Sharing is (s)caring? Interactions between buses and bicyclists on bus lanes shared with bicyclists

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Abstract

This paper presents the results of an observation study of interactions between bicyclists and buses on shared bus lanes. Straight sections of two bus lanes shared with bicyclists in Belgium have been observed, and all interactions between bicyclists and buses during two full weeks have been recorded and analysed. Additionally the lateral position and riding speed of bicyclists that are in interaction with buses is compared with the behaviour of a control group. One of the bus lanes is in line with road design guidelines in a number of countries that state that a sufficiently narrow bus lane (<3.5m) is hypothesized to be safer than a somewhat wider bus lane, the other bus lane is too wide according to these guidelines and is hypothesized to lead to unsafe overtaking manoeuvres.

The results show that dangerous interactions between bicyclists and buses are relatively frequent at both types of analysed bus lanes. Dangerous overtaking manoeuvres (a bus overtakes a bicyclist with an insufficient lateral distance) as well as dangerous bicycle-following situations (a bus drives behind a bicyclist with a small time headway) are quite common at both analysed bus lanes. The analyses could not confirm the hypothesis that a sufficiently narrow bus lane is safer than the wider bus lane. On the contrary, unsafe interactions even seem slightly more common at the narrow bus lane. Slightly more dangerous overtaking manoeuvres seem to take place at the narrow bus lane, but the difference is not statistically significant. Additionally, more bicycle-following situations take place at the narrower bus lane because overtaking is more difficult. The results show that buses often maintain unsafe time headways in these situations.

The presence of a bus has an influence on the behaviour of the bicyclists. Bicyclists that get overtaken by a bus, ride more closely to the edge than bicyclists that are not in interaction with a bus. While the road design guidelines assume that bicyclists take up a width of one meter from the edge on bus lanes shared with bicyclists, the observations show that bicyclists take up much less space while being overtaken. The presence of a bus does not have a significant influence on the lateral stability of the bicyclist. There are also some indications that bicyclists who are involved in an interaction with a bus ride faster than bicyclists who are not involved in an interaction with a bus.

Keywords
Traffic safety, bicyclists, shared use bus lanes, bus-bicycle interactions, overtaking proximity, time headway

Research highlights

- First study about bicyclists' safety at bus lanes shared with bicyclists
- Dangerous interactions are found to be quite common at bus lanes shared with bicyclists
- Current design guidelines might not be optimal

1 Introduction

Available space is often limited and may not allow to provide separate facilities for all road users. This is especially the case in urban areas. Allowing bicyclists to make use of bus lanes may be considered as a compromise to balance the needs of all road users. However, the safety effects of allowing bicyclists to make use of bus lanes have scarcely been investigated. Whether or not bicyclists should be allowed to make use of bus lanes is therefore subject of debate for policy makers and traffic engineers on an international level (Weinstein Agrawal et al., 2012).

This study makes use of semi-automated video observation software to analyse bicyclists' safety at bus lanes shared with bicyclists. A straight section of two bus lanes shared with bicyclists in Belgium have been selected for detailed analysis, and two full weeks of video footage have been analysed for each bus lane. Interactions between bicyclists and buses are analysed using surrogate safety indicators (overtaking proximity, time headway and minimum Time-to-Collision), and the behaviour of bicyclists that are in interaction with buses is being compared with the behaviour of bicyclists that are not in interaction.

2 Background

2.1 Bus lane safety and bus-bicycle accidents

While there is a significant body of literature assessing the impact of bus lanes on traffic flow (for buses as well as other traffic) and on bus punctuality, the impact of bus lanes on traffic safety has largely been overlooked (Tse et al., 2014). A meta-analysis of the effects of bus lanes on traffic safety suggests that bus lanes generally lead to an increase in the number of injury accidents (Elvik et al., 2009). It is however unclear what types of accidents increase due to the presence of bus lanes. Only one study was found that specifically investigated the impact of bus lanes on bicycle crashes. The study found indications that an increase of bicycle accidents may take place after the implementation of a bus lane (Devenport, 1987).

