García García, A.; Agustin Gomez, F.; Llorca Garcia, C.; Antonio Angel-Domenech (2015). Effect of width and boundary conditions on meeting maneuvers on two-way separated cycle tracks. Accident Analysis and Prevention. 78:127-137. doi:10.1016/j.aap.2015.02.019.

Effect of width and boundary conditions on meeting maneuvers on two-way separated cycle tracks

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Abstract

Cycle track design guidelines are rarely based on scientific studies. In the case of off-road two-way cycle tracks, a minimum width must facilitate both passing and meeting maneuvers, being meeting maneuvers the most frequent. This study developed a methodology to observe meeting maneuvers using an instrumented bicycle, equipped with video cameras, a GPS tracker, laser rangefinders and speed sensors. This bicycle collected data on six two-way cycle tracks ranging 1.3 to 2.15 m width delimitated by different boundary conditions. The meeting maneuvers between the instrumented bicycle and every oncoming bicycle were characterized by the meeting clearance between the two bicycles, the speed of opposing bicycle and the reaction of the opposing rider: change in trajectory, stop pedaling or braking. The results showed that meeting clearance increased with the cycle track width and decreased if the cycle track had lateral obstacles, especially if they were higher than the bicycle handlebar. The speed of opposing bicycle shown the same tendency, although were more disperse. Opposing cyclists performed more reaction maneuvers on narrower cycle tracks and on cycle tracks with lateral obstacles to the handlebar height. Conclusions suggested avoiding cycle tracks narrower than 1.6 m, as they present lower meeting clearances, lower bicycle speeds and frequent reaction maneuvers.

1. Introduction

Urban areas account for 40% of road fatalities (European Commision, 2013a). Although traffic safety has improved remarkably in recent years, it has been focused on the safety of motor vehicles. However, 50% of the victims of urban road crashes were pedestrians or cyclists (European Commision, 2013b).

In general, bicyclists identify safety as one of their highest priorities in selecting bicycle routes. A common characteristic of countries with a high cycling mode share is the provision of cycle tracks (separated bikeways along streets) on major routes. For this reason, physically separated bicycle paths have received increasing attentions from researchers. Wardman et al. (Wardman et al., 2007) forecasted that a completely segregated bicycle roadway would result in a 55% increase in bicycling. A survey conducted in Canada corroborated that physically separated pathways were preferred by cyclists and encouraged more cycling (Winters and Teschke, 2010). Another study in Canada reported that the injury risk of cycling on cycle tracks is less than cycling in streets (Lusk et al., 2011).

In absence of regulation, most of existing cycle tracks in Spain are two-way cycle tracks. These bicycle facilities accommodate the following maneuvers (Allen et al., 1998):

- Following: a faster bicycle reaches a slower one.
- Passing: after following, a faster bicycle passes the slower one.
- Meeting: two bicycles travelling in opposing directions cross.

Manar and Desmarais (Manar and Desmaris, 2013) studied bike-following behavior. They collected data in a controlled experiment installing GPS receivers in two bicycles. The bicycles ran on a 1.7 km, 1.5 m-wide (each direction) exclusive off-street cycle track. A similar cycle track was monitored, observing 253 couples of leading and following bicycles using a video camera mounted on a mast. They adapted and calibrated existing car-following models based on the observations. The results showed that the following bicycles did not move freely when headways were under 16 m. The authors suggested a minimal headway of 2.2 m, including bicycle length, which would lead to a 2,700 bicycles/h one-way capacity.

In order to increase capacity, passing maneuver allows faster bicyclists to travel at their own desired speeds. Passing maneuvers on cycle tracks have been also investigated. Khan and Raksuntorn (Khan and Raksuntorn, 2001) observed passing events on a separated 3 m-wide cycle track. This study used two video cameras installed on the sidewalk of a bridge over the cycle track. They measured passing and passed bicycle speeds, as well as bicycle lateral placement during the maneuver. The results showed that passed bicycles tended to move to the right while they were passed (from 0.86 to 0.58 m on average), while lateral spacing between the passing and the passed bicycle was 1.78 m. On average, a passing maneuver needed a distance of 91 m. Recently, Li et al. (Li et al., 2013) collected data of passing maneuver on cycle tracks in order to calibrate and validate a microsimulation model. Video cameras were installed to collect data in nine locations. Authors proposed a cellular automation model to predict the number of passes, and to classify them according to the lateral position of the passing and the passed bicycle.

Allen et al. (Allen et al., 1998) analyzed the frequency of both passing and meeting maneuvers on separated cycle tracks. The number of maneuvers determined the level of service of a cycle track, according to these authors. Their results showed that, on two-way cycle tracks meeting maneuvers are more than ten times frequent than passing maneuvers. The higher frequency of meeting maneuvers contrasts with the very limited knowledge about them. Only Khan and Raksuntorn (Khan and Raksuntorn, 2001) analyzed meeting maneuvers in detail. Using a 100 meeting maneuvers sample on a 3 m-wide cycle track, they concluded that the average lateral spacing between meeting bicycles was 1.95 m. Although authors expected a correlation between the spacing and the cycle track width, this was not explored as they only observed a 3 m width.

