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DOI
10.18757/ejtir.2018.18.4.3254

Publication date
2018

Document Version
Final published version

Published in
European Journal of Transport and Infrastructure Research

Citation (APA)
Janssen, B., Schepers, P., Farah, H., & Hagenzieker, M. (2018). Behaviour of cyclists and pedestrians near right angled, sloped and levelled kerb types: Do risks associated to height differences of kerbs weigh up against other factors? *European Journal of Transport and Infrastructure Research*, *18*(4), 360-371. https://doi.org/10.18757/ejtir.2018.18.4.3254

EJTIR

Issue 18(4), 2018
pp. 360-371
ISSN: 1567-7141
http://tlo.tbm.tudelft.nl/ejtir

Behaviour of cyclists and pedestrians near right angled, sloped and levelled kerb types: Do risks associated to height differences of kerbs weigh up against other factors?

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To create a safer environment for bicyclists and pedestrians, the usefulness of different types of kerbs as a separation between these two modes has been questioned by both researchers and practitioners. Right angled kerbs pose risks to cyclists due to their height but are assumed to separate them well from pedestrians. Sloped and levelled kerb types are more forgiving but allow road traffic users to move onto each other's infrastructure, creating a potential risk of collision. We examined the effects of different types of kerbs on cyclists' and pedestrians' behaviour. This is operationalized as a road user moving onto another traffic user's infrastructure (i.e. crossing the kerb). A total of 14,502 bicyclists and 3,578 pedestrians at 12 different locations in Amsterdam were observed. We also examined the motives for crossing the kerb, and some smaller studies were carried out on corners and intersections and in some other Dutch cities for making comparisons. The results show that cyclists moving on the sidewalk is a relatively rare event for all kerb types and no conflicts between cyclists and pedestrians were observed. We therefore consider it unlikely that the risks of the height difference weigh up against the advantages in terms of separating cyclists and pedestrians. Thus, in the ambition of separating bicyclists from pedestrians as well as designing a 'forgiving' kerb to accept that people make mistakes, both the sloped and levelled kerb types come out as best practice.

Keywords: *Behaviour, Curbs, Cyclists, Forgivingness, Kerbs, Pedestrians, Separation*

1. Introduction

Cycling and walking are environmentally friendly and healthy modes of transportation (Kelly, et al., 2014). The Netherlands is widely known for its high modal share of bicyclists, reaching 26% in 2016 (CBS, 2017), and even 41% in the Dutch capital Amsterdam (Fietsberaad, 2010). The importance of cycling for the Dutch is shown by their high percentage of bike ownership

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reaching 84%, by cycling tracks reaching over 35,000 kilometres of length (CBS, 2015) and half-a-year-longer life expectancy because of cycling (Fishman et al, 2015). Similarly, there is a significant percentage of trips in the Netherlands that are made by foot, reaching 19%, not even including before or after transport for the first and last mile (Spapé & Kalle, 2014).

However, cyclists and pedestrians are also vulnerable road users because of their unprotected state (Wegman & Aarts, 2006). Fatalities account for 26% of all traffic deaths worldwide (22% cyclist, 4% pedestrians; WHO, 2015). The Netherlands is a world leader in cycling safety (Schepers et al, 2017a), but the number of fatalities amongst cyclists is decreasing more slowly than other modes of transport (e.g. cars) and now constitutes 25% of all traffic deaths (CBS, 2016). The number of serious injuries in the Netherlands has been increasing in recent years constituting about 52% of all serious road injuries in 2017 (SWOV, 2017). Single-bicycle crashes (falls or collisions with obstacles) constitute the large majority of non-fatal bicycle crashes. Note that in contrast to cyclist falls, pedestrian falls are not included in the definition of a traffic accident because no vehicle was involved and therefore the resulting injuries and deaths are accordingly excluded from official statistics. Methorst et al. (2017) suggest that half of all Dutch pedestrian fatalities and the large majority of non-fatal pedestrian injuries in the Netherlands, Switzerland, and Austria, are due to falls.

By constructing bicycle tracks and sidewalks, vulnerable road users on road sections are separated from other traffic. This paper focuses on cycling and pedestrian safety related to kerbs (North American term: curbs) which are used to separate dedicated cyclists' tracks from pedestrians' sidewalks. Scientific research on this topic is lacking but field observations show that Dutch road authorities mostly use right angled or sloped kerbs with a height difference between the bicycle track and sidewalk surface that could reach up to 15cm, and sometimes only a visual separation without height difference, as illustrated in figure 1.

