAR measurements to make sure the outliers above the actual and true maximum do not affect our indicator for the maximum lateral position. Visual inspection of all tracks indicated less than 5% of highest LIDAR values represent noise.
- Lateral space for course holding (95th percentile lateral position minus 1stpercentile lateral position): additional variable for the space in which cyclists deviate from a straight line to the left and right. This measure is also referred to as Essential Manoeuvring Space (Lee et al., 2016).

For ease of reading, we use the terms minimum and maximum lateral position for the 1st respectively 95th percentile lateral position. These variables describe the proportion of pavement used by participants. The minimum value is of particular importance for the two conditions with oncoming cyclists because we expect participants to move closer to the verge while meeting another cyclist. Their median and maximum lateral position are also measured at a

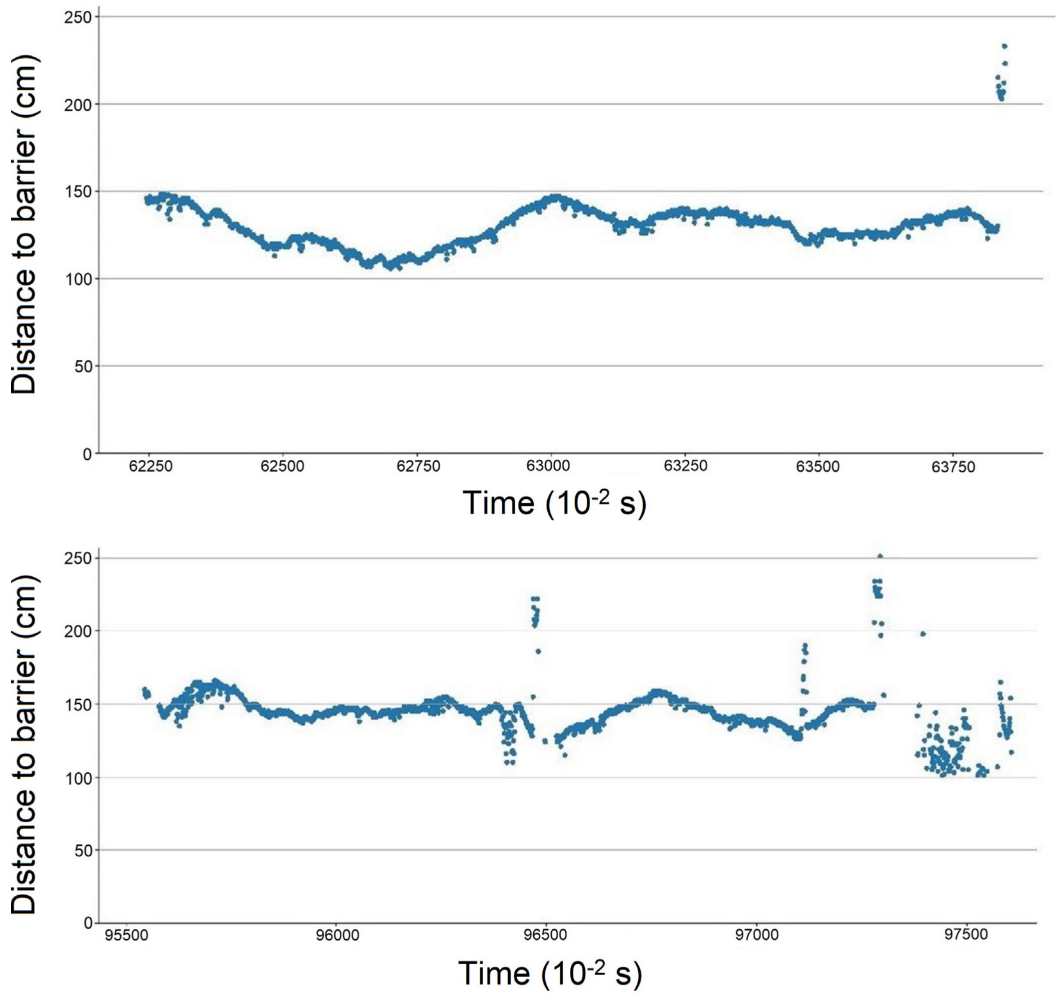

Fig. 5. LIDAR data of two trails without manual filtering.

portion of the study track before and after the meeting manoeuver and are therefore less affected by the meeting manoeuver than the minimum lateral position. Even more important from a safety perspective than the above described minimum lateral position, is whether cyclists ride off the cycle track, which was observed during the experiment. However, we did not include a variable for this in the analyses because no participants rode off the cycle track.

2.1.6. Analyses and models

For Study 1, a within-subject repeated-measures design is used. It involves multiple measures of the same variable taken on the same subjects under different conditions, meaning that these measurements cannot be considered as independent. This means that the requirement for linear regression of independent observations cannot be met. Instead, mixed effect models (MEMs) were used to model lateral position as MEMs allow to include a random intercept to allow individual differences to be captured. Also, in contrast to a repeated measures ANOVA, MEMs enable modeling of both continuous and categorical independent variables and can cope with the missing data of some trials (Kincaid, 2005; Singer, 1998). An unstructured covariance matrix was assumed. A random intercept for participants was included in all models. Lateral position (L) was modeled using a power model with a continuous variable for cycle track width (W): $L = cW^{\beta 1}$. It allows lateral position to change as follows as pavement width increases:

- β1 = 1: lateral position increases linearly with increasing width meaning that cyclists' lateral position is a fixed percentage of the pavement width.
- 1 > β1 > 0: lateral position increases less than linearly with increasing width. For instance, with a power of 0.5, lateral position increases by 41% if width doubles ($2^{0.5}$-1).
- β1 = 0: lateral position is constant and unaffected by width

The model was expanded to include a dummy variable (D) for the presence of a simulated oncoming cyclist: $L = c\, W^{(\beta 1+\beta 2D)}\, e^{\beta 3D}$. Log-linear transformation of the model was used to estimate the parameters using linear MEMs: $\ln(L) = \beta 0 + (\beta 1 + \beta 2D)\ln(W) + \beta 3D$. Constant c is equal to exp(β0). Parameter β2 describes the interaction between the pavement width and the presence of an oncoming cyclists to allow the impact of width to vary between the condition with and without oncoming cyclist. Parameter β3 describes the main effect of the simulated oncoming cyclist on lateral position. The transformation also has the advantage of reducing skewness of the data and is used to model the other dependent variables as well. Backward stepwise regression was used to achieve models containing variables significant to the 5% level.

2.2. Study 2: Analyses on lateral position reported in studies since 2010

2.2.1. Review

Since 2010, lateral position was studied in a number of Dutch observational studies, partly reported in grey and partly in scientific literature. Many studies were inspired by the Dutch Strategic Road Safety Plan 2008–2020 (VenW, 2008) in which, for the first time, prevention of single-bicycle crashes was a spearhead. In-depth crash studies in the years after publication of the plan showed that in about a quarter of all single-bicycle crashes the cyclist rode off the pavement (Boele-Vos et al., 2017; Schepers, 2013). Several studies since then started measuring cyclists' lateral position. Fietsberaad, the Dutch bicycle council, maintains a knowledge base of Dutch research on cycling including cycling safety. Together with Fietsberaad, all Dutch studies reporting lateral position were selected. In many cases the authors of the studies were contacted for additional data and study details. They were also asked whether they knew of additional suitable studies.