Most of the previous studies on either passing or meeting maneuvers were based on video recordings at fixed locations. However, other authors collected data from instrumented bicycles. This facilitated continuous data along segments, in contrast to fixed locations. Walker (Walker, 2007) and Chapman and Noyce (Chapman and Noyce, 2012) equipped bicycles with either laser or ultrasonic distance measurement devices to analyze the lateral spacing between bicycles and motor vehicles during passing maneuvers on two-lane rural roads. Parkin and Meyers (Parkin and Meyers, 2010) used also an instrumented bicycle to study how motor vehicles passed bicycle on cycle lanes adjacent to vehicle lanes. They detected that drivers are less respectful with lateral distances when passing bicycles on roads with designated cycle lanes. Lee et al. (Lee et al., 2011) used a high-accuracy GPS tracker on an instrumented bicycle to analyze the minimum maneuvering space and lateral clearance on a one-way cycle track. One hundred riders participated in the experiment, at three speeds: 10, 20 and 30 km/h. The minimum maneuver space vary inversely with speed, which indicated that speed reduction increased instability. On a 2 m wide cycle track, the maneuvering space was 1.48 m width and the additional comfortable lateral clearance was 0.42 m at 20 km/h. The conclusions suggested a minimum one-way cycle track width of 2 m. Other authors have used instrumented bicycles to observe the interaction between motor vehicles and bicycles. They used either a naturalistic procedure (Dozza and Fernandez, 2014) or quasi-naturalistic method (Chuang et al., 2013). However, they did not study the influence of road geometry on the interaction between bicycles on cycle tracks.

Additionally, van der Horst et al. (van der Horst et al., 2013) recently analyzed conflicts between bicycles, mopeds and crossing pedestrians. However, the authors only focused on one location, and not specifically on meeting maneuvers between oncoming bicycles.

Meeting maneuvers and conflicts involving oncoming bicycles should be a critical issue for the selection of cycle track widths. However, there is not much scientific evidence that support that selection. American Association of State Highway and Transportation Official (AASHTO) Guide for the Development of Bicycle Facilities (American Association of State Highway and Transportation Official, 2012) proposes a minimum width of 3 m for separated shared cycle tracks (for pedestrian and cycling), although no recommendation is proposed for exclusive off-road cycle tracks. Many other regional and local guidelines establish different criteria, although they never justify the proposed values. For instance, Transport for London (Transport for London, 2014) recommends a minimum of 2 m for low traffic volumes and a maximum of 4 m for higher. Dutch platform CROW (CROW, 2007) also recommends between 2.4 and 4.0 m widths, depending on traffic volume.

The majority of existing cycle tracks in Spain are located on sidewalks. There is usually a limited space availability and track width does not usually exceed 2 m, which generally is perceived by users as insufficient. However, there is no previous study, which has analyzed the link between width and lateral clearance of meeting maneuvers on such narrow cycle tracks. Therefore, this research was motivated by the absence of scientific basis on the selection of cycle track widths.

2. Objectives

The aim of this research was the observation of meeting maneuvers on two-way separated cycle tracks. This depended on the following objectives:

- Development of a methodology for quasi-naturalistic observation of cycle traffic on separated cycle tracks.
- Data collection of meeting maneuvers on a sample of two-way separated cycle tracks.
- Analysis of meeting maneuver dynamic variables and opposing rider’s response, as well as their relation with cycle track width and boundary conditions.
- Establishment of guidelines to determine the minimum cycle track width that ensures safe and comfortable meeting maneuvers.

The following hypotheses justified this study:

- On wider cycle tracks, meeting clearance and opposing bicycle speed are higher than on narrow cycle tracks.
- In presence of lateral obstacles, meeting clearance and opposing bicycle speed is reduced. The effect of obstacles to the handlebar height is higher than the effect of obstacles to the wheel height. In absence of lateral obstacles, clearance and speed are much higher.

3. Methodology

An instrumented bicycle collected the observational data. A cyclist rode along selected cycle tracks in normal conditions, at a speed set according to previous observations and centered on the right side of the cycle track. The objective was to collect data of every meeting maneuver in which the bicycle was involved. This method consisted in a quasi-naturalistic observational study, as the influence of the researchers was minimized and controlled.

3.1. Equipment

The bicycle was installed four video cameras to record video information on other users generating conflicts with the bicycle, such as other bicycles or pedestrians. In particular, the analysis focused on the meeting maneuvers and opposing rider's reactions to them. High definition cameras allowed the identification of the opposite rider characteristics (such as gender and age, estimated by watching the video, with a 5-year accuracy) and behavior (path changing, stop pedaling and braking, identified by watching the video). A 10 Hz GPS tracker continuously registered position of the instrumented bicycle with a 5 m accuracy. Video and GPS position were stored in a VBOX data logger.

A Laser Technology Inc. T100 laser system measured the clearance with the opposing bicycle and its relative speed in meeting maneuvers with a cm accuracy. This system had two laser rangefinders, perpendicular to bicycle axis, one of them in the front part of the bicycle and the other on the rear. Meeting clearance measurement was the average between both rangefinders and measurement time difference between the front and the rear sensors provided the relative speed, being the accuracy equal to 1 km/h, according to manufacturer. Additionally, as seen in Figure 1, two Laser Technology Inc. S200 rangefinders measured the clearance between the bicycle and any crossing vehicle or obstacle in front of and behind the bicycle. These measurements were not used to analyze meeting maneuvers. A laptop connected to all laser devices stored the measurements.

Figure 1. Instrumented bicycle

The laser pointer installed on the bicycle was oriented to the cycle track centerline. This facilitated the cyclist to ride at the desired position. All data storing devices, batteries and accessories were installed in a box fixed to the bicycle frame (Figure 1 and Figure 2).

As seen in Figure 3, laser sensors and cameras were relatively small. The box contained most of the equipment to avoid detection from oncoming cyclists. Besides, meeting maneuvers are not optional maneuvers. This made it possible to assume that opposing riders did not change their behavior when approaching the instrumented bicycle.