A study of seven major cities in different countries shows that some allow bicyclists to share bus lanes, while others do not (Weinstein Agrawal et al., 2012). This indicates that there is some disagreement on whether it is desirable to allow bicycles to share bus lanes or not. No studies have been found that specifically examine the safety of bicyclists when sharing a bus lane.

Buses and bicycles are at the opposite ends of the spectrum in terms of size, mass and manoeuvrability; while bicycles are small, light and agile, buses are large, heavy and rigid (Austroads, 2005). Therefore, safety conflicts may arise when buses and bicycles are sharing the same space on the roadway (Baumann et al., 2012). An Australian study (Austroads, 2005), focusing on bus-bicycle accidents on all roads, shows that the majority (55%) of accidents between buses and bicycles takes place at intersections. For non-intersection accidents, the most frequent type of accidents are angular crashes (60% of all non-intersection accidents). These accidents are mostly related to lateral movements of buses on the roadway, such as overtaking. The study also points out that of all types of bus-bicycle accidents the angular crashes and rear end crashes have the highest probability to result in a fatal outcome.

2.2 Subjective safety of bus-bicycle interactions

Baumann et al. (2012) performed a survey with bus drivers and bicyclists about bus-bicycle interactions. They concluded that the overtaking of a bicycle by a bus is considered an uncomfortable manoeuvre for both parties; 59% of bicyclists and 68% of bus drivers indicated that they feel uncomfortable while interacting with each other. This finding is indirectly confirmed by a stated preference survey towards bicycle infrastructure preferences. Caulfield et al. (2012) find that bicyclists are less likely to choose routes that have a bus lane with shared use with bicyclists. The only type of infrastructure that is considered as undesirable as the shared use bus lane is mixed traffic (i.e. no bicycle facilities present).

2.3 Overtaking of bicycles

The overtaking of bicycles by buses seems to have an important impact on safety. This section explores the issue of overtaking bicycles.

A particular point of concern in allowing bicyclists on bus lanes is the very different speed profile of buses and bicycles. While buses and bicycles appear to have a similar average speed, this average speed results from a constant relatively low speed for bicyclists and from a combination of frequent stops and relatively high driving speeds for buses. This difference in speed profiles leads to frequent overtaking manoeuvres between both types of road users, an issue that is commonly referred to as 'leap-frogging' (Veith & Eady, 2014; Weinstein Agrawal et al., 2012).

An analysis of injury accidents involving a bicyclist in 2010 in London shows that passing a cyclist too close is among the most frequently registered contributory factors of bicycle accidents (Transport for London, 2011). Walker (2007) found that large vehicles (including buses) pass bicyclists much closer than other types of vehicles. Due to their length and poor acceleration, buses and heavy goods vehicles take much longer to pass a bicyclist than shorter vehicles. It is suggested that a reluctance of drivers to stay out-of-lane in combination with lack of lengthy gaps in the adjacent lane and vehicle design issues that put bicyclists out of sight before overtaking is complete that cause drivers of long vehicles to pull back across before it is safe to do so, hence creating close proximities and frequent conflicts (Walker, 2007). Chuang et al. (2013) found a lower mean overtaking distance for buses than for other categories of road users as well, although it must be mentioned that the number of overtaking events by buses was relatively low in their sample. These results are also largely confirmed by a study by Pai (2011), who investigated overtaking, rear-end and door crashes involving bicycles. The author found that the variable 'bus as crash partner' significantly increased the probability of an accident being an overtaking accident.

In order to reduce the probability of overtaking accidents, traffic regulations in a number of countries stipulate minimal overtaking distances. For instance, Belgian traffic regulations (art. 40ter of the Belgian Traffic Code) state that drivers need to keep a lateral distance of at least one meter while overtaking a bicyclist. This rule is quite similar to the 'three-foot bicycle passing law' (3ft. = 0.91m) that is in place in a number of States in America (Love et al., 2012).

Dutch research shows that motor vehicle drivers very rarely pass a bicyclist with a lateral distance of less than 0.85m (CROW, 2006). At 50 km/h (approximately 30 mph), and where the overall width permits, the passing distance is typically around 1.05m. On the other hand, the study by Love et al. (2012) found that 17% of all motor vehicle drivers did not respect the three-foot bicycle passing law, and overtook the bicycle with a distance of less than 3ft. Walker (2007) found a mean overtaking distance for buses of 1.10m.