In addition to the Dutch studies, international studies since 2010 were found through the electronic database Scopus. The following search terms were utilized: 'lateral position,' and 'cycle,' or 'bicycle' and 'track' or 'path.' Both the term *cycle track* and *cycle path* are used in the literature. In this paper, we use the term *cycle track*.

Part of the Dutch studies used lateral position as an indicator of the impact of measures such as edge lines (Westerhuis et al., 2020) and behavior such as mobile phone use (De Waard et al., 2014). In such studies, cyclists' lateral position has been reported for multiple conditions. For reasons of comparability between studies, we took from those studies, cyclists' lateral position reported for the control condition without measures such as edge lines and mobile phone use.

2.2.2. Analyses

Ideally, we would model the relationship between lateral position and pavement width using a meta-analysis. Unfortunately, several reports lack details such as the variance to apply meta-analysis (Borenstein et al., 2007). Where in Study 1 the measurements of participants are not independent of each other, in Study 2 measurements on the same cycle track are not independent of each other. To account for this, mixed effect models (MEMs) were used to model lateral position. A random intercept was included for measurements of multiple groups at the same cycle track, that is, solo cyclists, the right or left cyclist of a duo, and cyclists meeting an oncoming cyclist from the other direction. We used a similar power model transformed to a linear model as described in the previous section. As lateral position is reported in literature for both one-way and two-way cycle tracks, a dummy variable is included in the analyses to account for a potential differences between those two groups. We also included dummy variables to compare the measurements of Study 1 with all other measurements to examine whether lateral position measured in the experiment differed from lateral position in past findings found through Study 2. Backward stepwise regression was used to achieve models containing variables at least significant to the 5% level.

3. Results of Study 1, the experiment

3.1. Participants

A group of 24 experienced cyclists between 19 and 27 years participated in the experiment. The group consisted of 11 male and 13 female students from Delft University of Technology (TU Delft). Of the 24 participants, 21 were from the Netherlands, 2 from India, and 1 from Greece. All participants were experienced cyclists and they all learned cycling at a young age (2–6 years old) except for one participant who learned cycling at the age of 13.

3.2. Descriptive statistics

Table 1 contains the descriptive statistics of the 18 participants with suitable lateral position data from 269 trials. The group consisted of 6 male and 12 female students whose ages ranged from 20 to 27. Higher values for lateral position are associated with a greater distance from the verge. On average, participants approached the verge to a minimum value of 21 cm on a 100 cm wide cycle track while their average maximum distance from the verge was 50 cm. Lateral space for course holding is the difference per trial between the maximum and the minimum, and thus the space that cyclists use around a straight riding line. The average lateral space for course holding per trial is close to the difference between the average maximum and minimum lateral position. The standard deviation shows that median lateral position and lateral space for course holding vary somewhat between participants. Finally, the researcher who observed participants during all trials did not observe any crossing of the cycle track edge.

3.3. Regression analyses

Table 2 describes the results of the regression analyses on the lateral position variables. Fig. 6 depicts the models to facilitate the interpretation of the results. The model for median lateral position of solo cyclists is for example: $\exp(0.89)W^{0.58}$. As indicated by the significant positive parameter for cycle track width, the minimum, median and maximum lateral position all increase with increasing pavement width, both with and without simulated oncoming cyclist. The significant negative parameters for the dummy for the parked bicycle in the models for median and minimum lateral position indicate that the simulated oncoming cyclist causes cyclists to ride closer to the verge. The significant and substantial interaction between the presence of the parked bicycle and width in regression on minimum lateral position reflects that minimum lateral position increases more strongly with pavement width in the conditions with as compared to without parked bicycle.

The low 0.21 parameter for cycle track width in regression on lateral space for course holding (right column in Table 2) shows that cyclists occupy only slightly more lateral space with increasing pavement width. The significant positive dummy for the parked bicycle reflects an increased occupied lateral space resulting from having to swerve more for the parked bicycle. There is a significantly negative interaction between the presence of the parked bicycle and width resulting from less need to swerve for the parked bicycle with increasing pavement width.

4. Study 2: Analyses on lateral position reported in studies since 2010

4.1. Description of the studies found in the review

Including the current study, together with Fietsberaad we found 13 Dutch studies published since 2010 from eight different first authors reporting lateral position on 41 cycle tracks, see Table 3. Of the six Dutch studies reported in scientific literature, five were also found using Scopus except for the study by De Waard et al. (2020) as lateral position was not mentioned in the title, abstract or keywords. Additionally, one suitable Danish study was found (Greibe & Buch, 2016). Two Chinese studies on physically separated cycle tracks were not usable because the first measured lateral position too roughly (pavement width divided into thirds) (Yan et al., 2021) and the second reported no specific values per cycle track (Yan et al., 2018). Even if the authors of the latter papers were to provide additional data, the number of non-Dutch studies

Table 1
Descriptive statistics per condition and for the total number of trials.

Variable	100 cm	150 cm	200 cm	150 cm + parked bicycle	200 cm + parked bicycle	Total
	Mean (SD)					
Median lateral position	36.4 (6.8)	48.9 (14.4)	54.9 (17.8)	37.2 (11.2)	46.3 (15.2)	44.8 (15.3)
Minimum lateral position	20.9 (8.1)	32.0 (13.5)	36.0 (17.8)	16.7 (7.0)	27.3 (11.7)	26.6 (14.0)
Maximum lateral position	50.2 (11.2)	64.8 (15.1)	69.9 (19.8)	57.9 (12.8)	64.5 (17.6)	61.5 (17.0)
Lateral space for course holding	29.2 (9.6)	32.8 (10.8)	33.9 (11.8)	41.2 (12.1)	37.2 (12.2)	34.8 (11.9)

Table 2
Results of linear mixed effects regression on the logarithm of lateral position variables.

Fixed coefficients	Median lateral position		Minimum lateral position		Maximum lateral position		Lateral space for course holding	
	B (SE)	*p*	B (SE)	*p*	B (SE)	*p*	B (SE)	*p*
Constant	0.89 (0.26)	<0.001			1.85 (0.25)		2.38 (0.39)	<0.001
ln(cycle track width)	0.58 (0.05)	<0.001	0.66 (0.02)	<0.001	0.45 (0.05)	<0.001	0.21 (0.08)	<0.01
Dummy parked bicycle (reference: no parked bicycle)	−0.22 (0.03)	<0.001	−6.72 (1.27)	<0.001		<0.001	3.72 (1.06)	<0.01
Interaction parked bicycle x width			1.22 (0.25)	<0.001	−0.02 (0.00)	<0.01	−0.60 (0.21)	<0.01