Front Rear

Figure 2. Front and rear laser sensors

Figure 3. Instrumented bicycle front view

3.2. Locations

The data collection was conducted during six weekdays in April 2013 with sunny weather conditions and dry pavement. The data collection covered morning peak and non-peak period in order to get various bicycle traffic conditions. During data collection, several cyclists rode the instrumented bicycle through a sample of six two-way cycle tracks in Valencia (Spain), riding round trips in natural conditions (Table 1 and Figure 4).

Site	Street	Cycle track width (m)	Boundary conditions type
1	Tarongers Av. (North side)	1.91 and 2.00	None, wheel height, handlebar height
2	Tarongers Av. (South side)	2.00	None, wheel height
3	Blasco Ibañez Av. (North side)	2.00 and 2.15	None, wheel height, handlebar height
4	Puerto Av.	1.60	None, wheel height, handlebar height
5	Peris i Valero Av.	1.80 and 2.00	Wheel height, handlebar height
6	Duc de Calabria St.	1.30 and 1.50	Handlebar height

Table 1. Cycle track characteristics

Initial position adopted by the instrumented bicycle during the circulation was 0.5 m right of the centerline in the travel direction. The laser pointer facilitated the rider to travel at the right position. Speed was set at 15 km/h, based on previous observations of bicycle free-flow speeds. For this purpose, a sample of 88 cyclists was observed using video cameras, without any intervention. The measured average speed was not different to 15 km/h, which is the maximum speed, according to local regulations.

As shown in the Figure 4, the selected segments covered a wide range of width and different boundary conditions. Boundary conditions were grouped in three categories: absence of lateral obstacle, lateral obstacle to the wheel height (under 60 cm) and lateral obstacle to the handlebar height (over 60 cm).

The absence of lateral obstacles (coded as “none”) was simply the existence of marking to separate the cycle track and the sidewalk. Obstacles to the “wheel height” were small bushes or curbs. Obstacles to the “handlebar height” were a hence or a line of streetlights. Boundary conditions varied along cycle tracks. Therefore, they were assigned individually to each maneuver as indicated in the section 3.3.


Site 1. Tarongers Av. (North side)
Site 2. Tarongers Av. (South side)
Site 3. Blasco Ibañez Av. (North side)
Site 4. Puerto Av.
Site 5. Peris i Valero Av.
Site 6. Duc de Calabria St.

Figure 4. Cycle tracks

When a meeting maneuver occurred, the cyclist riding the instrumented bicycle behaved naturally. This bicycle collected 336 valid meeting maneuvers. The riders did not perform any evasive maneuver or changed their trajectory, except in case of dangerous situations. Those exceptions were not analyzed, though.

Valid meeting maneuvers occurred on a tangent section, when the opposite bicycle was circulating in free-flow. Therefore, findings of this study do not consider curved sections or bicycle platooning effect on the meeting maneuvers. After a data reduction process, maneuver data, data regarding opposite bicycle and data regarding bike path for each specific location, was included in a meeting maneuver database.

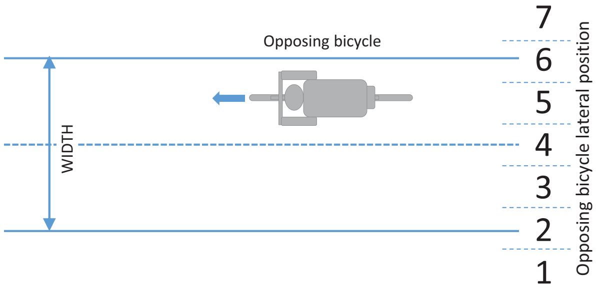
3.3. Data reduction

The analysis variables were divided into cycle track geometry and meeting maneuver dynamic. Tables 2, 3 and 4, and Figure 5 summarize all variables.

Laser speed system measures the distance to every obstacle in its field of view. When an opposing bicycle crossed the two parallel laser beams, the system provides the relative speed between the sensor and the bicycle. The distance to the bicycle was averaged between both laser sensors. It corresponded to the distance to the opposing cyclist body. The laser provided the distance MLD (meeting laser distance), according to Figure 5b.

A transversal video camera focused on the floor was calibrated using a grid. An estimation of half cyclist body width (HB) was obtained by subtracting the laser distance measurement (MLD) from the meeting spacing (MS) (obtained from video data in a sample of maneuvers). After that, using the average handlebar width of the opposing bicycle (in function of bicycle type), the handlebar of the instrumented bicycle (unique) and the half cyclist body width (HB), the variables MS (meeting spacing) and MC (meeting clearance) were calculated for the whole sample.

(a) Free flow



(b) Meeting maneuver

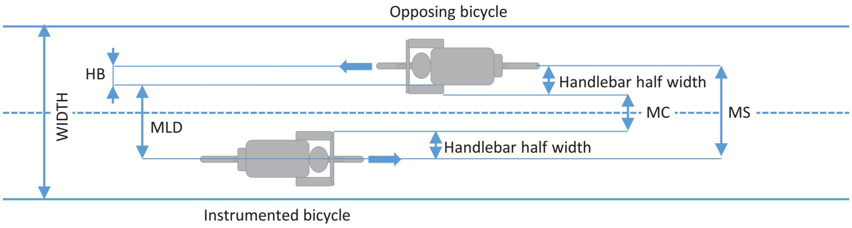


Figure 5. Free flow and meeting maneuver variables

Cycle Track Geometry			
Variable	Code	Range	Count
Cycle track width	WIDTH	Narrow: 1.3≤ Width ≤1.6 m	88
		Medium: 1.6 < Width ≤1.8 m	61
		Wide: 1.8 < Width≤ 2.15 m	187
Lateral obstacle	BOUNDARY_TYPE	None	34
		To the wheel height	192
		To the handlebar height	110