Figure 1. Kerb types applied in the Netherlands (From left to right: right angled kerbs, sloped kerbs, levelled kerbs)

Research on kerb safety is rare but the few studies that did address kerbs clearly show that its height introduces a risk to cyclists and pedestrians. A recent review study on pedestrian falls concluded that trip hazards such as kerbs play an important role in pedestrian falls (Schepers et al., 2017b). Kelsey et al. (2012) found that 6% of all outdoor falls among elderly occur while traversing kerbs when walking. Unfortunately, most studies on pedestrian falls do not specifically address kerb accidents, but include them in a broader category such as "sidewalk-, curb-, or street-accidents", comprising for instance 35% of outdoor falls in a study by Li et al., (2006). Similarly, only few studies on single-bicycle crashes report the share of kerb accidents. Schepers & Klein Wolt (2012) found that 21% of all single-bicycle crash victims rode off the cycling track and two-thirds of those hit a kerb. In Sweden, Umeå, Nyberg et al (1996) investigated single-bicycle crashes in which road factors were deemed to play a role. Half of all single accidents were related to road factors and kerbs played a role in 20% of those accidents (i.e. some 10% of all single-bicycle crashes). Also Babul et al. (2010) found that 9-16% of bicycle related accidents in the Canadian cities of Toronto and Vancouver were related to kerbs, fences and barriers. In a more qualitative study, Schepers (2008) found higher but also lower kerbs (only a few centimetres high) to be involved in single-bicycle crashes. Although difficult to quantify, research clearly shows that kerbs introduce a safety hazard to both cyclists and pedestrians. In-depth accident studies related to the kerb design were not found in the literature.

The risk of falls, introduced by right angled and sloped kerbs, raises the question of whether these kerbs have clear advantages in terms of reducing the risk of collisions between pedestrians and cyclists compared to a level separation between bicycle tracks and sidewalks. Although different kerb types with a height differences are commonplace in practice, no studies were found examining whether the advantages of this design solution outweigh the risks. Therefore, this study sets out to relate kerb design to the level of compliance of cyclists and pedestrians (to what extent do they use cycle tracks and sidewalks without traversing the kerb to enter each other's space) and potential conflicts in case of non-compliance. Mixed use paths without any formal separation are excluded from this study. The general research question we aimed to answer was whether the different types of kerbs are associated with differences in road user behaviour of cyclists and pedestrians.

After a literature review on the kerb design (section 2) and explaining the research methodology in section 3, this paper is split up in two studies. Study I is a large scale observational study at straight road sections in Amsterdam, as this city is known for its high volumes of cyclists and pedestrians. Study II is a small scale observational study in both Amsterdam and other Dutch cities with different volumes of cyclists and pedestrians which includes both straight road sections and intersections.

2. Literature review on kerb design

Research on the kerb design related to the behaviour of traffic users is limited and rarely goes into detail of different kerb types. Fietsberaad (2005) is the only research known in which the mixed use of bicyclist and pedestrian infrastructure was examined in relation to some kerb types. The results were based on 91 case studies in pedestrian areas (not bicycle tracks). The study shows that the separation between cyclists and pedestrians is - amongst other variables - dependent on the number of pedestrians and the width of the sidewalk. For high pedestrian intensities (>200 pedestrians per hour per width), a separation with height difference is preferred. It also shows that cyclists lower their speed, or even dismount their bikes and take other avoiding actions when pedestrian densities are high. This study did not investigate to what extent different kerb types lead to a different number of conflicts, how the results would differ for other areas (e.g. in residential areas, cycling tracks, intersections), and what the suggested solution would be for high numbers of bicyclists in particular areas.

Svensson et al. (2007) investigated to what extent pedestrians and bicyclists keep to their sides based on 107 locations, and how this is affected by different ground materials, separation measures, road widths, traffic flows, road markings and surroundings. The results of this study show that these design features are important, and that many variables affect the behaviour of pedestrians and cyclists in keeping their sides, but it does not go into detail regarding to what type of kerb should be applied.