Chuang et al. (2013) found that bicyclists demonstrate a weaker lateral control when they are being passed by a bus compared to when they are being passed by a different type of road user. The authors suggest that the size of a bus makes it appear to be closer to the bicyclists than smaller vehicles, which can affect the steering control behaviour of the bicyclists.

2.4 Other influences that affect the overtaking distance

Walker (2007) indicates that the further away from the road edge a bicyclist is riding, the more likely an overtaking event with a smaller lateral distance is. The author recommends therefore that bicyclists should not ride too far away from the road edge. On the other hand, riding too close to the road edge can bring more potentially hazardous obstacles into the rider’s path, such as drainage grates, road debris and car doors. A position around 0.5-0.75m therefore seems to be a reasonable compromise between both dangers according to the author.

Shackel & Parkin (2014) found that wider roads lead to larger overtaking distances, but also to higher overtaking speeds. Higher overtaking speeds can lead to a higher instability of the bicyclist due to turbulence. Also, higher overtaking speeds can lead to more severe injuries in case an accident would take place.

2.5 Official roadway design guidelines for bus lanes shared with bicyclists

As indicated before, an international comparison shows that different countries are divided on whether to allow bicycles to use bus lanes (Weinstein Agrawal et al., 2012). Most of the countries that do allow shared use of bus lanes with bicyclists have some specific design recommendations for bus lanes that can be accessed by bicyclists. A non-exhaustive overview of the guidelines in some of these countries is provided below. For a more elaborate description of regulations and recommendations for shared use of bus lanes with bicyclists in different countries, the reader is referred to Sørensen (2012).

In the region of Flanders (Belgium) where this study takes place, bicyclists are not by default allowed to use a bus lane. Apart from buses, only emergency vehicles and taxis are by default allowed to make use of bus lanes (Flemish Government - Roads and Traffic Agency, 2009). Road authorities can however allow them to use a bus lane by placing a specific traffic sign that indicates this permission. Additionally, road authorities have the possibility to stress this permission by painting a bicycle symbol on the pavement. The Flemish road design guidelines distinguish three types of situations for bus lanes shared with bicyclists (Flemish Government, 2014):

- Bus lane width is maximum 3.5m: bicyclists can be allowed to share the bus lane in built-up area, preferably only for short distances. The rationale behind this is that buses cannot overtake a bicyclist within the boundaries of this bus lane, since a bicyclist is assumed to have a width of 1m from the edge of the road and a bus has a width of around 2.50m. The bus therefore needs to exit the bus lane to overtake a bicyclist.
- Bus lane width is between 3.5m and 4.5m: the guidelines do not recommend to allow bicyclists to share bus lanes that are 3.5-4.5m wide. The rationale is that this width could allow buses to overtake bicyclists within the boundaries of the bus lane, but only with a dangerously small (<1m) margin. The hypothesis is that this could lead to dangerous situations.

- Bus lane width is larger than 4.5m: it is assumed that bicyclists could be overtaken safely within the boundaries of the bus lane. However, in this situation a separate bicycle lane is to be preferred over a shared-use bus lane.

The overall recommended width for all bus lanes is 3.05m for bus lanes with a speed limit of 50km/h (Flemish Government - Roads and Traffic Agency, 2009). It should be kept in mind that road authorities are not obliged to follow these recommendations. Therefore, in practice, all three types can be implemented.

A number of countries such as Germany and Austria have similar guidelines to Flanders. In Germany, bus lane widths of less than 3.5m or more than 4.75m are considered to be safe designs, while a width between 3.5m and 4.75m is considered unsafe (Forschungsgesellschaft für Straßen- und Verkehrswesen, 2010). Austrian guidelines recommend a bus lane width of 3.0-3.25m, or 4.25-4.75m (Österreichischen Forschungsgesellschaft Straße - Schiene - Verkehr, 2014).