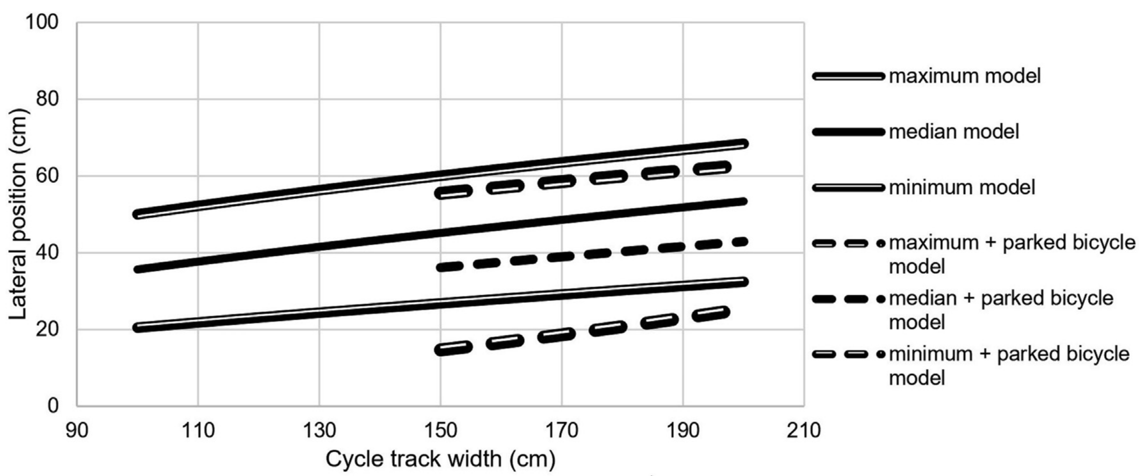

Fig. 6. Lateral position according to the models in Table 2.

would be small compared to the number of Dutch studies. For this reason, it was decided to limit Study 2 to Dutch studies and to discuss the Greibe and Buch (2016) study in the discussion on transferability of the results, together with the Vienna study by Zamanov (2010) that was obtained by word of mouth.

The 12 cycle tracks of the Janssen study (Janssen, 2017) were classified into four groups that differed in width by a maximum of 7 cm as the study was under-sampled with only 15 cyclists per cycle track. These four groups together with the 29 cycle paths from other studies add up to 33 study locations that are used for the analyses, further referred to as cycle tracks for ease of reading: 11 one-way, and 22 two-way tracks. If studies reported lateral position in both directions of the two-way tracks these values were averaged. Lateral position was reported for the following groups of cyclists (we excluded measurements of mopeds):

- Solo cyclists riding alone without interaction with other cycle track users: reported for all 33 cycle tracks
- Duo cyclists:
- The right cyclist of the duo: reported for 18 cycle tracks
- The left cyclist of the duo: reported for 13 cycle tracks
- Lateral position of solo cyclists while meeting an oncoming cyclist: reported for four cycle tracks

Together the studies yield 68 lateral position measurements of these groups of cyclists at 33 cycle tracks. To the extent that studies report on the space occupied laterally by cyclists, they use the Standard Deviation of the Lateral Position (SDLP) instead of lateral space for course holding as in Study 1.

In the left column of Table 3, we classified the studies by the study method used to determine lateral position. Lateral position at two-thirds of the cycle tracks was measured by video-observations either form the side of the road or from a bicycle handlebar, while fiber cables and LIDAR were used in the other studies. By splitting the video observations according to the method used to measure lateral position in the images, we get four study methods:

1. Video observations per strip: a perspective grid was overlayed on the video to split the image of the cycle track in a number of equally wide strips so that the numbers of meeting cyclists per strip can be measured. For those the average lateral positions were estimated as the weighted average (weight equal to the proportion of cyclists per strip in the total) under the assumption that cyclists were in the center of their strip.
2. Video observations continuous: since 2015, several researchers started using software that takes into account the distortion of the image and allows observing a continuous value for the lat-

Table 3
Dutch Studies on lateral position published since 2010.

Study methods	Munici-pality	Number and types of cycle track	Age range (years)	Remarks	References
Video observations from the side of the road per strip	Utrecht, Westland, Den Haag	3 one-way2 two-way tracks	All ages	Numbers of cyclists per strip were reported bar charts and tables. To avoid reading numbers from bar charts in the research report, these numbers were provided by R. van der Horst (personal communication, email message, 14–5-2022). Average lateral position was determined by the weighted average with a weight equal to the proportion of cyclists per strip in the total.	De Goede et al. (2013, p. 31-36)
Video observations from the side of the road per strip (2014) and with exact lateral position measurement (2015, 2020)	Groningen	3 one way1 two-way	2014: 20–31; 2015: all ages; 2020: 17–22	From the 2014 study, data were taken from participants in the control condition and those cycling with a companion, both with two hands on the handlebars without phone use. Mean lateral and SDLP position were determined by multiplying mean strip position and SD of strip position with strip width. From the 2015 study, data were taken from control condition without phone use. To avoid reading numbers from charts in the paper, lateral position was provided by D. de Waard (personal communication, email message, 3–6-2022). From the 2020 study, lateral position of Dutch cyclists was taken as provided by D. de Waard (personal communication, email message, 7–6-2022).	De Waard et al. (2014, p. 201), De Waard et al. (2015, p. 46), De Waard et al. (2020)
Video observations from the side of the road per strip	Amsterdam	9 one-way and 3 two-wayaggregated into 4 width classes	All ages	The study was conducted at 12 locations where the lateral position was measured of 15 cyclists. Because of these small numbers, the locations were aggregated into 4 classes within which the widths differed by a maximum of 7 cm: 143–150 (1 one-way; 2 two-way tracks), 180 (5 one-way tracks), 195–200 (2 one-way; 1 two-way tracks), and 277 cm (1 one-way track). The width classes were classified as one-way or two-way depending on which occurred most often in the class.	Janssen (2017, p. 86)
Video observations from the side of the road and from a bicycle handlebar with exact lateral position measurement	Groningen, Kampen, Súdwest-Fryslân, Zwarte-waterland	5 two-way	2017 Groningen: all ages 2017 Kampen: 52–85 2020 Zwartewaterland & Kampen: 52–85 2020 Súdwest-Fryslân: 51–78	Data were taken from control locations without edge lines and treatments of or objects in the shoulder. F. Westerhuis provided average lateral position and its standard deviation averaged across regular and electric bicycles (personal communication, email message, 31–3-2022).	Westerhuis et al. (2017), Westerhuis et al. (2020)
Video observations from a bicycle handlebar with exact lateral position measurement	Groningen	1 one-way1 two-way	62–73	Data was used of participants in a normally sighted control group who rode a fixed route on a regular and on an electric bicycle. In addition, D. de Waard and B. Jelijs provided the SDLP for the same groups and condition (personal communication, email message, 20-6-2022). Lateral position and SDLP on both bicycle types were averaged to acquire one estimate for each cycle track.	Jelijs et al. (2020, p. 258-259)
Configuration of three fiber optic cables transverse to the pavement	De Bilt, Loon op Zand, Overbetuwe, Rotterdam, Utrecht, Waalwijk, Zeist, Zeewolde	1 one-way8 two-way tracks	All ages	Daylight measurements were taken from all 9 cycle tracks. Of the study with measurements at two cycle tracks in Elst and Zeist, those without edge lines were taken (Pol et al., 2022). A study at five wide cycle tracks was measured only once so that measurements at three cycle tracks with conspicuous edge and middle markings had to be included. The other two cycle tracks of the latter study (Pol et al., 2022) and two narrow cycle tracks at a third study (Pol, 2022) lacked edge markings. While exact lateral position was measured in all three studies, cycle track width was divided in strips and numbers of meeting cyclists were reported per strip in two studies while the report of the third also reported average lateral position. M. Pol provided raw lateral position data to determine the average lateral position per cycle track for the first two studies as well (personal communication, email message, 13-4-2022).	Pol, Brouwer, and Beterams (2020), Pol (2022), Pol, Brouwer, and Beterams (2022)