Research by Nemire et al. (2016) shows that a height difference of only 6mm can present a hazard to healthy pedestrians. In terms of slope, the same research suggests to design a slope no greater than 1:2 (rise:run), based on American national standards (Council of American Building Officials, 1992). However, no research was found on what slope is specifically most useful for kerbs.

A separation of cyclists and pedestrians is suggested by the United States Access Board (2017). Clearly visible separation elements such as white markings are recommended. Visibility factors are more important for older or partially sighted people who have more problems seeing and hearing other modes of traffic. A reported issue for older road users is the limited awareness of passing cyclists, who are relatively quiet when moving around.

3. Research methodology

Section 3.1 describes how data is gathered and how the kerb is translated into a researchable object. All possible related variables are explored and defined in section 3.2. Section 3.3 explains how the gathered data is analysed and how the behaviour is coded into measurable terms.

3.1 Data collection method

Data was gathered using an observational study on kerbs by means of video camera recordings. For study I, observations were carried out on 12 locations in the city of Amsterdam. For collecting enough data, each location was filmed for two hours (four locations from 08:00 to 10:00, four from 12:00-14:00, and four from 16:00 to 18:00) for a straight road stretch of 30 meters. Locations were chosen such as to have a limited amount of variability in the infrastructural design (e.g. related to width, colours, obstructions). This study only considered locations within built-up areas, and bicycle-pedestrian infrastructure that is physically separated from car traffic.

The behaviour of cyclists could be different in corners and intersections and for other Dutch cities. Study II checks whether these situations lead to different results from those of Study I. For the study on corners and intersections, 11 more locations in Amsterdam were observed for one hour per location.

For the study in other Dutch cities, an additional 8 locations in four other cities were observed for one hour per location. The other cities were chosen based on a clear difference in terms of population, intensities and bicycle infrastructure from Amsterdam. The selected cities were Arnhem, Delft, Eindhoven and Venlo.

To differentiate the kerb types, the following three definitions apply (see figure 1):

- Right kerb: A right angled (~90°) edge or design element physically and optically separating pedestrians from bicyclists.

The right angle has a significant vertical height difference which is the key design element that differentiates this kerb from others. In practice, bicyclists are unable to ride up this type of kerbs without substantial physical effort, correct angle, and a certain speed.

- Sloped kerb: An obtuse angled (>90° and <180°) edge or design element physically and optically separating pedestrians from bicyclists.

This slope enables bicyclists to ride up the kerb without much effort in comparison to the right kerb.

- Levelled (flush) kerb: A visual separation (e.g. line or difference in colour or texture) without a height difference, optically separating pedestrians from bicyclists.

3.2 Variables

Within the scope of this study, it was not possible to collect sufficient observational data related to accidents (incident resulting in damage or injury) or near-accidents (incident that could have resulted in damage or injury under slightly different circumstances), since these are rare events. Therefore, the study focused on the question to what extent a road user moves into another road user's space for different kerb types. For cyclists, this behaviour is referred to as 'Cyclist On Sidewalk' (COS), and for pedestrians this is referred to as Pedestrian On Bicycle track (POB). Table 1 below summarizes the different variables that were considered in this study.

Table 1. Included variables (dependent and independent).

Variable name	Variable Type	Categories
Dependent variables		
Cyclist On Sidewalk (COS)	Nominal	-
Pedestrian On Bicycle track (POB)	Nominal	-
Independent variables		
Colour Contrast	Dichotomous	0 if LRV<30; 1if LRV>30*
Kerb Height (cm)	Continuous	-
Kerb slope (degrees)	Continuous	-
Kerb type	Nominal	0 if Right 1 if Sloped 2 if Levelled
Obstructions and installations	Dichotomous	0 if none 1 if one obstruction
One- or Two-way bicycle track	Dichotomous	0=one-way 1=two-way
Traffic intensities (n)	Continuous	-
Width bicycle path (cm)	Continuous	-
Width Sidewalk (cm)	Continuous	-
Width shoulder (cm)	Continuous	-

*LRV = Light Reflectance Value; see text for further explanation.

The colour difference between the bicycle track and kerb was measured on a Light Reflectance Value (LRV) scale. The research tool for assessing the LRV was applied on the camera images, measuring the brightness of a combined set of pixels. For simplicity reasons, the LRV was not measured on continuous scale but on a dichotomous scale, using 30 LRV as a threshold necessary for spatial orientation (ISO215442).