Table 2. Variables of cycle track geometry

Opposing cyclist			
Variable	Code	Range	Count
Opposing rider's age	AGE	15 to 60	336
Opposing rider's gender	GENDER	male	229
		female	107
Opposing rider wear helmet	HELMET	yes	20
		no	316
Opposing bicycle type	TYPE	urban	101
		mountain	121
		racing	8
		public shared	106

Table 3. Variables of opposing cyclist

Meeting maneuver			
Variable	Code	Range	Count
Relative lateral position before meeting (relative to the width)	OLP1	1 to 7 coded as seen in Figure 5	336
Relative lateral position after meeting (relative to the width)	OLP3	1 to 7 coded as seen in Figure 5	
Meeting laser distance	MLD	-	
Half cyclist body width	HB	equal to 0.25 m	
Meeting spacing	MS	-	
Meeting clearance	MC	-	
Opposing bicycle speed	VO	-	
Cyclist changes the normal trajectory	T	yes	220
		no	116
Cyclist stops pedaling	P	yes	49
		no	287
Cyclist brakes	B	yes	7
		no	329
Number of evasive actions performed by opposing cyclist	NUMBER_ACTIONS	0	104
		1	194
		2	32
		3	6

Table 4. Variables of meeting maneuver

4. Analysis

The analysis included the evaluation of the lateral positions before and after the meeting maneuver, the meeting spacing, the opposing bicycle speed and the opposing rider's reaction: stop pedaling or braking actions. Each analysis step evaluated the impact of cycle track width and boundary conditions type.

Besides, the potential effect of opposing cyclist characteristic was analyzed. However, no statistically significant effect was found for any of the opposing cyclist characteristics (age, gender, use of helmet or bicycle type).

4.1. Lateral position before and after the meeting maneuver

This analysis compared the relative lateral position of cyclists before and after the meeting maneuver, and in relation to the cycle track width. The position before and after the meeting maneuver may be associated with the desired position of free-flow bicycles, without opposing traffic. As seen in Figure 5a, opposing lateral position was coded from 1 to 7, using both the front and rear video cameras. Both discrete variables (before and after lateral position), as well as their difference, were estimated using an ordered probit model. This model, commonly used for crash severity modeling (Kockelman and Kweon, 2002) assumes the existence of a latent variable Y*, as shown in the equation 1.

$$Y_j^* = \beta_i \cdot X_{ij} + \varepsilon_j \qquad (1)$$

where:

- βi is a coefficient of the explanatory variable i.
- Xij is the value of the explanatory variable i for maneuver j.
- εj is the error term, assumed to came from a normal distribution.

The outcome of the model Yj is defined in the equation 2.

$$Y_j = \begin{cases} k_1 \ if -\infty \leq \ Y_j^* \leq \mu_1 \\ k_2 \quad if \ \mu_1 \leq \ Y_j^* \leq \mu_2 \\ \quad \quad \quad \cdots \end{cases} \qquad (2)$$

where:

- k1, k2, etc. are ordered classes.
- μ1, μ2, etc. are the thresholds to be estimated.

The probability of the latent variable Y of being in the class k_l or lower is estimated according to the equation 3.

$$P(Y_j \ \ \leq k_l) = P(Y_j^* \leq \mu_l) = \Phi\,(\mu_l - \ \beta_i \cdot X_{ij}) \qquad (3)$$

where:

- Φ is the standard normal cumulative distribution

This model was estimated using a maximum likelihood procedure, implemented in statistical software R. Table 5 shows the results of the estimation of the models of lateral position before the meeting maneuver (OLP1), lateral position after (OLP3) and its difference (OLP3-OLP1). Figure 6 plots the frequency distributions.

		OLP1			OLP3			OLP3-OLP1		
		Coefficient	t-value		Coefficient	t-value		Coefficient	t-value	
Explanatory variable	IS_NARROW	-0.914	-5.752	***	-0.752	-4.407	***	0.484	2.737	**
	IS_MEDIUM	not significant			-0.541	0.009	**	not significant		
	IS_HANDLEBAR	-1.239	-4.166	***	-1.871	-4.410	***	not significant		
	IS_WHEEL	-0.805	-2.854	*	-1.222	-2.973	**	not significant		
Thresholds	3|4	-3.501	-10.673	***	-4.016	-9.006	***	not significant		
	4|5	-1.637	-5.945	***	-2.296	-5.583	***	not applicable		
	5|6	1.481	5.394	***	1.388	4.630	***			
	-1|0	not applicable						-1.491	-12.8885	***
	0|1							1.522	12.9443	***

significance codes: ***: 0.001, **: 0.01, *: 0.05

Table 5. Estimation of OLP1, OL3 and OLP3-OLP1 models

As can be seen in Figure 6a and b, on narrower cycle tracks most of cyclists circulated closer to the centerline, while in wider tracks they were closer to the outer edge (higher OLP1 and OLP3). Besides, the boundary condition type affected the position, being both OLP1 and OLP3 lower with boundary conditions, especially those to the handlebar height. Figure 6c concludes that the number of cyclists that moved to the right after the meeting maneuver (OLP3-OLP1 was positive) was slightly higher on narrow cycle tracks. The class “not narrow” correspond to “wide” or “medium”.