A number of other countries, however, take a very different departure point. They only recommend a minimum bus lane width for bus lanes shared with bicyclists, in order to facilitate (safe) overtaking manoeuvres. The Australian design guidelines recommend a minimum bus lane width of 3.7-4.3m, depending on the speed limit for the buses (Veith & Eady, 2014). In the United Kingdom, bicyclists are generally allowed to make use of the bus lane. A width of at least 4.0m (but preferably 4.5m) is therefore recommended in English guidelines (Department for Transport, 2008). In Denmark, a minimum bus lane width of 4.5m is suggested in case of moderate volumes of bicyclists; for high volumes, separate bicycle facilities are recommended (Vejdirektoratet, 2009). In Sweden, a minimum width of 4.5-5.0m is recommended for bus lanes with shared with bicyclists, depending on the speed limit for the buses (Vägverket & Svenska Kommunförbundet, 2004).

It can be concluded that there are two dominant views on how bus lanes should be designed in case it is decided to allow bicyclists to use the bus lane. A number of countries suggest to make the bus lane either wide enough to facilitate safe overtaking of bicyclists by buses OR narrow enough to prevent overtaking of the bicyclists within the borders of the bus lane, while a number of countries only suggests a minimum width in order to facilitate overtaking.

3 Research questions

The main research questions that will be explored in this study are the following:

1) Does the presence of an approaching bus have an influence on the bicyclists' behaviour when riding on a shared-use bus lane?
2) How frequently are bicyclists on shared-use bus lanes involved in dangerous interactions with buses?
3) Do differences exist between smaller and wider bus lanes?

4 Methodology

4.1 Study locations

We observed two bus lanes that allow shared use with bicyclists in the region of Flanders, Belgium. One bus lane is located in the city of Kortrijk and has a width of 3.1m (Figure 1, left side). The second bus lane is located in the city of Ghent, and has a width of 4.2m (Figure 1, right side). Both bus lanes are located in an urbanized area with a speed limit of 50 km/h.

Figure 1 – Observation sites: Kortrijk (left) (3.1m wide - in line with guidelines) and Ghent (right) (4.2m wide – not in line with guidelines).

4.2 Video data collection and analysis

At each site, a video camera was mounted in a lighting pole to record oncoming bicyclists and buses on the bus lane. The images in Figure 1 are snapshots from the video footage that is analysed. Two full weeks of video, recorded in fall 2014, are analysed. The recorded time period is identical for both locations to keep elements such as length of day and weather conditions equal.

The video footage is processed using T-Analyst, a semi-automated video analysis software developed at Lund University (Lund University - Transport and Roads, 2015). The software is calibrated to transform the image coordinates of each individual pixel to road plane coordinates, which allows to accurately determine the position of an object in the image and to calculate its trajectory. This allows the calculation of road users' speeds and positions, distances and traffic conflict indicators in an accurate and objective way (Polders et al., 2015).

Some of the collected indicators (such as lateral position – see further) require a high level of accuracy in the measurements. To ensure a sufficiently high accuracy, the length of the stretch of road that is analysed is limited to 40m at each observation site. No intersections are present on the observed road stretches.

All interactions between bicyclists and buses that take place in this road stretch during the observation period are selected for detailed analysis. An interaction is defined as a situation in which two road users approach each other with such closeness in time and space that the presence of one road user can have an influence on the behaviour of the other (De Ceunynck et al., 2013). It can be seen as an elementary event in the traffic process that has the potential to end in a collision (Laureshyn et al., 2010). This definition is operationalized as each situation at the observation sites where a bus approaches a bicyclist to a distance of less than 28m, which equals the distance covered by a bus in 2s at a speed of 50 km/h. These situations can either be bicycle-following situations where a bus is driving behind a bicycle, or situations where the bicycle gets overtaken by the bus. Since there are no bus stops present in the observed road stretches, no situations where a bicycle overtakes a bus have been observed.

In order to answer the first research question ("does the presence of an approaching bus have an influence on the bicyclists' behaviour?"), a quasi-experimental research design was set-up. The behaviour of bicyclists that are in interaction with a bus (the 'experimental' group) is compared with the behaviour of a sample of free-flow bicyclists that have been randomly selected from the same observation period (the 'control' group).