All study locations should have no, or as little as possible, obstructions and installations. This eliminates these objects from the research. However, for some locations it was not possible to clear all obstructions. The obstructions and installations could be reduced to locations in which none or just one obstruction was present. This enabled taking this variable into account in a dichotomous way.

3.3 Data analysis method

The video data was manually analysed and coded into researchable terms. To measure whether the kerb type was a significant contributing variable, a binomial logistic regression was used. The dependent variable was a 'cyclist on the sidewalk' (COS) with 1 (cyclist moved onto the sidewalk) and 0 (cyclist did not move onto the sidewalk). For the pedestrians, the dependent variable used was a 'pedestrian on the bicycle track' (POB) with 1 (pedestrian moved onto the sidewalk) and 0 (pedestrian did not move onto the sidewalk). A similar research method was used for the non-Amsterdam cities and the research on corners and intersections. Statistical tests were carried out to examine whether significant relations exist between the variables.

The collected data allowed for more elaborate analysis. The motives for a COS were analysed as well by observing the video material. Also, an additional proximity analysis was performed for a sample of 3,761 cyclists. Based on the video recordings, cyclists were rated into 4 categories related to the proximity of other cyclists, which are: 0 cyclists within 1m, 1 cyclist within 1m, 2 cyclists within 1m, or 3 cyclists within 1m. By including this variable, it would be possible to analyse how this relates to the proximity of COS specific cases, and whether other cyclists influence this behaviour.

4. Results study I

This section presents the results of Study I. First, a general overview is given. The next sections discuss the results regarding bicyclists (4.1), COS motives (4.2) and pedestrians (4.3).

The overall results of the video observations in Amsterdam are presented in table 2. These results show the total number of observed cyclists and pedestrians, sorted by kerb type, and the number of identified COS and POB. In total, 42 COS and 120 POB cases were observed.

Table 2. Frequency table per kerb and user type. (COS = Cyclist On Sidewalk)

	Right	Sloped	Levelled	Total
Cyclists	4445	5332	4725	14502
- COS	1 (0.02%)	5 (0.09%)	36 (0.76%)	42 (0.3%)
Pedestrians	1228	569	1781	3578
- POB	7 (0.57%)	2 (0.35%)	111 (6.23%)	120 (3.4%)

4.1 Bicyclists

From the total amount of 14,502 cyclists, 42 COS cases were observed (0.3%), of which most (36/42) occurred in the levelled kerb type category. A binomial logistic regression was performed which takes into account the effects of all included variables on the likelihood of cyclists moving onto the sidewalk (COS). The estimation results of this model are presented in Table 3. The binomial logistic regression model was statistically significant, $\chi 2(8) = 54{,}581$; $p < .005$. The kerb type was found as the only statistically significant variable. Other factors such as the width of the sidewalk or the colour contrast were not found to have a significant impact on the likelihood of a cyclist to move onto the sidewalk. No risky encounters or (near-) accidents were observed.

Table 3. Results of the logistic regression between COS and all included independent variables.

Variable	B	S.E.	Sig.	Odds ratio
Kerb Type (ref.) (levelled)				1
Kerb Type (1) (right)	-3.442	1.253	0.006	0.032
Kerb Type (2) (sloped)	-2.386	1.107	0.031	0.092
Width of Sidewalk	0.000	0.001	0.412	1.000
Width of Bike track	0.002	0.003	0.520	1.002
Width of Shoulder (if accessible)	0.000	0.001	0.917	1.000
One way or two way(1)	-0.568	1.820	0.755	0.567
One way or two way (ref.)				1
Presence of Colour contrast(1)	0.743	1.038	0.475	2.101
Presence of Colour contrast (ref.)				1
Obstructions or Installations(1)	-0.102	1.272	0.936	0.903
Obstructions or Installations (ref.)				1
Constant	-6.477	3.061	0.034	0.002

4.2 COS motives

From the video analysis, 42 cases out of 14,502 were found in which a cyclist moved onto the sidewalk. For these specific cases, a qualitative analysis was conducted to see what might be the reasons for COS behaviour. Data on the possible "motives" of cyclists to move onto the sidewalk was gathered by observing the video material, and the 42 COS cases in particular. The most common reason for cycling on the sidewalk appeared to be passing another cyclist (6 cases), coming to a complete stop on the sidewalk to check their phone (4 cases), or to turn left or right (3 cases). In two cases the COS movement could be related to safety, because the cyclist avoided another cyclist and as a result avoided a possible collision. In both these cases, the sloped or levelled kerb assisted the cyclist in moving away from the bicycle track, avoiding a possible collision with the other cyclist. No further risky encounters or (near-) incidents following a COS or POB were observed.