(*continued on next page*)

Table 3 (*continued*)

Study methods	Munici-pality	Number and types of cycle track	Age range (years)	Remarks	References
Video observations from the side of the road per strip	Kapelle	1 two-way	All ages	Data were taken from before the application of edge lines. To avoid reading numbers of cyclists per strip from bar charts in the research report, the numbers were provided by H. Godefrooij (personal communication, email message, 5-4-2022). Average lateral position was determined by the weighted average with a weight equal to the proportion of cyclists per strip in the total.	(Godefrooij, 2021)
LIDAR	Delft	3 two-way	19–27	Values taken from Table 1	Current study, See Section 2

eral position rather than an approximation with a strip. To our knowledge, the quality of the methods has not yet been compared but it seems reasonable to assume that this method is more accurate than the first study method.

3. Fiber cable: one researcher in 2020 measured the lateral position by a configuration of three fiber cables on the pavement (Pol, Brouwer, & Beterams, 2020) to measure speed and lateral position. The measurement is likely to be accurate even during darkness. A disadvantage compared to the former methods is the inability to measure the SDLP as measuring cyclists at one position cannot measure swerving from left to right.
4. The current study measured lateral position using LIDAR (See Section 2).

Table 3 also contains a column for the age range of cyclists included in the studies. Most of the studies are observational in which all present cyclists were measured irrespective of their age. These are classified as "all ages." Studies that involve participants from a specific age range use partly younger and partly older participants. With a wide geographic and age-group distribution, the results of Study 2 seem reasonably representative for Dutch cyclists.

To the extent that reports indicate sample sizes, they do not compare well. Video observations and LIDAR involve multiple measurements per cyclist while fiber cable measurements involve only one measurement per cyclist. On the other hand, fiber cables tend to be measured for several weeks at a time because continuing to measure does not require additional work once the cables are in place. Even with only one measured value per cyclist, the number of measurements on cycle tracks measured with fiber cable is therefore larger (usually over 10,000; Pol et al., 2022) than on cycle tracks measured with other methods.

4.2. Description of lateral position in the studies

Fig. 7 depicts lateral position on the 33 cycle tracks for three groups of cyclists and four study methods according to the studies found in the literature review. The legend distinguishes between the first author of the studies by color. The method of study is identified by the sign (+, –, ○, or ■). The three trend lines draw the regression models described in the next section. The top graph relates to solo cyclists. The groups of cyclists interacting with other cyclists are depicted separately in the bottom graph of Fig. 7.

SDLP was measured in only 10 studies of which 9 measured solo cyclists (Fig. 8). The mean SDLP was 15 cm and varied considerably between 9 and 28 cm. The substantial variation is due to the fact that it not only depends on steering left and right to keep the bicycle upright (Kooijman et al., 2011), but also to change the steering direction, for example, to avoid a manhole cover. The latter explains the highest 28 cm measurement by Westerhuis (Westerhuis et al., 2017). The small number of observations and large variation in outcomes renders the data unsuitable for regression analysis.

4.3. Regression on lateral position in the studies

Table 4 describes the results of the regression analysis on cyclists' lateral position along the 33 cycle tracks for three groups of cyclists. The analyses started with dummy variables for both the right cyclist of duos and the cyclist meeting an oncoming cyclist, but both are combined in one dummy variable because of the almost similar regression parameter for both. Compared to a solo cyclist without interaction, both groups ride significantly closer to the verge, while the left cyclist of a duo keeps more distance from the verge. There was no significant interaction between these dummy variables for groups and cycle track width, meaning that

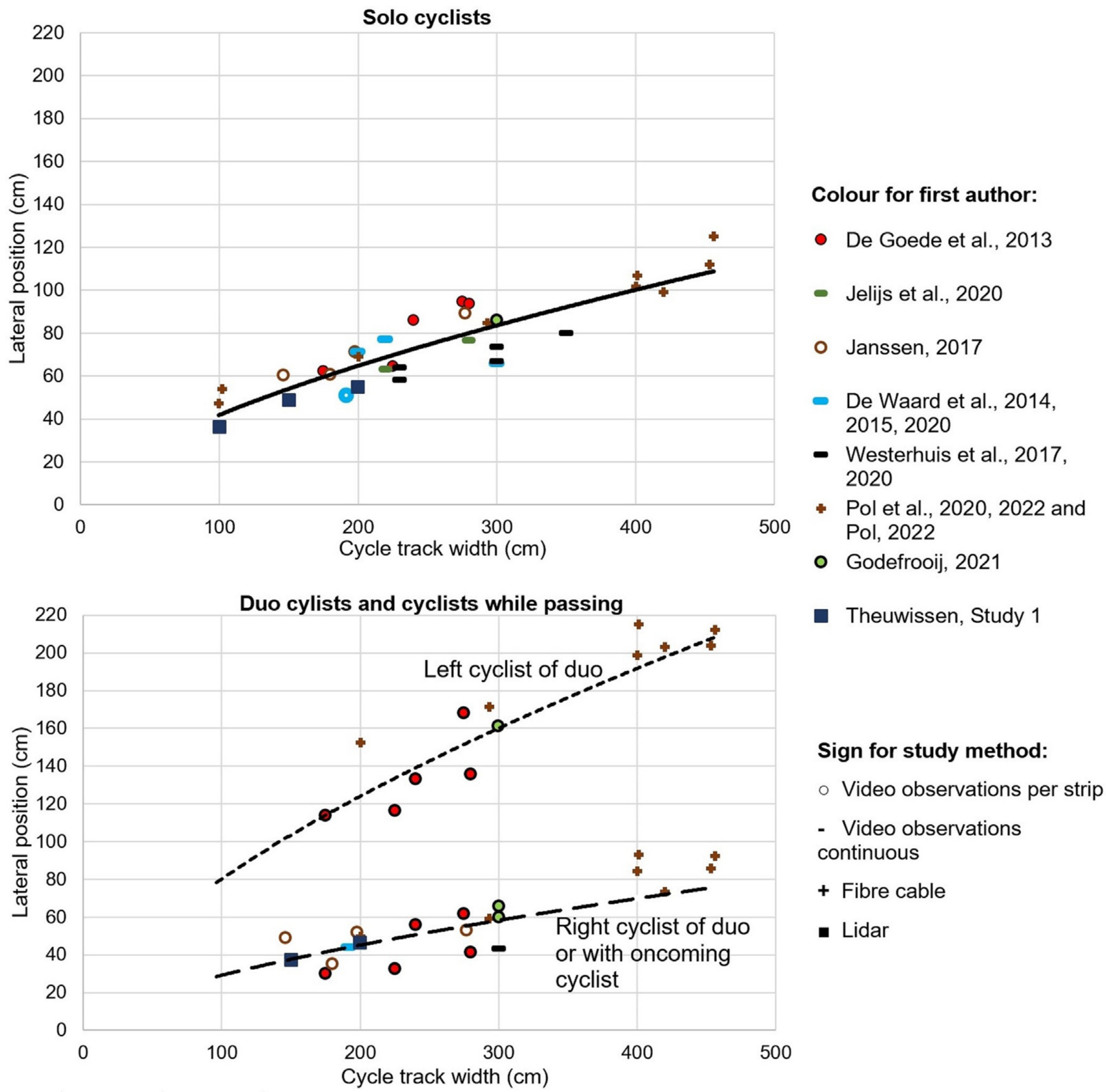

Fig. 7. Lateral position according to the studies in the literature.

