FREQUENCY OF CONFLICTS ON SEPARATED CYCLE TRACKS AS A FUNCTION OF CROSS SECTION CHARACTERISTICS

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ABSTRACT

Vulnerable Road Users represent a serious safety concern, being pedestrians or cyclists involved in up to 50% urban road crashes. Separated cycle tracks reduce the level of interaction between bicycles and pedestrian or motor vehicles. However, there is still a significant number of conflicts among them. This study analyzed the frequency of conflicts between cyclists, pedestrians and motor vehicles on bidirectional cycle tracks, as a function of boundary conditions (marking, fences, trees, parked vehicles, etc.) and width.

Data was collected in a quasi-naturalistic study. An instrumented bicycle equipped with four cameras, four laser rangefinders, a microphone and a GPS tracker was ridden on six cycle tracks. Researchers rode the bicycle at selected tracks with a variety of width and boundaries. A total of 985 conflicts (47% involving pedestrians) were observed after 10 hours and 130 km travelled distance. Meeting maneuvers were described by relative speed, lateral clearance and evasive actions of the oncoming rider (stop pedaling or braking). Conflicts involving motor vehicles or pedestrians were analyzed and classified by severity (either TTC or subjective perception) and typology (crossing users, meeting maneuvers with other bicycles or standing objects).

This study compared conflict rates and conflict type distributions among locations, in order to detect the effect of different track boundary characteristics and width. The results provided recommendations to better design cycle tracks to reduce conflicts.

INTRODUCTION

Urban areas account for 40% of road fatalities *(1)*. Traditionally, road safety improvements concentrated in motor vehicles. However, 50% of the victims of urban road crashes are pedestrians or cyclists *(2)*.

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 attention from researchers. Wardman et al. *(3)* 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 *(4)* . Another study in Canada reported that the injury risk of cycling on cycle tracks is less than cycling in streets *(5)*.

However, although separated cycle tracks avoid mixed traffic, there is still a significant interaction between bicycles and others users. Intersections, pedestrian crossings and motor vehicle crossings represent potential conflict hotspots. Besides, depending on cycle track boundary characteristics (characteristics of the edges and separation between tracks and their surroundings), other users (mainly pedestrians) may occupy cycle tracks generating additional conflicts.

Previous research

The level of safety on separated cycle tracks has been analyzed in terms of crash studies *(6)*. They concluded that one-way tracks were safer than two-way tracks. Most of studies were focused at intersections, though *(7, 8)*

The strong spatial and temporal dispersion of crashes makes it difficult to understand the causes and the factors related with the infrastructure that affect their occurrence. Consequently, some authors proposed to analyze crashes as a surrogate measure of conflicts. A conflict is usually defined as an “interaction between a bicycle and motor vehicle, pedestrian, or other bicycle such that at least one of the parties had to change speed or direction to avoid the other” (Hunter et al., 1999).

The study of objective parameters to analyze the severity of a conflict began long time ago, for motor vehicle traffic. Perkins and Harris *(9)* defined in 1967 the Time to Accident (TA) which is the time left to an accident at the moment in which a vehicle begins an evasive action (breaking or changing the direction). In 1972 Hayward *(10)* developed this parameter and defined the Time to Collision (TTC) as “the time required for two vehicles to collide if they continue at their present speed and on the same path” (if there is no possibility of an accident the TTC is infinite). The TA is usually taken as Time To Collision at Breaking Time (TTCbr), which indicates the time left for the maneuver in an encounter *(11)*. In the same research van der Horst stated that the lower the minimum TTC reached (TTCmin) the higher is the risk of an encounter. Other parameters, such as Post-Encroachment Time (PET), or Conflict Speed (CS), defined as the speed of a vehicle at the moment when the conflict occurs have also been used by researchers to study the severity of a conflict. Nevertheless, all the studies mentioned above studied motor vehicles conflicts.

With respect of conflicts involving VRUs (Vulnerable Rad Users), van der Horst et al. *(12)* installed video cameras at fixed locations to extract trajectories of cycle track users. In that study, conflicts were analyzed using the DOCTOR method (Dutch Objective Conflict Technique for Operation and Research). This method indicated that there was a relationship between some indicators (such as TTC and PET) and conflict severity perceived by individual observers. The study *(12)* was limited, however, to two locations and did not consider neither segment data nor the effect of specific infrastructure factors, such as cycle track geometry.

Apart from video surveillance, instrumented bicycles have been already used to observe the interaction between motor vehicles and bicycles, in order to characterize conflicts between them. Walker *(13)*, Chapman and Noyce *(14)* or Chuang et al. *(15)* 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. Dozza and Werneke *(16)* analyzed data from a naturalistic study involving 16 cyclists, 332 trips, 1459 km and 114 h. The authors identified 63 critical events, using a trigger installed on the bicycle, personal interviews and kinematic triggers (identification of extreme values of acceleration rates). Authors selected a comparable number of baseline (not conflictive) events, to carry out an odds ratio analysis, to identify whether specific factors were more common among the critical events or not. However, this study did not consider geometrical characteristics of cycle tracks, since data was not concentrated in particular facilities. The causes of each critical event were analyzed, resulting in a 29% of conflicts related to pedestrians, a 33% to motor vehicles and a 16% to other bicycles. Dozza and Werneke *(16)* found a quite small sample of critical events, as they only focused on severe conflicts and even on a certain number of accidents.