In most cases however, the COS movement was unclear (22 out of 42), meaning that cyclists did not necessarily go onto the sidewalk for a particular (observable) reason, or they might not even be aware of it. Although it is not possible to give a clear categorisation, observations of unclear behaviour relate to the possibility of moving more freely due to the flexibility that the levelled or sloped kerb offers. Some cases relate to somewhat playful behaviour of cyclists, or people that cycle next to each other and want to make use of the sidewalk so they can both move more freely. These reasons are however very hard to identify, and it is unclear what the actual motives for cycling on the sidewalk are. Therefore, these examples are therefore categorised as 'unclear'.

A motive for COS might also be related to the proximity of other cyclists. By studying the same dataset, it was shown that in 24 out of the 42 COS cases (57%), at least one cyclist was within a distance of 1m from the subject cyclist. All in all, the number of other cyclists that were in their proximity was 1,296 out of 3,761 (35%).

When comparing both figures, it becomes clear that the number of cases in which other cyclists were within 1m was greater for the specific COS cases than the average (57% vs 34.5%). This difference is statistically significant ($z = 2.83$; $p < 0.005$) at 95% confidence interval (2-tailed).

4.3 Pedestrians

120 POB cases were observed of the 3,578 pedestrians observed in total (3.4%). The levelled kerb type had the largest share of POB's. A binomial logistic regression was performed to test the effects of all included variables on the likelihood of a POB. The logistic regression model was statistically significant, $\chi2(8) = 1321.317$; $p < .0005$. The levelled kerb type was taken as a reference. The results of the logistic regression (see Table 4), show that the levelled and sloped kerb type are not significantly correlated to the POB cases. No risky encounters or (near-) accidents were observed.

Table 4. Results of the logistic regression that is used to relate the POB (Pedestrian On Bicycle track) with all related variables

Variable	B	S.E.	Sig.	Odds ratio
Kerb Type (ref) (levelled)				1
Kerb Type(1) (right)	-3.852	1.737	0.027	0.021
Kerb Type(2) (sloped)	1.295	2.944	0.660	3.652
Width of Sidewalk	0.004	0.002	0.122	1.004
Width of Bike track	-0.018	0.010	0.091	0.983
Width of Shoulder (if accessible)	0.002	0.002	0.297	1.002
One way or two way(1)	9.890	6.755	0.143	19733.063
One way or two way (ref.)				1
Presence of Colour contrast(1)	-4.321	3.280	0.188	0.013
Presence of Colour contrast (ref.)				1
Obstructions or Installations(1)	-2.113	2.787	0.448	0.121
Obstructions or Installations (ref.)				1
Constant	11.486	8.409	.172	97302.841

5. Results Study II

Study II examined the generalizability of Study I results. Section 5.1 presents the results of the research on corners and intersections, and section 5.2 presents the results of the observations in other Dutch cities, and compares these to the results from Amsterdam in Study I.

5.1 Results corners and intersections

The results from the analysis on corners and intersections in Amsterdam are shown in Table 5.

Table 5. Results corners and intersections

Cyclists observed		COS	%	Corrected*
Levelled	949	16	1.7%	(1.7%)
Sloped	300	31	10,3%	2.7%
Right	229	57	24,9%	4.3%
Total	1478	104	7.0%	

*Most locations near sloped and right angled kerbs are also near pedestrian crossings. A cyclist then has the possibility to cut off corners by using the levelled edges, designed for (ambulatory) pedestrians. The corrected values show the number of COS excluding the COS cases at pedestrian crossings.

It is important to note that even though a high percentage of COS was measured, no (near-) accidents (incidents resulting in or could have resulted in damage or injury under slightly different circumstances) were observed. Looking at the difference between the corrected and not-corrected percentages, a relatively high percentage took a shortcut via the sidewalk when levelled edges were applied for pedestrians at corners and intersections. Table 6 shows the results of both studies on straight roads and on the corners and intersections.