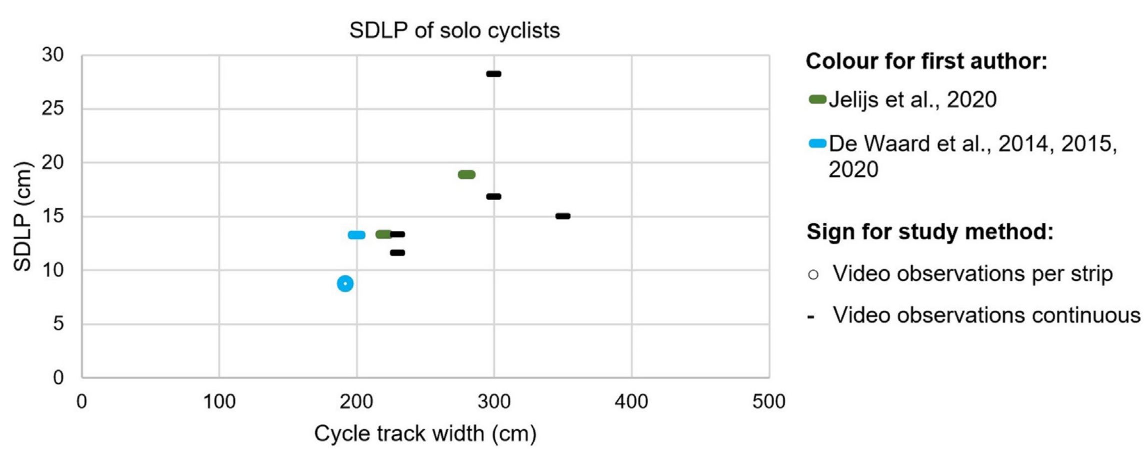

Fig. 8. SDLP of solo cyclists reported in literature.

lateral position within the entire width spectrum differed equally between groups, that is, 30% less lateral distance for the right cyclist of a duo compared to a solo cyclist (exp(-0.36)-1), and 92% more for the left cyclist of a duo. In addition, the lateral position did not appear to differ between one-way and two-way cycle tracks and between Study 1 and all the other measurements. To

Table 4
Results of linear mixed effects regression on the logarithm of lateral position.

Fixed coefficients*	**Regression coefficients**	
	B (SE)	*p*
constant	0.84 (0.33)	0.01
ln(cycle track width)	0.63 (0.06)	<0.001
dummy right duo cyclist or with oncoming cyclist (ref: solo cyclist)	-0.36 (0.03)	<0.001
dummy left duo cyclist (ref: solo cyclist)	0.65 (0.04)	<0.001

* Excluded as not significant: dummy two-way cycle track; interaction dummy left duo cyclist x width, interaction dummy right duo cyclist or with oncoming cyclist x width; dummy Study 1.

facilitate the interpretation of the results of the regression analysis, the model is depicted for the three groups of cyclists in Fig. 7.

5. Discussion

The experimental Study 1 with three simulated cycle tracks shows that an increase in cycle track width causes cyclists to ride further away from the verge as well as keep more distance from an oncoming cyclist. The cross-sectional Study 2 was based on lateral position measured along an additional 28 real-life Dutch cycle tracks. Study 2 yielded similar results as Study 1, indicating good external validity of the results of Study 1. Both studies show that lateral position varies with roughly the 0.6 power of cycle track width, that is, doubling pavement width increases lateral position by some 50% ($2^{0.6}$−−1). According to both studies, cyclists ride closer to the verge when there are oncoming cyclists. Study 2 shows that, compared with a solo cyclist without interaction, a right-hand cyclist of a duo and a cyclist meeting an oncoming cyclist ride 30% closer to the verge. In Study 1, cyclists rode only 20% closer to the verge while meeting the parked bicycle used to simulate an oncoming cyclist. The smaller impact may be caused by the parked bicycle being predictable, not swerving, and therefore less realistic than the oncoming bicycles studied in Study 2. A left-hand cyclist of a duo keeps 92% more distance from the verge, an effect that was only part of Study 2.

We can also discuss the results relative to the center of the cycle track. Solo cyclists seem to ride in the middle instead of to the right on very narrow cycle tracks with widths up to about 100 cm. At 102 cm and 100 cm wide pavements, Pol (2022) found an average lateral position of 54 cm and 47 cm. In Study 1, cyclists kept more to the right along the 100 cm width condition with a lateral position of 36 cm, but the experimental conditions were less realistic than the two real-life two-way cycle tracks in the study by Pol (2022). If the width exceeds 100 cm, then cyclists tend to keep to the right and do so more the wider the cycle track is. This is in line with findings by Garcia et al. (2015) who found that cyclists ride centered on the right half of the cycle track on wider cycle tracks and closer to the centerline of the cycle tracks of narrower width.

In conclusion, since severe injuries due to single-bicycle crashes and collisions between cyclists currently comprise over 80% of all severely injured cyclists and over half of all severe road injuries in the Netherlands, the topic of cycle track widths must be studied to inform policy makers to adopt safer design guidelines (Aarts et al., 2021). The finding that cyclists approach the verge closer at narrower tracks is important as cyclists ride off the track in approximately a quarter of all single-bicycle crashes. Cyclists also keep less distance from each other on narrower cycle tracks, which can contribute to collisions between cyclists. Recent crash studies have shown that reduced pavement width is associated with a higher risk of bicycle crashes (Hoogendoorn, 2017; Van Weelderen, 2020), but it is difficult to derive design requirements from these studies. Section 5.1 of this study discusses how the results of the current study may inform design guidelines for cycle tracks after which Section 5.2 addresses the transferability of the results, Section 5.3 the research limitations, research recommendations.

5.1. Practical Applications: The findings in relation to minimum cycle track width in design guidelines

The lack of empirical research underpinning current design guidelines makes it difficult to explicitly compare them against the findings of this study. In an attempt to do so we compare our findings with the line of reasoning in the influential current Dutch *Design Manual for bicycle traffic* (CROW, 2016), which is fairly similar to the first version of this guideline published in 1993 (CROW, 1993). These Dutch guidelines have often been repeated in guidance in other countries (Parkin, 2018). The 75 cm width per cyclist in the *Design Manual for bicycle traffic* (CROW, 2016) is based on the average width of a Dutch bicycle of 55 cm and lateral space for course holding of an average cyclist under favorable circumstances of 20 cm. The width of the 25 cm buffers between cyclists for safe meeting and overtaking (buffer b in Fig. 1) and between a cyclist and the verge (buffer a in Fig. 1) are not explicitly explained. In the remainder of this section, we contrast the results of this study and related literature with the above-described assumptions to advise on the minimum width of a cycle track.