4.3 Collected variables about behaviour

For all events (both interactions and free-flow bicyclists), the following data related to bicycle behaviour are registered:

- Lateral position of bicycle at 5 points (every 10m of the 40m road stretch)
- Speed of bicycle at 5 points

For all interactions, a number of additional variables are registered that describe :

- Distance headway and time headway (at each measurement point of the bicycle, the headways between the bicycle and the bus are calculated)
- Lateral position and speed of bus at 5 points
- Specifically for interactions that include an overtaking manoeuvre, the following variables are additionally registered:
    - Lateral overtaking proximity
    - Position of bus during overtaking (within bus lane, entirely on the adjacent roadway, or partly on both)
    - Speed and lateral position of bicycle during over taking
- A number of situational aspects that could affect the process of the interaction:
    - The presence of a barrier on the adjacent lane (i.e. a vehicle that could prevent the bus from leaving the bus lane to overtake)
    - The presence of a barrier downstream on the bus lane (e.g. other bicyclists or buses that could discourage the bus driver to overtake the bicyclist)
    - Weather and light conditions

4.4 Indicators to describe dangerousness of interactions

The minimum Time-to-Collision (TTC_{min}), the overtaking proximity and the time headway are the surrogate safety measures that are used to evaluate whether interactions are to be considered dangerous situations or not (research questions 2 and 3).

Time-to-Collision is defined as "the time remaining until a collision between the vehicles would occur if they continued on their present course at their present rates" (Hayward, 1972). Research suggests that

TTC_{min} values lower than 1.5s are rarely observed in normal interactions and can therefore be considered as dangerous events (van der Horst, 1990).

The literature review has shown that the overtaking proximity is an important aspect of bicyclists' safety. Since the Belgian Traffic Code imposes a minimum lateral distance of one meter when overtaking a bicyclist, overtaking manoeuvres with a margin of less than one meter are considered as dangerous events in this study.

Time headways (the gap between two vehicles driving behind each other, express in seconds) are highly defining for the risk of rear-end collisions (Evans & Wasielewski, 1982). In case the leading vehicle needs to make an emergency stop, a sufficiently large time headway is needed to allow the following vehicle to react and stop in time as well. A general rule of thumb is that a vehicle should keep a time headway of at least two seconds from the vehicle in front of it (the so-called two-second rule) (Michael et al., 2000). This rule is based on the reaction time of drivers, which can vary from less than one second to about two seconds (Lamm et al., 1999). Some may consider a time headway of 2s quite conservative and difficult to maintain in everyday traffic. However, reaction time is dependent on the complexity of a decision (Alexander & Lunenfeld, 1990). A bus driver's decision to make an emergency stop is considered to be more complex than for most other drivers, because the bus driver needs to take the presence of passengers into account. An emergency stop could lead to injuries for passengers in the bus. Therefore, a relatively long reaction time of 2s is assumed for bus drivers in accident reconstruction literature (Burg & Moser, 2007). As a result, time headways of less than 2s will be considered as dangerous situations in this study.

5 Results

The database consists of 519 records in total, 262 of which are bicycle-bus interactions and 257 are free-flow bicyclists. It can be seen that for the narrower bus lane 60% of all interactions lead to overtaking, while this number rises to 72% for the wider bus lane. Given the limited length of the analysed road sections, these numbers are very high. It therefore seems that buses will overtake bicyclists whenever they can. The proportion of interactions leading to overtaking is slightly higher at the wider bus lane, but the difference is not statistically significant and therefore only indicative ($X^2(1)=2.04$; $p=0.153$).

Table 1 – Number of observed situations.

	Narrower bus lane	Wider bus lane	Total
Free flow bicyclists (no interaction)	171	86	257
Interaction without overtaking	91	10	101
Interaction with overtaking	135	26	161
Total	397	122	519

The following sections will analyse behavioural aspects of bus-bicycle interactions such as lateral position and speed, and the occurrence of dangerous interactions between bicyclists and buses.