García et al. *(17)* analyzed non critical events, studying the effect of width and boundary conditions on the characteristics of meeting maneuvers using an instrumented bicycle. They concluded that bidirectional cycle tracks should have, at least, 1.8 m wide. This distance should be increased if lateral obstacles are placed in the boundaries. Though their study was limited to meeting maneuvers, with no consideration of other conflicts. Angel-Domenech et al. *(18)* used the same data collection method to analyze the relation between subjective and objective severity measures of conflicts with other users crossing and circulating on the cycle tracks.

Conflicts between bicycles and other users (pedestrians, motor vehicles and other bicycles) should be a critical issue to determine geometrical characteristics of two-way cycle tracks. Specifically, width and boundary characteristics might be related with frequency and severity of conflicts. This paper combines the study of meeting maneuvers and conflicts involving other users on bidirectional cycle tracks.

OBJECTIVES

The aim of these study is to observe and analyze conflict frequency and characteristics on bidirectional, exclusive cycle tracks in urban environments. In particular, the following objectives are included in the paper:

- Development and application of a quasi-naturalistic methodology to observe conflicts using objective and subjective variables.
- Classification and study of main conflict characteristics, including meeting maneuvers with opposing bicycles and conflicts caused by other users entering or standing in the cycle track.
- Compare conflict frequency with average daily bicycle volume, track width and boundary conditions.
- Extrapolate the number of observed conflicts to the entire bicycle flow in an average day.
- Identify contributing geometric design features that increase the frequency of conflicts on cycle tracks.

METHODOLOGY

The proposed approach was based on the observation of conflicts from an instrumented bicycle, that was riden along cycle tracks collecting data of its interaction with other users. Whithin these data, certain events were classified and characterized as conflicts, according to the definitions provided later in this section.

Observation method

A racing bicycle was equipped with several devices to carry out the data collection *(17)*. The bicycle had four video cameras installed to record video information about the conflicts in which the instrumented bicycle was involved. A laser pointer was used to help the bicycle riders to set and maintain their lateral position on the cycle track, as well as to track his lateral position during data reduction. A 10 Hz GPS tracker continuously registered position and speed of the instrumented bicycle. A microphone was installed to register the rider's subjective risk perception of every meeting maneuver and conflict, based on a Likert scale from 1 to 5 (where 5 is the maximum risk perception and 1 the minimum). Video, audio and GPS position were stored in a VBOX data logger.

Besides, 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. A laptop connected to all laser devices stored the measurements. Additionally, two Laser Technology Inc. T100 laser systems were installed perpendicular to the bicycle axis to measure the relative speed of opposing bicycles. All storing devices, batteries and accessories were installed in a box held to the bicycle frame. Cameras and laser rangefinders were placed in front and rear racks, adapted for this specific use.

Two riders, both male and last-year posgraduate students rode the bicycle during the data collection. To avoid the effect of the instrumented bicycle riders' behavior, cyclists follow current regulations and adopted a free flow speed according to the other bicycle users of the city. A sample of cycle tracks was selected previously in order to measure the average free-flow speed of bicycles, using external static video cameras. A target speed was set at 16 km/h, riding at a speed equal to the average speed of other users, being the study quasi-naturalistic. Besides, they rode centered of their lane as did not use the bell. The lateral position was checked using a laser pointer, which was installed on the bicycle, pointing to the cycle track centerline when cyclist was at the desired position.

Additionally, bicycle counts at the selected cycle tracks were provided, for the whole year, by the City Hall of Valencia (Spain). As a result, the Average Annual Daily Traffic of Bicycles (*AADTb*) was calculated for each location. Hourly bicycle volumes for every working day were available as well.

Study locations

Data collection was conducted in six weekdays in April 2013 with sunny weather conditions and dry pavement. The data collection covered morning peak and non-peak periods in order to get various bicycle traffic conditions. The study was conducted within the city of Valencia, Spain.

Six two-way cycle tracks were selected. They covered a wide range of cycle track width and diverse boundary characteristics, although all of them were located in consolidated urban areas. The analysed tracks were bidirectional and separated from motorized traffic in every case.

The selected locations and their characteristics are shown in Table 1.

The boundary condition types have been aggregated into two main categories, from the point of view of the permeability of other users, as shown in the Fig 1a:

- Impermeable: along the entire cycle track length, there is a physical separation with the rest of users that makes it difficult to them to enter the track (bushes or fences).
- Permeable: there is no physical separation along the entire cycle track that blocks the entrance of other users (trees, street lamps, curbs or marking).