5.1.1. Width per cyclist

The assumed 20 cm width for course holding is based on an experiment by Godthelp and Wouters (1980) in which they determined the course deviations of cyclists steering along a 15 cm wide marked track. A cyclist riding straight ahead under favorable circumstances needed 20 cm, which increased to 30 cm in case of side wind or a poor road surface and to 60 cm while riding through curves. It is questionable whether steering along a 15 cm track resembles steering behavior on a real-life cycle track. For instance, participants in Study 1 needed on average 33 cm along a straight 150 cm wide cycle track under favorable circumstances without interaction with other cyclists. Study 1 shows that the lateral space for course holding increases with the width of the cycle track, but cyclists are likely to be able to reduce the space if this is necessary for interaction such as meeting another cyclist. However, a space around 30 cm seems to be too little under common conditions. From the bicycle model described by Meijaard et al. (Meijaard et al., 2007) and steering motions observed during normal cycling by Van den Ouden (2011), it has been estimated that the necessary width for course deviations at a forward speed of 18 km/h is around 40 cm (see also Schwab & Meijaard, 2018). This seems to be a more realistic starting point for an average cyclist under normal conditions.

Regarding the physical contour of the bicycle, the current guideline assumes 55 cm similar to the customary handlebar widths 40 years ago (Godthelp & Wouters, 1980). The current 58 cm Dutch average bicycle width is only slightly wider (Methorst et al., 2011). The above substantiated average width for course holding and the physical contour of the bicycle add up to around 100 cm *width per cyclist* instead of the 75 cm assumed in the current Dutch guideline. The Dutch recommended dimension is narrower than the 120 cm in some foreign guidelines (Parkin, 2018), which take into account the deviations from the mean (as discussed further in Section 5.1.3).

5.1.2. Buffer between a cyclist and verge while meeting

Empirical research on the lateral position of a meeting cyclist to underpin a buffer between a cyclist and the verge was lacking at the time the design guidelines were developed. Rather, a normative value was set that was assumed to provide enough room to avoid riding off the cycle track. To update the guidelines, empirical information is needed based on the distance a cyclist keeps from the verge when meeting another cyclist while maintaining a safe space from an oncoming cyclist to avoid a collision. It has been shown that cyclists do indeed keep more than 25 cm distance from the verge, for example on a 1.5 meter cycle track a distance of 37 cm is kept from the verge according to Study 1 in the condition with simulated oncoming cyclist (See Table 1) and 38 cm distance from the verge according to the lateral position model of Study 2 for a cyclist meeting an oncoming cyclist. The Dutch guideline specifies that, for a pavement width of 150 cm, the verges must be easy to ride over and free of obstacles, in order to allow cyclists be able to ride safely within 25 cm of the verge and keep sufficient distance from oncoming cyclists. However, the 25 cm distance is too conservative especially since in Study 1, the verge was designed easy and safe to cross, yet cyclists kept a distance of 37 cm from the (easy to cross) verge. When comparing bicycle tracks with a vertical, diagonal or levelled curb, Janssen (2017) found that cyclists did indeed cycle closer to a levelled curb. However, the difference with a right-angled curb was small. In order to take the relationship between cycle track width and lateral position into account, we use the lateral position model of Study 2 in the remainder of this section to advise on cycle track width instead of a constant distance as assumed in the current guideline.

5.1.3. Buffer between oncoming or overtaking cyclists

The average Standard Deviation of Lateral Position (SDLP) of 15 cm found in Study 2, based on studies in real-life conditions, takes into account not only the zig-zag motion to balance the bicycle, but also the fact that the average line of riding (along which cyclists zig-zag) is never completely straight (i.e., lateral position over a longer stretch is never perfectly constant). For instance, cyclists steer around a manhole, swerve somewhat more to the left or right while looking for other traffic. Assuming 95% of cyclists steer within two 15 cm standard deviations for swerving to the left and to the right, the lateral space for course holding will be 60 cm, a width similar to what Godthelp and Wouters (1980) measured at curves. A lateral space of 60 cm (30 cm left and 30 cm right), seems a reasonable starting point to take into account the lateral displacement of a large proportion of cyclists and circumstances (i.e., 20 cm more than the average width per cyclist mentioned in the previous section). This additional space is still conservative. In an in-depth study of bicycle crashes it was found that greater lateral displacement preceding a crash resulted from carrying baggage (Boele-Vos et al., 2017) and so there are many scenarios imaginable where a cyclist suddenly swerves.

Regarding the physical contour of the bicycle, CROW has recently advised to assume a standard bicycle of 64 cm in design of cross-sections to accommodate characteristics representative of most of the vehicle fleet (CROW, 2021). This is still 11 cm less than the 75 cm legal maximum bicycle width in the Netherlands, but some 5 cm more than the average width mentioned in the previous section. Many countries including the Netherlands allow wider three- and four-wheeled cargo bikes on cycle tracks. On average, these bicycles have a small share in the Netherlands (CROW, 2022). A greater share could be reason for even more width.

The experiment of Study 1 was conducted during daylight under favorable conditions with healthy young adults. For Study 2, we took lateral position during daylight. In the study by Pol, Brouwer, and Beterams (2020), fiber cables were used, which allowed for lateral position measurements during darkness as well. They found cyclists to ride closer to the center of the track during darkness. Their lateral position was 10 to 20 cm higher during darkness on a bicycle track without edge markings than during the day. This is important for road safety because vision is impaired in darkness and crash risk is correspondingly higher (Schepers & Den Brinker, 2011; Twisk & Reurings, 2013). Cyclists also cycle closer to the center of the cycle track if high obstacles are present to their right, (e.g., fences and trees). Garcia et al. (2015) found a 20 cm smaller lateral distance between meeting cyclists when obstacles in the shoulder were higher than the handlebars. Cyclists operating the screen of a smartphone also ride over 10 cm closer to the center (De Waard et al., 2014, 2015). Although this is banned in the Netherlands, a street measurement in 2021 showed that 3% of cyclists were still operating a screen (NDC Nederland, 2021).

Based on these studies, a 50 cm buffer between meeting cyclists seems to be a good starting point to accommodate variations in steering behavior, vehicle width, and circumstances.

5.1.4. The findings in relation to minimum cycle track width in design guidelines

The continuous lines in Fig. 9 depict the lateral positions of two cyclists meeting each other in opposite directions according to the lateral position model of Study 2 as approximation of buffer a of Fig. 1 between the verge and cyclist. Dashed lines depict lateral position plus the cyclists' contours (average physical contour plus space for course holding) towards the center of the cycle track. It appears that a pavement width of 250 cm is needed to allow for a 50 cm buffer b between the spaces of both meeting cyclists to accommodate common variations of steering behavior and vehicle width between cyclists and circumstances.