5.1 Behavioural aspects of bus-bicycle interactions

5.1.1 Analysis of lateral position of bicyclist

To address the question whether the presence of a bus influences the behaviour of a bicyclist, the lateral positions of the bicyclists that are in interaction with a bus are compared to the lateral positions of the free-flow bicyclists in Table 2. For each of the three groups at each of both locations, the mean lateral position of the bicyclist over the five measurement points is shown. The lateral position is expressed as the lateral distance (in m) between the edge of the roadway and the centroid of the bounding box around the bicyclist (which approximately corresponds with the contact point of the tyres on the road). Lower values therefore indicate a position more closely to the edge of the road. Furthermore, the results from four MANOVA-tests are shown that compare the five lateral position measurements from the bicyclists that are in interaction with a bus with the control group of free flow bicyclists.

It can be seen that bicyclists generally take a lateral position further away from the edge of the road in the wider bus lane. The lateral position of bicyclists that are involved in an interaction without overtaking (bicycle-following situation) does not differ significantly from the lateral position of free flow bicyclists. There is however a significant difference between bicyclists involved in an interaction with overtaking and free flow bicyclists. Bicyclists that get overtaken by a bus are on average positioned significantly more closely to the edge of the road than free flow bicyclists.

Table 2 - Lateral position of bicyclists per type of situation and per location.

		Lateral position at narrower bus lane	Lateral position at wider bus lane
Free flow bicyclists	Mean of 5 measurements	0.56m	0.82m
	MANOVA	/ (control group)	/ (control group)
Interactions without overtaking	Mean of 5 measurements	0.55m	0.80m
	MANOVA	F(5,256)=0.847; p=0.518	F(5,90)=2.230; p=0.058
Interactions with overtaking	Mean of 5 measurements	0.32m	0.45m
	MANOVA	F(5,300)=9.947; p<0.001	F(5,106)=2.956; p=0.015

The previous analysis can however not clarify whether bicyclists are more likely to get overtaken because they are already riding more closely to the edge, or that they start riding more closely to the edge because they are getting overtaken. Therefore, Table 3 shows the lateral position of the bicyclists at the entry of the observed road section as well as while being overtaken by the bus for interactions with and without overtaking.

It can be seen at both locations that the lateral position of the bicyclists that do not get overtaken when entering the observed road section is further away from the edge of the road than bicyclists that get overtaken. So it seems that bicyclists that are getting overtaken by a bus are on average already riding more closely to the edge of the road at the entry point of the observed road section than bicyclists that do not get overtaken. This could suggest that bicyclists riding more closely to the edge of the road are more likely to get overtaken than bicyclists riding further away from the edge of the road. When we compare the lateral position of the bicyclists at the entry point of the observed road section with the lateral position during overtaking, it can be seen that the difference is quite small at the narrower bus lane. This indicates that bicyclists are not really starting to ride more closely to the edge of the road as a consequence of being taken over at the narrower bus lane. At the wider bus lane, there is a more pronounced difference between these lateral positions, which suggests that bicyclists at the wider bus lane position themselves more closely to the edge of the roadway while getting overtaken.

Table 3 - Lateral position of bicyclists at entry point versus during overtaking.

	Lateral position at narrower bus lane		Lateral position at wider bus lane	
	Interactions without overtaking	Interactions with overtaking	Interactions without overtaking	Interactions with overtaking
Position at entry of road section	0.45m	0.25m	0.94m	0.65m
Position during overtaking	/	0.21m	/	0.36m

The absolute position is only one element of the lateral position of bicyclists. Since we have multiple measurement points, the standard deviation of the lateral position (SDLP) can be calculated. The SDLP provides an indication of the lateral stability or the amount of swaying of the bicyclist. The SDLPs for the three types of situations are compared for each of both locations using ANOVA tests (Table 4). As can be seen from the table, there are no statistically significant differences between the three types of observed situations (nor for any the individual locations nor for both locations combined). This suggests that the presence of a bus does not have a significant influence on the lateral stability of the bicyclist.

Table 4 - SDLP of bicyclists.