Figure 6. Frequency distributions of OLP1, OLP3 and its difference

4.2. Meeting spacing and clearance

This section focuses on the characterization of the lateral distance between the two meeting bicycles. Figure 7 shows the cumulative distributions of meeting spacing and meeting clearance. Both meeting spacing (MS) and meeting clearance (MC) came from normal distributions at the 95% confidence level (Kolmogorov-Smirnov test p-values of 0.216 and 0.592 respectively). Figure 7 shows that the differences between both variables represent more than 50% of their value (mean values of 0.65 m vs. 1.15 m). This result justify the transformation from spacing to clearance, as explained in the section 3.3. Despite the reduced dispersion in handlebar widths, the following analysis steps considered the meeting clearance, since it reflects better the proximity of a conflict between the two involving bicycles.

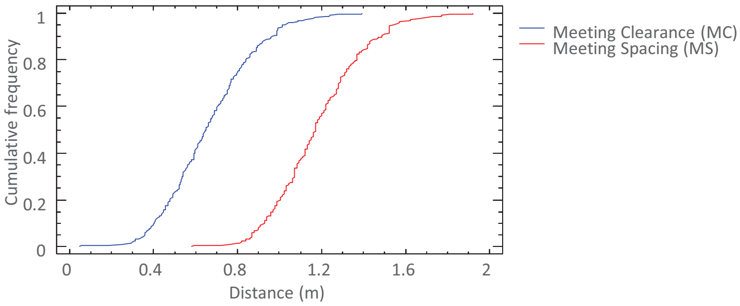


Figure 7. Cumulative distributions of meeting spacing and meeting clearance

Parameter	MC		
	Estimate	t-statistic	
CONSTANT	0.891309	30.8217	***
IS_NARROW	-0.249832	-11.1886	***
IS_MEDIUM	-0.197071	-7.5335	***
IS_WHEEL	-0.101086	-3.1108	**
IS_HANDLEBAR	-0.200533	-5.9214	***
R-squared	41%		
Standard error of est.	0.168229		
significance codes: ***: 0.001, **: 0.01, *: 0.05			

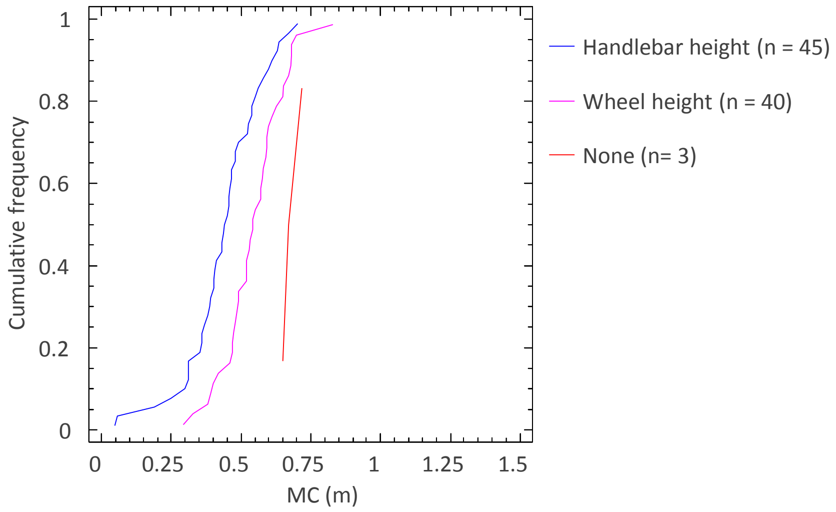
Table 6. Linear regression model for MC

Table 6 shows the results of the estimation of a linear regression model for MC. The effect of cycle track width and boundary conditions type was significant at the 95% confidence level. Without obstacle and on wide cycle tracks, the average MC was equal to 0.89 m. Reducing the width to the range between 1.7 and 1.9 reduce the MC 0.19 m, while the reduction with narrower tracks was 0.25 m. On the other hand, the presence of and obstacle to the wheel height reduce the average of MC 0.10 m, being 0.20 if the obstacle was to the handlebar height.

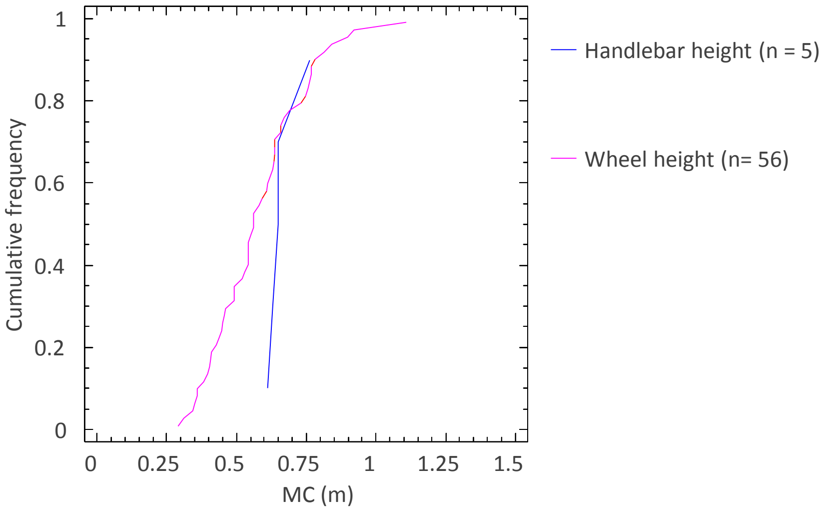
The same results of the regression model, are shown in Figure 8. It plots the empirical cumulative distributions of meeting clearance for wide, medium and narrow tracks, either in absence or in presence of obstacles.

The frequency of meeting maneuvers with a very low clearance (under 0.3 m) was almost zero on wide tracks and on tracks without lateral obstacles, although it increased up to 20% in case the cycle track was narrow and with lateral obstacles to the handlebar height. The lateral clearance increased for wide cycle tracks, being in a significant proportion above 1 m (Almost 40% in wide tracks without lateral obstacles and 20% in lateral obstacles to the wheel height). The general tendency shows that clearance increased with width (from Figure 8a to 8c) and decreased with the presence of obstacles (being “none” in red the largest, and obstacles “to the “handlebar height” in blue the lowest).