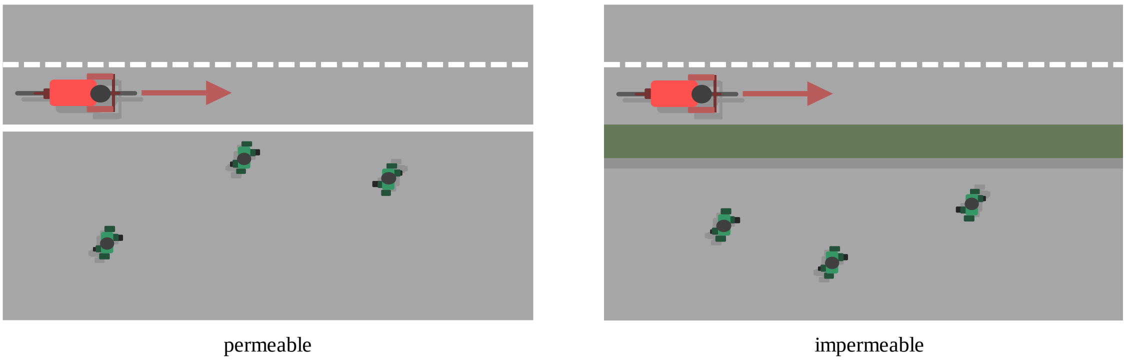
If the two types are present along the entire length of the track, the track is categorized as "mixed".

Table 1. Characteristics of the analised cycle tracks

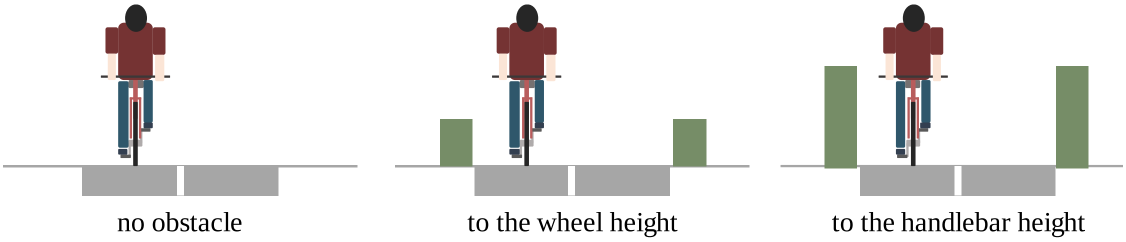
Location	Length (Km)	Location in cross-section	Width (m)	Boundary conditions
1 - Peris i Valero	1.410	Roadway	2.0 - 1.8	Trees and curb, parallel parking lane
2 - Duc de Calabria	0.720	Sidewalk	1.5	Trees, parallel parking lane
3 - Blasco Ibáñez	2.940	Sidewalk/roadway	2.0	Bushes, trees, none
4 - Port	2.520	Sidewalk	1.8	Trees, parallel parking lane
5 - Tarongers (North)	1.530	Sidewalk	2.0	Bushes, trees
6 - Tarongers (South)	1.530	Sidewalk	2.1	None

Alternatively, as shown in Fig 1b the boundary conditions were grouped into three main categories as a function of the lateral obstacle height:

- No boundaries: there is no physical separation at the border of the track (i.e. marking).
- Obstacle to the wheel height: there is an obstacle at the border shorter than 0.5 m (i.e. curbs).
- Obstacle to the handlebar height: there is an obstacle at the border taller than 0.5 m (i.e. bushes).



(a) permeability of boundaries



(b) lateral obstacle height

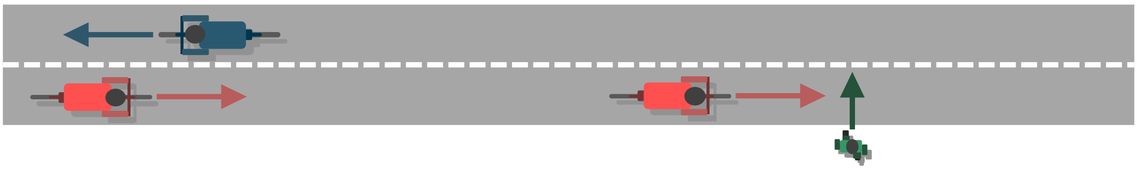
Figure 1. Boundary conditions categories

Conflict typologies and characterization

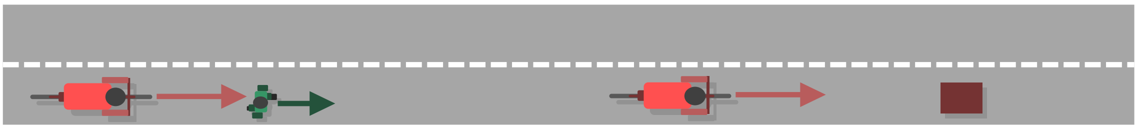
Based on the observations and according to previous research *(19)*, conflicts were defined as "interactions between a bicycle and other users such that at least one of the parties had to change speed or direction to avoid the other". This definition was extended to include meeting maneuvers with opposing bicycles, although only at certain cases involved an evasive maneuver.