	SDLP Narrower bus lane	SDLP Wider bus lane	SDLP both bus lanes
Free flow bicyclists	0.147	0.177	0.157
Interactions without overtaking	0.188	0.254	0.166
Interactions with overtaking	0.164	0.177	0.195
ANOVA	$F(2,394)=1.616$; $p=0.200$	$F(2,119)=2.328$; $p= 0.102$	$F(2,516)=1.932$; $p=0.146$

5.1.2 Analysis of bicyclists’ riding speed

Additional to affecting the bicyclists’ lateral position, the presence of a bus may also affect the bicyclists’ riding speed. For each of the three groups at each of both locations, the mean riding speed of the bicyclist over the five measurement points is shown in Table 5. Furthermore, the results from four MANOVA-tests are shown, that compare the five speed measurements from the bicyclists that are in interaction with a bus with the control group of free flow bicyclists.

For the narrower bus lane, it can be seen that bicyclists involved in interactions without overtaking (i.e., there is a bus driving behind them) have a significantly higher riding speed than the control group of free flow bicyclists. There is no significant difference in riding speed between the interactions with overtaking and the free flow bicyclists.

At the wider bus lane, a different pattern can be observed. Here we see that bicyclists that are involved in an interaction with overtaking have a significantly higher riding speed than the control group of free flow bicyclists. Bicyclists involved in interactions without overtaking do not have a significantly higher riding speed than free flow bicyclists.

Table 5 – Bicyclists' riding speed.

		Bicyclists' speed at narrower bus lane	Bicyclists' speed at wider bus lane
Free flow bicyclists	Mean of 5 measurements	5.04m/s	5.04m/s
	MANOVA	/ (control group)	/ (control group)
Interactions without overtaking	Mean of 5 measurements	5.43m/s	5.29m/s
	MANOVA	F(5,255)=2.730; p=0.020	F(5,89)=0.948; p=0.454
Interactions with overtaking	Mean of 5 measurements	4.85m/s	5.35m/s
	MANOVA	F(5,300)=1.206; p=0.306	F(5,105)=2.436; p=0.039

5.1.3 Speed of buses during overtaking

The driving speed of the buses while overtaking a bicyclist is shown in Table 6. It can be seen that the overtaking speed of the bus is higher at the wider bus lane than at the narrower bus lane. An ANOVA-test shows that this difference is statistically significant, $F(1, 133)=15.567$; $p<0.001$.

Table 6 – Overtaking speed of buses.

	Narrower bus lane (N=111)	Wider bus lane (N=24)
Mean	11.8m/s (42.4km/h)	13.7m/s (49.3km/h)
Standard error	0.198m/s	0.426m/s
Minimum	4.7m/s	8.4m/s
Maximum	18.8m/s	19.0m/s

5.2 Occurrence of dangerous interactions

5.2.1 TTC_{min}

Dangerous TTC_{min} values would generally occur when a bus approaches a bicyclist at relatively high speed, and only brakes very late to avoid a rear end collision. Figure 2 shows a histogram of observed TTC_{min} values of bus-bicycle interactions at both bus lanes combined. The red vertical line indicates the cut-off between severe and non-severe events. It can be seen that very few severe TTC_{min}- values were observed. Most TTC_{min}-values are well above this threshold value. This suggests that such aggressive approaching of a bicyclist by a bus driver is very infrequent at bus lanes with shared use by bicyclists.