Table 6. Comparison of %COS between straight roads and corners & intersections.

% COS	Straight road	Corners and intersections	Corners and intersections (corrected)
Levelled	0.76%	1.7%	1.7%
Sloped	0.09%	10.3%	2.7%
Right	0.02%	24.9%	4.3%

This table indicates that cyclist behaviour near corners and intersections was very different from that on straight road sections. In general, much more cyclists took the shortcut via the sidewalk when they were in a corner or intersection, even when the numbers are corrected for levelled edges designed for pedestrians. These results are further discussed in the discussion section.

5.2 Results compared to other Dutch cities

The results of the observations in other cities than Amsterdam are shown in Table 7. The right angled kerb type is not included in this part since the main Amsterdam study revealed that COS and POB were very rare and did not show any difference.

Table 7. Results compared to other Dutch cities

	Cyclists observed	COS	%	Pedestrians observed	POB	%
Sloped						
Amsterdam	5332	5	0.1%	569	2	0.4%
Other cities	667	6	0.9%	206	1	0.5%
Levelled						
Amsterdam	4725	36	0.8%	1781	111	6.2%
Other cities	371	28	7.5%	546	56	10.2%

The results show both differences as well as similarities. Differences can be found in the relative number of COS between Amsterdam and the other cities. COS occurred almost 10 times as often in other cities than in Amsterdam. A similarity can be found in the difference between sloped and levelled kerb types. For both Amsterdam and other cities, the levelled kerb had more COS and POB than the sloped kerb type.

6. Discussion

In the present study we aimed to answer whether the different types of kerbs are associated with differences in road user behaviour of cyclists and pedestrians. A significant relation was found between the COS behaviour and the kerb types: most cyclists on the sidewalk were observed in the levelled kerb type category, and the kerb type was found to be the only statistically significant variable related to the COS cases. None of the other variables included in the analysis affected the behaviour of cyclists (e.g. width of sidewalk or presence of colour contrast). The proximity of other cyclists played a role as well. Cyclists often moved to the sidewalk when at least one cyclist was within a distance of 1m from the subject cyclist. This happened in about half of the observed COS cases.

For pedestrians, the levelled kerb type had the largest share of pedestrians observed on the bicycles track, but the levelled and sloped kerb types were not significantly correlated to the POB cases. The study showed no significant differences between how often pedestrians were observed on the bicycle track and the various kerb types and therefore follow-up studies were not executed. Since the POB variable did not reach significance in the statistical tests, no further conclusions can be formulated related to pedestrian behaviour. Probably (other) infrastructure characteristics are of a higher influence than the kerb type.

The results from the corners and intersections differed from those of straight road sections. It is, however, harder to relate the results of the corners and intersections to specific variables because more variables affect the behaviour (e.g. type of corner, length, sharpness of turns, entrances of buildings) than is the case on straight road sections. The results are therefore hard to analyse and compare. What does become clear is that cyclists move onto the sidewalk more often than on straight road sections. Cutting off corners is a common behaviour, even when a right angled kerb type is applied. At most locations with right angled kerbs, there are lower edges at pedestrian crossings which allow cyclists moving onto the sidewalk more easily. High intensities of cyclists waiting at a traffic light increased the number of COS at intersections.

Differences were found between the observations conducted in Amsterdam and the other Dutch cities. The dataset obtained in the other cities was much smaller than Amsterdam, and included more variation in terms of infrastructure. Results from these sections should thus be treated with care, and future larger scale research in some other cities is needed to come up with more definitive answers. In the other Dutch cities included in this study COS occurred more often than in Amsterdam. No direct reason could be found for this difference. A possible explanation is that quiet streets (low traffic intensities) give road users the opportunity to move more 'freely', since there is a lower risk of coming across other traffic to collide with. Or, the other way around, cyclists and pedestrians might prefer to cycle and walk on dedicated infrastructure when the traffic intensities around them become higher in order to avoid a collision. Despite the increase in the number of cyclists that moved onto the sidewalk, also in the other cities no (near-) accidents were encountered. In both Amsterdam and the other cities similar results with regard to kerb type were observed: the levelled kerb had more COS and POB than the sloped kerb type.