Accordingly, the following four categories were proposed (Figure 2):

- Static object: parked cars, garbage bags, stopped pedestrians or any other static object on the cycle track.
- Crossing: a bicycle, a pedestrian or a motor vehicle crosses the bicycle path perpendicularly.
- Circulation: a pedestrian walking (or a motor vehicles driving) along a part of the cycle track to either, saves an obstacle on the sidewalk or takes a shorcut.
- Meeting: crossing between two opposing bicycles circulating in opposing direction.



(a) meeting (b) crossing



(c) circulation (d) static object

Figure 2. Conflict types

The following list contains all the variables that characterized every observed conflict:

- Location (time and geographic coordinates).
- Type of conflict (static object, crossing, circulation, and meeting maneuver).
- Second unit involved in the conflict (opposing bicycle, car, pedestrian, vehicle door, moped, van, etc.)
- Subjective risk perception (1 to 5 Likert scale) of the instrumented bicycle cyclist, in case the conflict is not a meeting maneuver. It was not recorded for meeting maneuvers, due to their high frequency and to avoid overloading the cyclist.
- Evasive action of the opposing bicycle, if a meeting maneuver (classified as change of trajectory, stop pedaling and/or braking).
- Boundary condition, at the side from where the second unit entered the cycle track (if a crossing), at the side of the opposing bicycle (if meeting maneuver) or at the instrumented bicycle side (otherwise).

In this paper, the data obtained by the laser rangefinders was not used. Further details on the results that these measurements provided can be found in the analysis of lateral clearance in Garcia et al. (2015) and in the analysis of conflict indicators in Angel-Domenech et al. (2014).

ANALYSIS

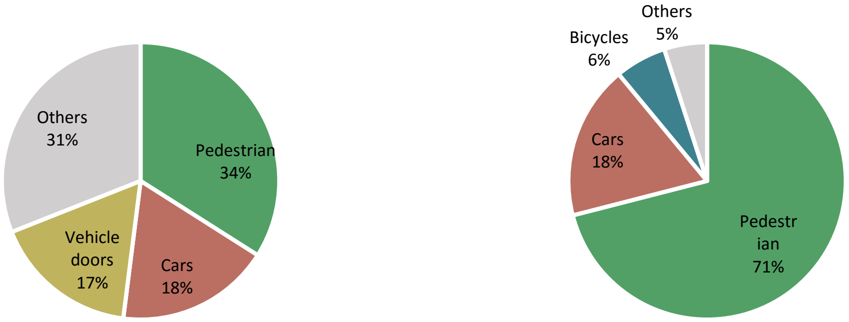
The analysis was divided into the following subsections: the descriptive analysis of conflicts and the analysis of conflict frequency.

Description of the conflicts

This subsection describes the main properties of the observed conflicts.

<u>Second user type</u>

The Figure 3 describes the type of the second user involved in the conflicts, by conflict type. As can be seen, the most significant second user type is the pedestrian. This is because the cycle track located on the sidewalk is the most common type of cycle track in the observed area. The interaction with cars is quite significant, even though conflicts at intersections were discarded from the observations. This is explained by the presence of parked cars and entrances to private and public parking that cross the cycle track. Obviously, the participation of cycles is the unique second unit type in meeting maneuvers, but a certain proportion of them is appreciable in the case of crossing events.



(a) Static object (b) Crossing

(c) Circulation (d) Meeting

Figure 3. Involvement of other users in conflicts

Subjective risk perception

Figure 4 shows the distribution of non-meeting conflicts by severity, measured in terms of risk perception. As can be observed, the crossing and circulation conflicts presented higher frequencies of severe conflicts, categorized as level 3 or higher. On the other hand, the conflict type ‘static object’ did not present any severe conflict of risk level 4 and 5.