According to our findings, duo cyclists keep less distance between themselves than they do from oncoming cyclists. On a 250 cm wide track, cyclists keep around 90 cm wheel to wheel distance. Because cyclists can coordinate their movements and course with each other and can react to each other more easily as compared to meeting cyclists, it is questionable whether we should assume the same required dimensions as when discussing meeting cyclists. For example, when passing a manhole or pothole, one cyclist can go around it on the right and the other on the left, or they can ride behind each other for a while, and so forth. In contrast to meeting, cycling next to each other is voluntary. On the other hand, cyclists on narrower cycle tracks sometimes hook in each other's handlebars (Hoogendoorn, 2017), a risk that can be reduced by offering sufficient pavement width. With the results of this study, it remains difficult to determine an exact minimum width for duo cyclists.

5.1.5. Guideline update

Fietsberaad, the Dutch bicycle council, has recently published new recommendations for the minimum width of cycle tracks that may be incorporated into a future update of the *Design Manual for bicycle traffic* (CROW, 2022). The report also looks at (one-way) cycle/moped tracks and busy cycle tracks where additional pavement width is needed due to capacity and safety. The results of recent empirical studies on the lateral position of cyclists were also included, which contributed to raising the requirements for the minimum width of cycle tracks. While the minimum width of a standalone bidirectional cycle track where mopeds are not allowed was 150 cm, the report recommends a minimum width of 230 cm, whether it is a standalone cycle track or cycle track along a carriageway. The recommended width increases substantially as there are more oncoming or overtaking cyclists. These new recommendations are more consistent with the analysis of the previous sections and with recommendations in foreign guidelines that are rarely lower than 250 cm (Schröter et al., 2021).

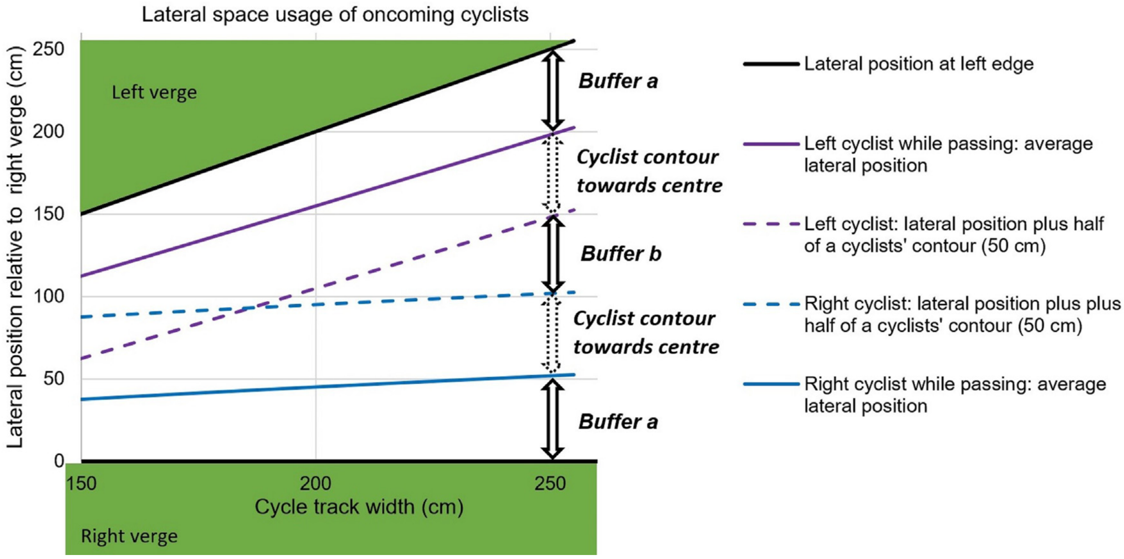

Fig. 9. Lateral position of meeting cyclists relative to the verge (buffer a) plus space for their physical contours towards the centre of the track (half the width per cyclist) to determine at which cycle track width buffer b between the two spaces per cyclist is at least 50 cm.

5.2. Transferability of the results to cycle tracks outside of the Netherlands

This study focuses on bicycle tracks to substantiate cycle track width requirements in guidelines. The results are not applicable for mixed-traffic streets or width requirements for visually separated bicycle lanes. Also, both Study 1 and Study 2 were conducted in the Netherlands, a cycling country with a head start when it comes to existing, designing, and building comfortable and safe cycle tracks (Pucher & Dijkstra, 2003; Schepers et al., 2017b). This raises the question of the extent to which the results are transferable to other countries. De Waard et al. (2020) compared cycling performance between Dutch and non-Dutch students including their lateral position. Non-Dutch students kept 5 cm less distance to the curb than Dutch students, a small difference that was significant only at the 10% level. SDLP hardly differed. Tasks such as steering behavior may barely differ at the control level, so steering behavior may also differ little between countries. On the other hand, whereas the ages of Dutch and non-Dutch students were similar in the study by De Waard et al. (2020), a larger share of cyclists in cycling countries such as the Netherlands and Denmark are children and elderly compared to countries where cycling is rare (Goel et al., 2021). Both differences in characteristics of the population of cyclists and infrastructure design may contribute to differences in lateral position.

In this light, we contrasted our results with those of studies on lateral position at cycle tracks by Zamanov (2010) in Vienna, Khan and Raksuntorn (2001) in Denver, Colorado, Fonseca-Cabrera et al. (2021) in Valencia, and Greibe and Buch (2016) in Copenhagen. By video observations, Greibe and Buch (2016) measured lateral position at 8 one-way cycle tracks between 185 and 285 cm wide. Their linear regression model to describe lateral position of solo cyclists (0.21 W+21) yields a 60 cm lateral position at a 185 cm wide track and 81 cm position at a 285 cm track. These estimations hardly differ from those of the lateral position model of Study 2 (i.e., 62 cm at a 185 cm wide track and 81 cm at a 285 cm track). Exactly similar to the model of Study 2, Khan and Raksuntorn (2001) measured a lateral position of 84 cm among solo cyclists at a 300 cm wide cycle track in Denver.

Several studies have measured the difference in lateral position between meeting cyclists rather than the lateral position of cyclists relative to the cycle track edge. To compare with these studies, the

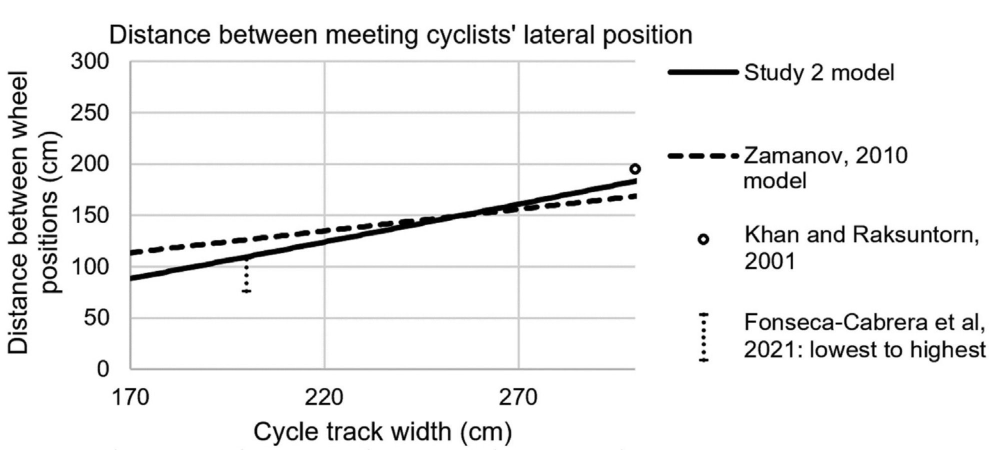

Fig. 10. Difference between meeting cyclists' lateral position.