The results show that COS is a relatively rare action and that forgiving kerb types separate almost equally well as a right angled kerb. In our study no risky encounters or (near-) accidents were observed. A subjective safety session with 25 participants in the age group '60 and older' (Rijkswaterstaat, 2017) also supports the argument of using forgiving kerb types. The study revealed that participants felt safe and had mostly positive feelings towards the levelled and sloped kerb types. They are forgiving for cyclists, but also support diverting to the sidewalk or bicycle track just in case something happens. An additional accessibility benefit is created for e.g. wheelchairs and buggies.

In this study we have focused on the behaviour on kerbs in relation to traffic safety. However, also other aspects are of importance. Whenever new kerbs are designed, all other functions of kerbs (e.g. constructive, accessibility) should also be considered. We studied behavioural aspects of road users near different kerb types. No (near) accidents were observed and we used previous research as reported in the literature to relate our findings to the safety of different types of kerbs. Furthermore, this study only addressed situations that were physically separated from motorised traffic, excluding the behaviour of cars / car drivers. These can be considered limitations of the study. Nevertheless, our findings revealed new and relevant insights with regard to behaviour of cyclists near kerbs.

6.1 Transferability of findings

Contextual factors within the observations were kept stable as much as possible. This allowed combining and then comparing the kerb types within Amsterdam and the other Dutch cities. For comparing situations on an international scale, Amsterdam might have some city-specific characteristics that make it hard to generalize our findings. One of the factors is the high number of bicyclists and pedestrians. Intensities like these might only be found in for instance Antwerp, Copenhagen, or Munich. Such cities can benefit from our results when (re-) designing their streets. For cities with lower intensities of cyclists, the application of forgiving kerb types can still be advised given that no (near-) accidents were found, also for the other less busy Dutch cities. Whether the forgiving kerb type functions as a good separation in such situations is then yet another discussion that will depend on the case-specific demands and characteristics.

7. Conclusion

The primary goal of this research was to find out how different types of kerbs, varying in slope, relate to the behaviour of cyclists and pedestrians. Available literature shows that right angled kerbs are usually not preferred or recommended since they do not allow cyclists to make mistakes, in other words, they are not forgiving. As was expected, the study showed that right angled kerbs (0.01% COS) separate bicyclists from pedestrians better than sloped and levelled kerbs. However, both the sloped (0.09% COS) and levelled (0.76% COS) kerbs show relatively low amounts of COS as well. All kerb types thus prove to function well in terms of separating cyclists and pedestrians.

COS behaviour increases at corners and intersections. Cyclists cut off corners when space allows them to (i.e. when there are no pedestrians). The observations performed in other Dutch cities show that COS might occur relatively more often in less crowded cities than Amsterdam. More research is needed as the number of observations in other cities was smaller than in Amsterdam. No (near-) accidents were observed in neither Amsterdam nor in other cities. Therefore, we consider it unlikely that the risks of the height difference weigh up against the advantages in terms of separating cyclists and pedestrians.

8. Recommendations

In the ambition of separating bicyclists from pedestrians because of their different speeds and masses, as well as designing a 'forgiving' kerb to accept that people make mistakes, both the sloped and levelled kerb types come out as best practice. This is due to their forgiving state (they allow for making mistakes) and additional accessibility benefits. When selecting the best kerb type, a trade-off should be made in terms of forgivingness and level of separation. If separation of cyclists and pedestrians is considered relatively more important, a sloped kerb is preferred. If a higher level of forgivingness is considered relatively more important, a levelled kerb would be preferred.

Further research is recommended on the traffic safety and forgivingness of sloped kerb types. It is unknown what the safety effects are when a cyclist rides onto a sloped kerb unintentionally. Other factors that might influence the safety of sloped kerbs are visibility factors, which are related to the (absence of) shadow effect and height (low kerbs may be less visible). More research is needed on different (international) cities for comparing results. The non-Amsterdam cases show that COS might be more common in other situations (e.g. for lower intensities), but more data is needed to support this argument. Further study is also recommended on corners and intersections for which safety issues related to the visibility might appear. This requires more data and a more thorough research approach than applied here. A follow-up study could also investigate the relationship with the surroundings in terms of land-use or level of activity.

Finally, besides research on the specific dimensions of the treated kerb types, other less common kerb types might give promising results as well. Examples are rounded kerbs, a lowered sidewalk (downward kerb) and levelled kerbs with rumble strips.

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