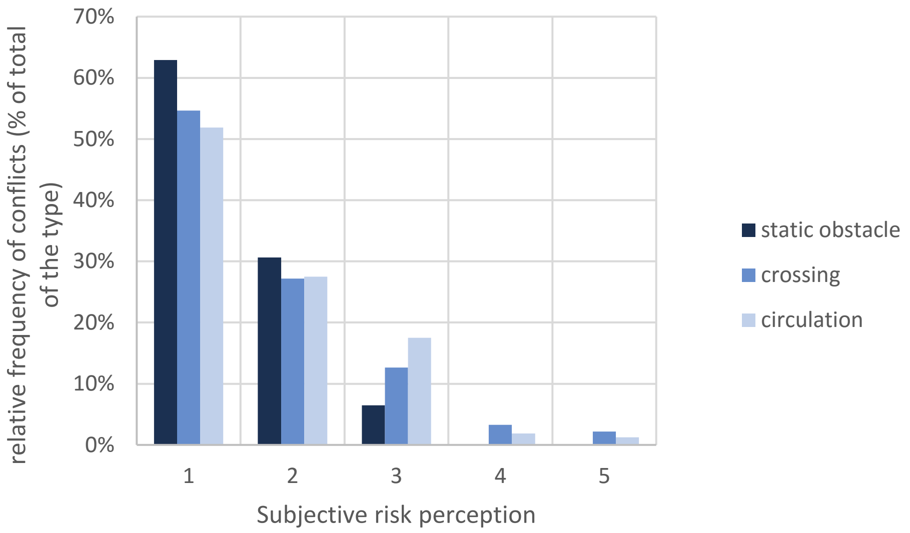


Figure 4. Distribution of non-meeting conflicts by type and severity

In absence of a subjective risk perception of meeting maneuvers (as explained in the methodology section, this was a consequence of the higher frequency and not to overload the cyclists), the number and type of evasive actions was used a surrogate measure of risk *(17)*. By ordering the type of evasive action (or combination of actions), from higher to lower frequencies, it is assumed to establish a rank of severity of these actions. Accordingly, the less severe action was to change the trajectory, while the most severe actions involved always braking (Figure 5).

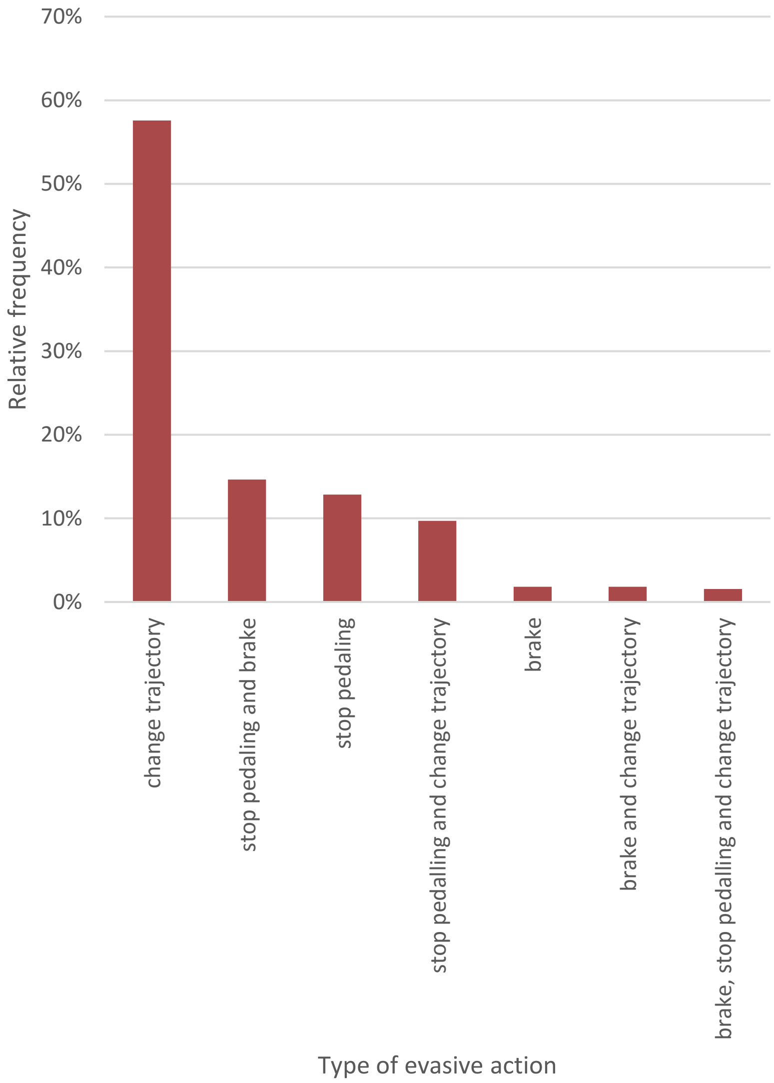


Figure 5. Distribution of meeting maneuvers by type of evasive action of the opposing bicycle

Conflict frequency

Once the most significant type of conflicts was categorized, the next step in the analysis focused on the quantification of conflict frequency. The Table 2 shows the recorded conflict rates at the observed locations, that the instrumented bicycles recorded during the data collection. From this point, a subset of conflicts is defined as non-compliant conflicts, involving a violation of the cycle track regulations, mainly derived by the invasion of the track by other users at a non-permitted location.

Table 2. Observed conflict rates for non-meeting maneuvers

Cycle track	Conflict rates (conflict/bicycle/h)				
	All conflicts	All non-compliant conflicts	Non-compliant crossing	Non-compliant circulation	Non-compliant static object
1 - Peris i Valero	65.5	42.6	17.3	12.7	12.7
2 – Duc Calabria	93.0	72.0	18.8	18.8	34.4

3 - Blasco Ibañez	90.9	53.9	13.0	19.4	21.4
4 - Puerto	72.3	52.7	19.7	14.6	18.3
5 - Tarongers N	28.0	11.8	0.0	10.7	1.1
6 - Tarongers S	62.3	48.8	5.2	29.9	13.6

As can be seen, there is a huge dispersion in the conflict rates across the selected locations. Given the fact that the data collection was carried out in working days, always at the same time of the day, there is potential affection of location and traffic factors, as analysed in the following subsections.