(a) Narrow cycle track



(b) Medium cycle track



(c) Wide cycle track

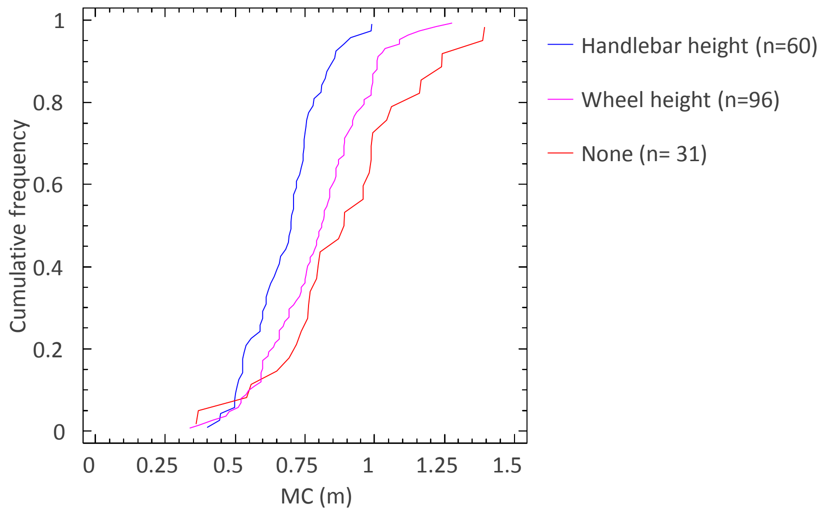


Figure 8. Meeting clearance distributions vs. cycle track width and boundary conditions

4.3. Opposing bicycle speed

Opposing bicycle speed (VO) was calculated as the difference between relative speed (measured by the laser sensor) and instrumented bicycle speed (measured by the GPS tracker). Opposing vehicle speed came from a normal distribution at the 95 percent confidence level (K-S test p-value of 0.152). Table 7 shows the estimation of a linear regression model for VO. In this case, the only statistically significant factor was the binary variable indicating that the cycle track is narrower than 1.7 m. This resulted in a reduction in the average speed of 3.6 km/h. However, the lower R-square coefficient is associated with a very high dispersion due to other factors, such as bicycle and cyclist characteristics. Therefore, this model did not provide valuable conclusions.

Parameter	VO		
	Estimate	t-statistic	
CONSTANT	17.7219	73.4648	***
IS-NARROW	-3.63296	-7.70726	***
IS_MEDIUM	not significant		
IS_WHEEL	not significant		
IS_HANDLEBAR	not significant		
R-squared	15%		
Standard error of est.	3.7989		
significance codes: ***: 0.001, **: 0.01, *: 0.05			

Table 7. Linear regression model for VO

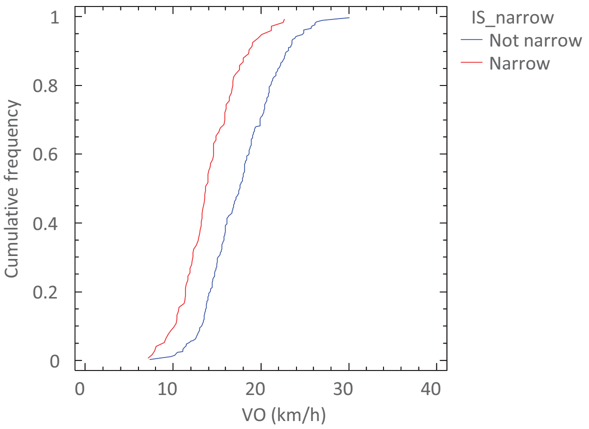


Figure 9. Opposing bicycle speed vs. cycle track width

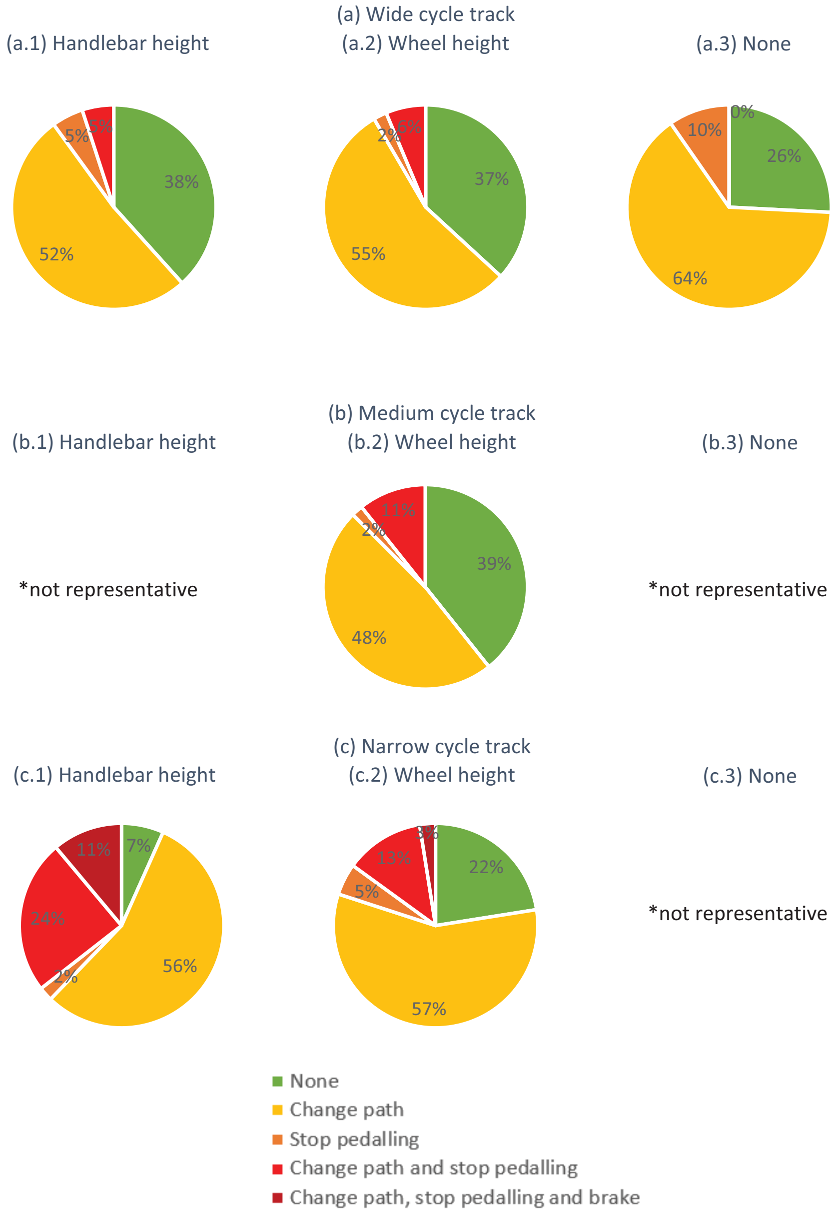
Figure 9 shows the empirical distribution of opposing vehicle speeds on narrow, and medium and wide cycle tracks.