lateral position of meeting cyclists relative to the cycle track edge according to the Study 2 model was converted to the difference in lateral position between meeting cyclists, see Fig. 10. Using photos Zamanov (2010) studied how much distance meeting cyclists kept from each other on 15 two-way cycle tracks in Vienna. To estimate the distance between the physical contours of meeting cyclists, the distance between their wheels was reduced by 60 cm. Adding this 60 cm to Zamanov's linear regression model of the median space between meeting cyclists yields a model for the space between their lateral positions (0.423 W – 18.25 + 60 = 0.423 W + 41.75). Khan and Raksuntorn (2001) measured a 195 cm meeting distance at a 300 m wide cycle track (in their paper called 'lateral spacing for meeting events'). Fonseca-Cabrera et al. (2021) used a standing e-scooter equipped with two distance meters to measure the lateral distance to meeting other e-scooters and cyclists at 2 m wide cycle tracks. Their outcomes seem relevant as the lateral distance to e-scooters and cyclists hardly differed in their study. Fig. 10 shows the range of lateral distances, from the lowest at cycle tracks along discontinuous concrete curbs to the highest at a cycle tracks without edge elements. Using an instrumented bicycle equipped with video cameras and laser rangefinders to observe meeting clearance at six cycle tracks in Valencia, Garcia et al. (2015) found meeting clearance increased with the cycle track width. Because cycle tracks of different widths were combined into three width classes, the results could not be included in Fig. 10. On average, the measured differences in lateral meeting distance between the Study 2 model and the estimates from the other three studies in Fig. 10 are fairly small where Study 2 lies between the values of other studies.

The other measurements in the Greibe and Buch (2016) study involved overtaking cyclists, a group that was not measured in Study 2. The lateral position of the cyclist being overtaken is between that of a solo cyclist and that of the right-hand cyclist of a duo in Study 2. The lateral position of the overtaking cyclist is greater than that of the left-hand cyclist of a duo and smaller than that of an oncoming cyclist in Study 2. While overtaking, cyclists in the Greibe and Buch (2016) study keep more distance from each other than duo cyclists and less distance than meeting cyclists in Study 2. Using video observations, Mohammed et al. (2019) measured the difference between the lateral positions of overtaking cyclists at two 2 m wide sections of a cycle track at the Brooklyn Bridge in New York City. According to their study, the difference is somewhat smaller than what the Greibe and Buch (2016) model predicts on a 2 m wide cycle track.

Given the results by De Waard et al. (2020) and similarities between our results and those of Zamanov (2010) and Greibe and Buch (2016), we may tentatively conclude that our results are transferable to regions and cities with a modest to high amount of cycling such as in Vienna and Copenhagen.

5.3. Research limitations and research recommendations

Unfortunately, several knowledge gaps remain after this study. Firstly, this study provides empirical lateral position data, but not what distances between cyclists and to the verge are required to avoid a large proportion of actual crashes in which a cyclist rides off the cycle track or collides with an oncoming cyclist. Conflict observation studies, naturalistic cycling studies, and in-depth accident studies may help to provide more insight into this and get more certainty about the minimal buffer zones to underpin design guidelines from a safety perspective. Secondly, more research on lateral position while overtaking is needed as it may be the most critical manoeuver on a one-way cycle track. In addition to measuring the lateral position, similar to Yan et al. (2018) it can also be investigated what proportion of cyclists decides not to overtake and/or not to ride next to each other at cycle tracks with varying width. In this line of reasoning a cycle track should be wide enough for the vast majority of cyclists to choose to cycle next to each other or overtake. As cycling is a social activity, this would also be desirable on one-way cycle tracks. The new Fietsberaad recommendations on cycle track width also give greater weight to being able to cycle comfortably side by side (CROW, 2022).

Study 1 and 2 also had a number of more technical limitations. Even after filtering the data, a small part of the LIDAR measurements in Study 1 were noise. The determination of the maximum and minimum lateral position is therefore less accurate. With a more sophisticated filter and modeling approach, such noise could be further filtered out in future research. For instance, Lee et al. (2020) used a stationary LIDAR on a tripod and estimated cyclists' trajectory from the LIDAR point cloud using a Gaussian curve model that allows to exclude points too far away from the modeled trajectory. Another limitation of Study 1 that can be overcome by this approach is the identification of the part of the trajectory where cyclists swerve to avoid the parked bicycle that simulated an oncoming cyclist. In Study 1, the lateral position was measured for the entire track with the simulated oncoming cyclist and not only the meeting maneuver. According to Study 2, lateral position measured in Study 1 while meeting hardly differed from other studies with other measurement methods. However, it is plausible that a slightly lower lateral position would have been measured in Study 1 if constrained to the meeting maneuver. Another way to tease out the lateral position specifically during meeting or overtaking would be to photograph or video record this maneuver as was done in the studies by Greibe and Buch (2016) and Zamanov (2010). Another limitation of both Study 1 and 2 is that lateral position in overtaking maneuvers was not included. The study by Greibe and Buch (2016) shows that overtaking is not comparable to meeting and duo cycling.

A limitation of Study 1 is that the group of participants consisted of students under 27 years of age that the two-thirds proportion of women is relatively high, which raises the question of the extent to which the results are representative of the entire population including older cyclists. An indication that the results of Study 1 may be representative with regards to lateral position while cycling is that a similar relationship between width and lateral position was found in Study 2. As described in Section 4.1, the results of Study 2 seem reasonably representative for Dutch cyclists. This would suggest that lateral steering behavior does not differ substantially between younger and older cyclists. Accordingly, Westerhuis and De Waard (2014) found only small differences in lateral position when comparing a group of older cyclists (mean age 64 years) with a group of younger cyclists (mean age 32 years).

This study was conducted in the Netherlands, where almost no standing e-scooters are allowed and accordingly no studies on their lateral position were conducted. The rise of micromobility in many other countries makes it necessary to take such modes into account in the design of cycle tracks as well. A study by Fonseca-Cabrera et al. (2021) suggests that the lateral position of standing e-scooters is similar to that of cyclists, but more research on this issue is needed to inform design guidelines.

6. Conclusions

With both an experimental study and cross-sectional study, we found that an increase in cycle track width causes cyclists to ride further away from the verge and keep more distance from an oncoming cyclist. Doubling pavement width increases lateral position by some 50%. Given a cyclists' lateral position while meeting an oncoming cyclist, common variations between cyclists' steering behavior, and vehicle width and circumstances, a cycle track width of 250 cm is needed for safe meeting maneuvers.

Declaration of Competing Interest

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

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