Annual Average Daily Traffic of bicycles

Firstly, the frequency of conflicts was compared with the *AADTb* of the cycle track. The number of meeting maneuver was not plotted, as it is expected proportional to the bicycle volume at the observation area. The Figure 6 shows the comparison of conflict frequency and *AADTb*. A significant relationship between *AADTb* and conflict rates was found, identifying more conflicts at the locations were the presence of bicycles is lower. However, the average daily bicycle volume is not able to explain all the variability of the frequency conflicts, identifying some locations were number of events is lower than the general trend.

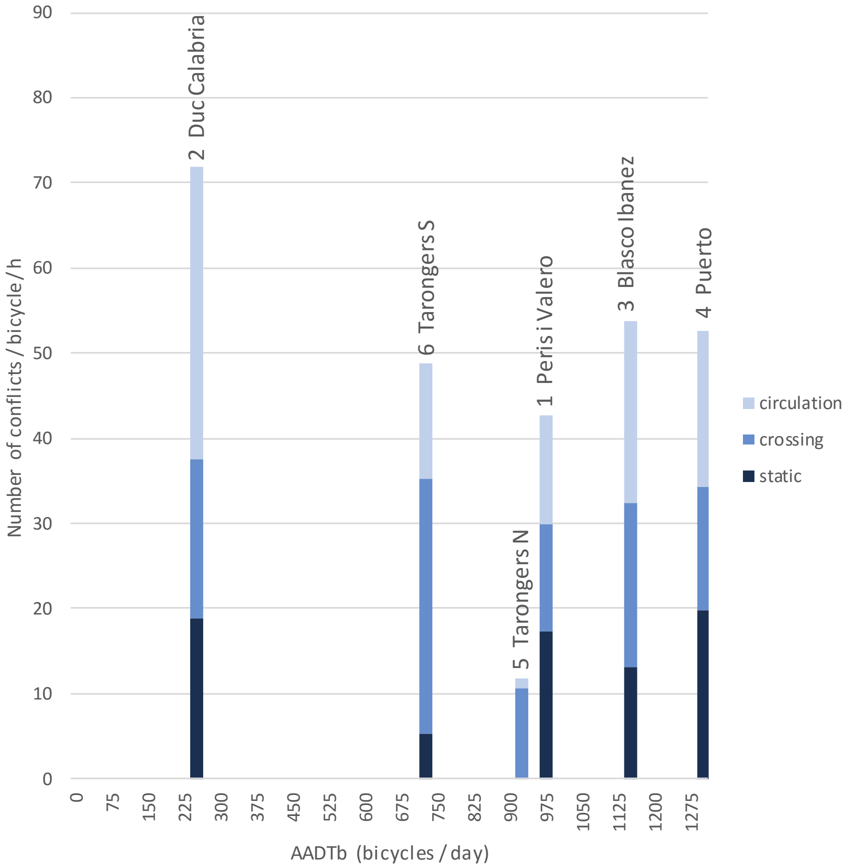


Figure 6. Frequency of non-meeting conflicts vs. location *AADTb* (only rule non-compliant conflicts)

<u>Boundary conditions</u>

The impact of the boundary conditions in the frequency and type of conflict was analyzed. The Figure 7 plots the number of conflicts as a function of the permeability of boundary conditions.

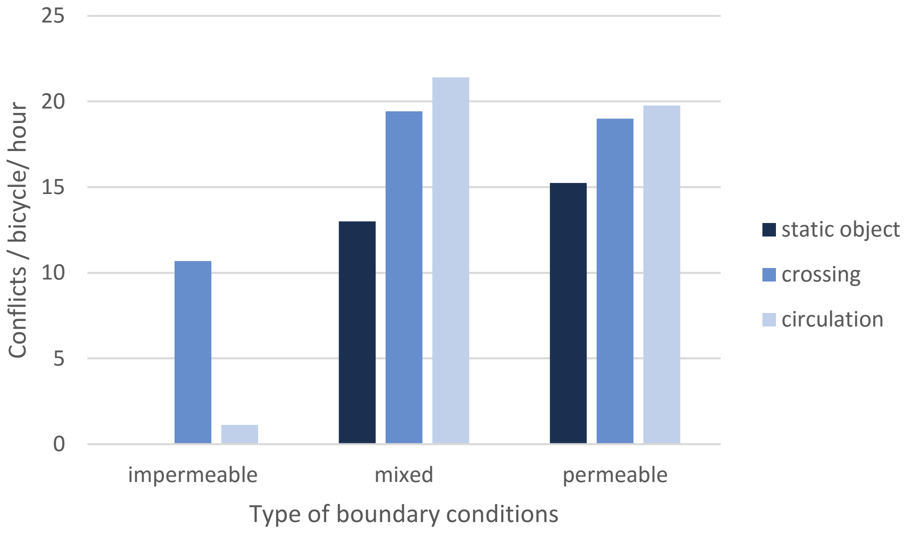


Figure 7. Frequency of non-meeting conflicts vs. boundary conditions type

Figure 7 shows that the number of non-meeting conflicts increases strongly when the boundary conditions are defined as ‘permeable’, which obviously facilitates the occupation of the track by other users.