4.4. Opposing rider's reaction

Opposing rider's reaction was characterized by the observation of three different behaviors: change of trajectory, stop pedaling and braking. Figure 10 shows the frequency of each type of maneuver (or their combination), for the different cycle track widths and boundary conditions type.

As can be seen in Figure 10, the number and intensity of evasive actions is higher for narrow cycle tracks. On these tracks, only a small part of riders did not perform any action. On the other hand, up to 11% of riders braked on tracks with lateral obstacles to the handlebar height.

On medium and wide tracks, a significant number of riders (between 26% and 39%) did not perform any action. Besides, more than half of the cyclists changed their path without neither stopping pedaling nor braking.



*sample size lower than 10 observations

Figure 10. Observed frequency of opposing rider's evasive maneuvers

The effect of geometry on the number of actions was verified using an ordered probit model, as explained in section 4.1. In this case, the outcome variable was the number of evasive actions performed by a driver.

As can be observed in Table 8 and Figure 11, the only geometrical variable that affected the number of actions was the dummy variable IS_NARROW. Narrower tracks accumulated a higher number of evasive actions.

		Coefficient	t-value	
Explanatory variable	IS_NARROW	0.841	5.753	***
Thresholds	0|1	-0.316	-4.019	***
	1|2	1.511	13.764	***
	2|3	2.507	12.864	***
significance codes: ***: 0.001, **: 0.01, *: 0.05				

Table 8. Estimation of number of actions model

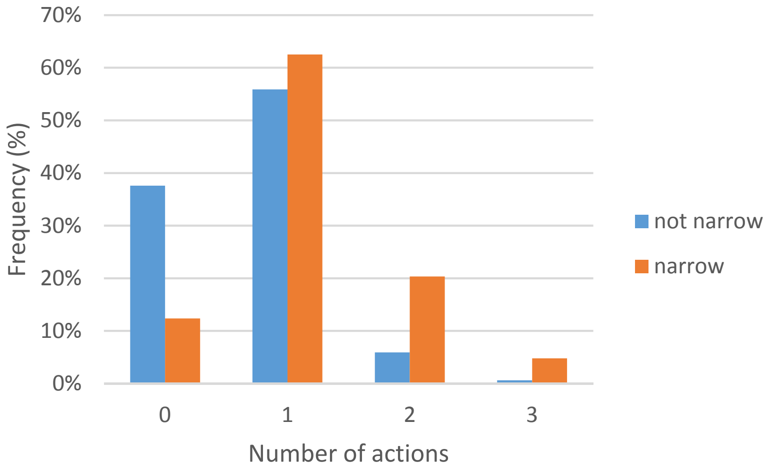


Figure 11. Estimated frequency of number of evasive actions

5. Discussion

This section compares the results of the present study with existing studies and standards. The development of a new methodology allowed analyzing of new variables that have not been considered in the past by other instrumented bicycle-based studies (Chapman and Noyce, 2012; Dozza and Fernandez, 2014; Parkin and Meyers, 2010; Walker, 2007). In comparison to previous work, this study focused in the interaction with other users, analyzing their behavior in deep. The new instrumented bicycles was able to measure accurately opposing bicycle speeds (and not only the passing or meeting spacing), as well as the reaction of other cyclists (i.e. if they braked or not).

According to Allen et al. (Allen et al., 1998), meeting maneuvers are the most common on two-way separated cycle tracks. In this study, 336 meeting maneuvers were observed on tangent sections without intersections. Only a few following and passing maneuvers were observed, which agrees with Allen et al. results. This shows the fact that meeting maneuvers are not optional for cyclists travelling on two-way cycle tracks.