With respect of meeting maneuvers, the previous categories were not used, as they do not reflect the interaction with opposing traffic but with crossing users. On the contrary, the lateral obstacle height was used.

The Figure 8 plots the severity of the observed meeting maneuvers, for each boundary condition type. The most severe actions are found for those tracks with obstacles to the handlebar height, while the absence of obstacles may facilitate the change in the path of the opposing bicycle, allowing safe meeting maneuvers even if the cycle track width is low.

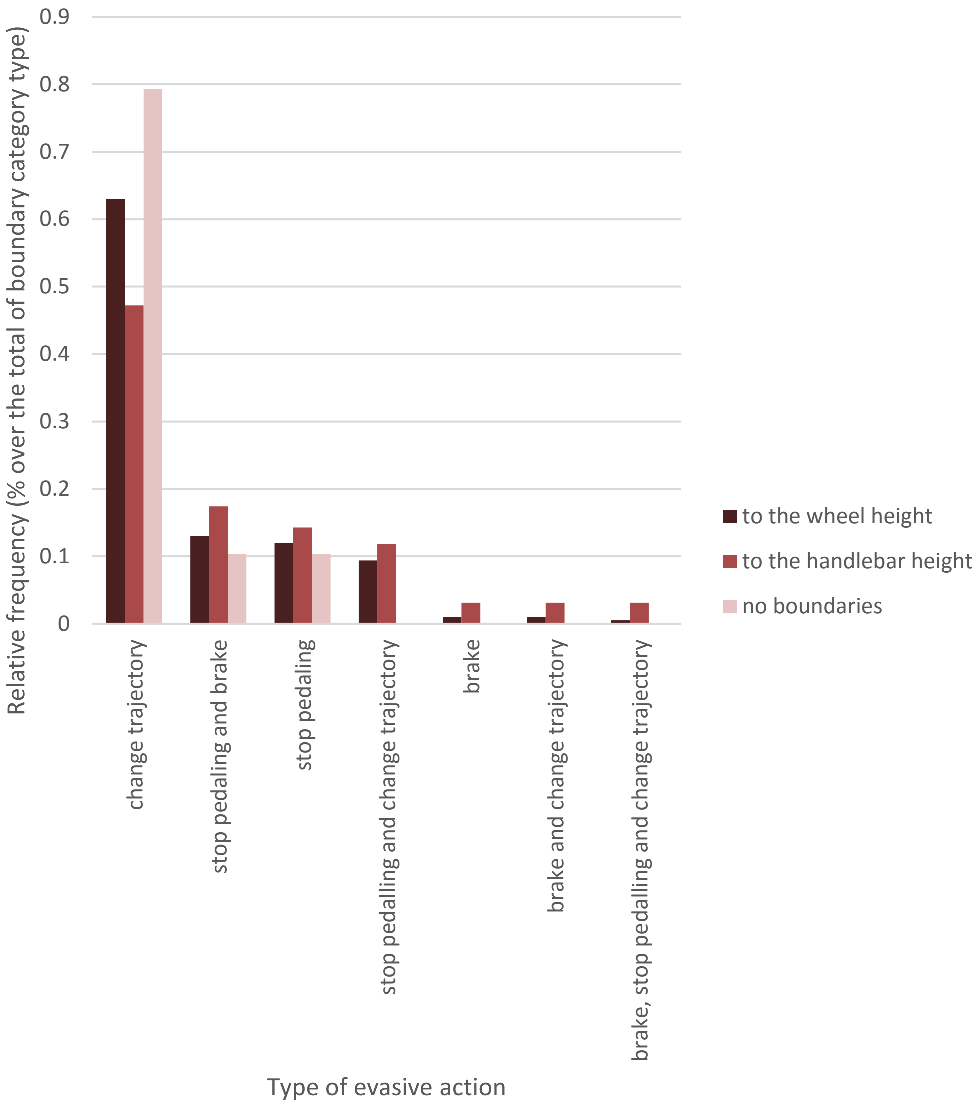


Figure 8. Frequency of evasive actions by type of boundary conditions

Extrapolation of the number of conflicts

Based on the previously obtained conflict rates (per hour) for each cycle track, and on the hourly traffic volumes across an average working day, this subsection provides an estimation of the total number of conflicts per working day on the selected locations.

This extrapolation was based on the following assumptions: the rate between bicycle volume and conflicts is constant for every location; the recorded behavior corresponds with an average behavior of the circulating bicycles; each bicycle travels half of the total length of the cycle track at the average speed; lastly, the presence of other users is proportional to the bicycle volume. Besides, the conflicts where two bicycles were involved were counted as only one event.

According to this, the Table 3 shows the number of conflicts, segmented by type and severity. The total number of conflicts at working days along the year would be around 7 million, 140 thousand of them categorized as severe. Therefore, the density of conflicts at working days along the year would be around 650,000 conflict/km, 13,000 of them categorized as severe (2%).

Table 3. Extrapolated number of conflicts per working day at locations by type and severity

Cycle track	Daily bicycle volume (working days)	Number of conflicts per working day						
		All conflicts	Non-compliant crossing		Non-compliant circulation		Non-compliant static object	
			All	Severe	All	Severe	All	Severe
1 - Peris i Valero	1093	3155	595	33	611	19	833	0
2 - Duc Calabria	280	585	115	6	217	7	118	0
3 - Blasco Ibañez	1296	10827	2256	124	2551	80	1549	0
4 – Puerto	1447	8238	1624	89	2087	65	2248	0
5 - Tarongers N	1113	1487	554	30	59	2	0	0
6 - Tarongers S	849	2532	1186	65	553	17	212	0
All locations		26824	6330	347	6078	190	4960	0

DISCUSSION

The study provided an insight in diverse conflict types on exclusive, bidirectional cycle tracks. Though Thomas and De Robertis *(6)* identified two-way cycle tracks more dangerous, compared to one-way tracks, almost every cycle track in the observation area is bidirectional. Consequently, a variety of conflicts need to be taken into account, from meeting maneuver with opposing bicycles to other users crossing or circulating on the cycle track.

The consideration of meeting maneuvers as conflicts, in agreement with van der Horst et al. *(12)* is realistic, as the existence of evasive actions was very common in the observations. Assuming that conflict severity and frequency are inversely proportional, the riskier evasive action when meeting opposing bicycles was braking, followed by stop pedaling. This result may influence the operation of the cycle track under high demand situations, as it requires lower speed for the meeting cyclists *(20)*. A slight change of the cyclists' normal straight trajectory was quite common in the observations and therefore associated with less risky meeting maneuvers.

The impact of the properties of the boundary conditions on meeting maneuvers was quite strong. At locations where the cycle track is separated by lateral obstacles to the handlebar height (such as fences or bushes), and given that all the cycle tracks are narrower than 2.15 m, the relative frequency of cyclists braking or stop pedaling increased, showing riskier situations. This is described as the result of the absence of space to adapt the trajectory to keep sufficient clearance to the opposing rider. From the point of view of the two-way bicycle traffic flow the best type of boundary conditions is the one that does not involve a physical separation.

On the other hand, after analyzing the conflict with users that do not belong to the cycle track bicycle flow, it was found that pedestrians pay a significant role in the observed cycle track conflict typologies. The conflicts defined as crossing and circulation affected pedestrian in 71%

and 91% of the cases, respectively. This can be understood as the cycle tracks are located most of times on the sidewalk or close to it.

Regarding the type of conflict involving other users, the most severe conflicts, as registered by the instrumented bicycle riders, were the crossing and the circulation. The unexpected characteristics of these type, in contrast to static objects on the track, might explain the higher severity.

When comparing the average daily bicycle volume of the observed locations, the higher conflict frequencies (of conflicts caused by other users) were found at the location with less bicycles. A higher amount of riders in a general basis might discourage other users to enter in the cycle track. However, the bicycle demand level is not the only factor that can decrease the frequency of conflicts. The properties of the boundary conditions, in terms of permeability (capacity of other users to cross them), impact clearly on every conflict type frequency. Those locations where the cycle track consists on discontinuous physical barriers (such as trees) or without a psychical separation concentrated the highest conflict frequencies.

The extrapolation of the observed conflict rates to the overall number of conflicts provided a surprisingly high number of conflicts at the selected locations, for an average working day. It reveals a high level of interaction between bicycles and the rest of users. Even after filtering only the severe conflicts (coded as risk level 4 or 5), it was found that the number is quite high, which may justify further analysis and the necessity of improving the infrastructure, users' behavior or both.

CONCLUSION

This paper analyzed diverse types of conflicts on separated cycle tracks in the area of Valencia (Spain) using quasi naturalistic observations.

Apart from a deeper understanding of the main types and properties of the conflicts, the study identified safe and risky geometric design features. The design of cycle tracks focused mainly on the width that allows a safe meeting of two bicycles. However, it should take into account boundary conditions as well: ideal boundaries to reduce the invasion of other users are fences or bushes. On the contrary, if they are placed close to the edge of the cycle track they can increase the severity of meeting maneuvers, reducing the available space to adapt the trajectory when meeting other bicycles. Both continuous physical barriers and buffer areas to the ground level at the track borders seem to be positive to increase safety of separated bidirectional cycle tracks. The environment of the cycle track is an additional decision factor, to establish the adequate boundary conditions, as the separation from other users would only be required when their presence is significant (i.e. pedestrians on sidewalks or close to parking lanes). If these design requirements are not fulfilled, the conversion from separated tracks to mixed use infrastructure might be considered.

Further work is needed to adapt the present study results to the increasing number of electric bicycles in the existing infrastructure. Electric bicycles ride at higher speeds, and therefore, additional track widths may be required to facilitate meeting with other bicycles with safety. At the same time, because of the higher speed and weight, the separation between pedestrian and cycles has to be reinforced by means of non-permeable boundary conditions.

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