Khan and Raksuntorn (Khan and Raksuntorn, 2001) found that meeting spacing on a 3-m wide two-way cycle track was on average 1.95 m, after analyzing 100 maneuvers. In the present study, this spacing was 1.15 m on several cycle track widths ranging 1.3 to 2.15. This result shows that on narrow cycle tracks, like the ones considered in the present study, the meeting clearance is reduced significantly, which may be related to conflictive maneuvers. Khan and Raksuntorn (Khan and Raksuntorn, 2001) did not analyze meeting maneuvers as potential conflicts. Besides, this study discovered a strong relationship between meeting clearance and cycle track width, which was already predicted (but not studied) by Khan and Raksuntorn (Khan and Raksuntorn, 2001).

Compared to the AASHTO guideline (American Association of State Highway and Transportation Official, 2012), the analyzed cycle track sections are much narrower. However, that guideline establishes a 3-m wide cycle track for a mixed pedestrian and bicycles flow and not for an exclusive bicycle path. Compared to London and Dutch recommendations (CROW, 2007; Transport for London, 2014), the observed cycle tracks are much narrower.

Moreover, those guides do not take into account the boundary conditions. The results of this research showed that boundary conditions affected to both free flow circulation and meeting maneuvers, though. Therefore, different criteria should be defined for each different boundary type.

6. Conclusions

This study investigated the characteristics of meeting maneuvers on off-road two-way cycle tracks. This was possible thanks to the observation of meeting maneuvers from an instrumented bicycle following a quasi-naturalistic methodology. In the observations, the instrumented bicycle behaved as a normal user of the cycle track, and collected geometric, dynamic and behavioral data regarding oncoming bicycles and meeting maneuvers.

The instrumented bicycle was ridden on six different separated cycle tracks in Valencia (Spain). Track width ranged between 1.30 and 2.15 m. The selected cycle tracks had different boundary conditions, such as fences, curbs, on-street parking, street lighting, bushes, hedges or trees. On these cycle tracks, 336 meeting maneuvers were characterized.

The main results are:

1. Observed cyclists rode in free flow conditions on their theoretical position (centered on the right half of the cycle track) on tracks wider than 1.6 m and without lateral obstacles. On the other hand, they rode closer to the centerline on cycle tracks narrower than 1.6 m either before or after the meeting maneuver.
2. On cycle tracks narrower than 1.6 m, results suggested that cyclists move to the right (outer edge) after meeting maneuvers, which might be associated with a perception of risk after meeting an opposing bicycle.
3. The existence of lateral obstacles made cyclists to ride closer to the centerline, being the effect of obstacles to the handlebar height higher than the effect of the obstacles to the wheel height.
4. It is necessary to define properly what lateral separation is exactly. In this research, meeting clearance between the inner ends of the handlebars of the meeting bicycles was, on average, almost that half of meeting spacing, measured between bicycles axes. Meeting clearance was selected for the analysis because it better reflects the objective risk of a meeting maneuver and considers handlebar width dispersion. In fact, meeting clearance represented a traffic conflict indicator for meeting maneuvers on two-lane cycle tracks.

5. Mean meeting clearance on wide cycle tracks (over 1.8 m) and without lateral obstacles was equal to 0.89 m. However, it varied in function of cycle track width and boundary conditions type:
    a. On cycle tracks between 1.6 m and 1.8 m wide, it was reduced 0.20 m, and on cycle tracks narrower than 1.6 m, it was reduced 0.25 m.
    b. On cycle tracks with obstacles to the wheel height, it was reduced 0.10 m, and on cycle tracks with obstacles to the handlebar, height it was reduced 0.20 m.
6. Opposing rider's reaction was characterized by the performance of these maneuvers: change of trajectory, stop pedaling and braking:
    a. The frequency and number of maneuvers was higher on tracks narrower than 1.6 m.
    b. The action "braking" was only significant on cycle tracks narrower than 1.6 m.
    c. On cycle tracks wider than 1.6 m, most of riders either changed their trajectory or did not perform any maneuver.

The validity of these results is limited to off-road separated cycle tracks narrower than 2.15 m with not congested traffic characteristics, being this the most common conditions in Spanish cities. The extrapolation of the results outside the observed geographical area should be carried out with caution. Although bicycle dimensions are quite similar in all locations, rider's behavior may be different. The existence of too narrow cycle tracks in a location could be related with a riskier behavior of the riders, which are used to that poor infrastructure.

The conclusions indicated a strong relationship between cycle track geometry and characteristics of meeting maneuvers, which are the most frequent on this cycling facility. The results of this research have facilitated recommending a minimum two-way cycle track width of 1.6 m. On these narrower tracks, cyclists did not ride on their own half side in absence of opposing traffic, but moved onto the centerline, suggesting that width was insufficient. Cycle tracks narrower than 1.6 m presented very low meeting clearance between two opposing bicycles (a mean meeting clearance of 0.64 m, being equal to 0.44 m if the cycle track has lateral obstacles to the handlebar height). Besides, the speed of oncoming bicycles was lower (a mean of 14.1 km/h) and a significant number of reaction maneuvers was observed. Specifically, almost that 35 percent of riders stopped pedaling and almost that 11 percent of them even braked on narrower tracks with obstacles to the handlebar height. These two types of maneuvers represented an uncomfortable behavior. The characteristics of boundary conditions affected the meeting clearance and the opposing rider's reaction as well. For cycle tracks delimitated by lateral obstacles, additional width should be provided, especially if the obstacle height exceeds the handlebar height.

Although a 1.6 m cycle track width is still significantly narrower than the current guidelines; this study provided a scientific evidence for a minimum width based on the reaction of opposing drivers to forced meeting maneuvers. Further work is required in the extension of the observations to include other widths and boundary conditions, in order to analyze the interaction of both effects with more detail. Besides, this methodology may be applied to study meeting maneuvers involving e-bikes, as they might require higher clearances (due to their higher speed) and, as a consequence, different design criteria.

7. References

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