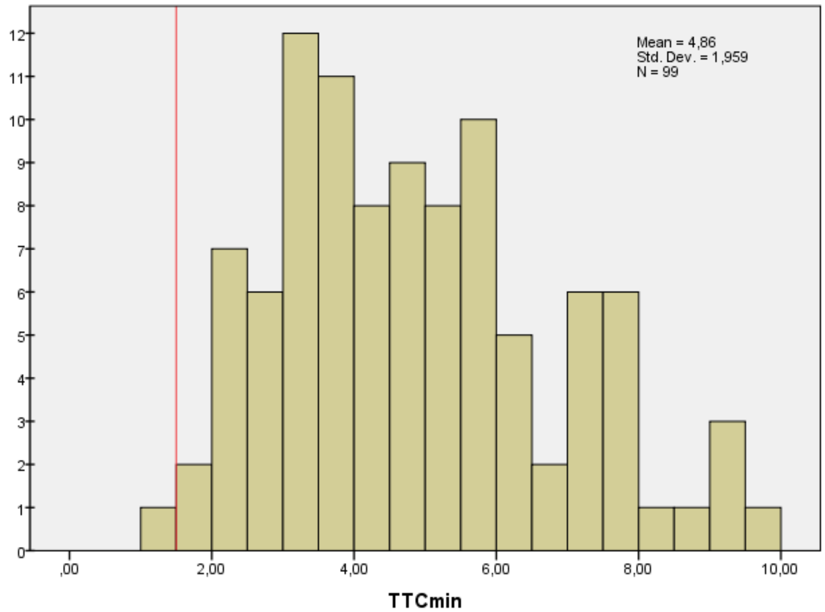

Figure 2 – Distribution of TTC_{min}- values (both bus lanes combined)

5.2.2 Overtaking proximity

The distribution of the overtaking proximity for all interactions with overtaking at both bus lanes is shown in the box plots in Figure 3. The black line in the box represents the median value, and the sides of the boxes represent the upper and lower quartile value. The whiskers indicate the variability outside the upper and lower quartiles, and the individual points that are plotted are deemed to be outliers. The critical value of 1m is indicated by the red vertical line.

The box plots show that the median overtaking distance is the same at both bus lanes, 1.1m. A higher dispersion of overtaking distances is however observed at the narrower bus lane. This implies that there are more situations with a large overtaking distance at the narrower bus lane, but also more situations with an overtaking distance that is (too) small. At the narrower bus lane, 33% of all overtaking manoeuvres take place with an overtaking distance of less than 1m, while this is the case for 21% of the overtaking manoeuvres at the wider bus lane. The proportion of overtaking manoeuvres that has an overtaking distance of less than 1m is however not significantly different between both bus lanes, $X^2(1)=1.312$; p=252.

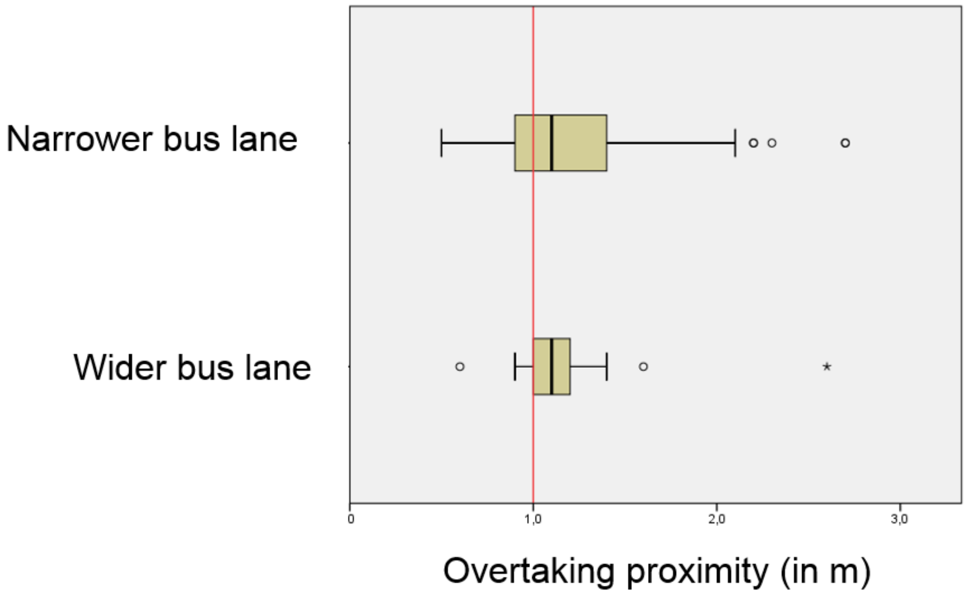

Figure 3 – Overtaking proximity at both bus lanes.

5.2.3 Time Headway

The distribution of time headways for all interactions without overtaking are shown in Figure 4. Because the number of interactions without overtaking is low at the wider bus lane (N=10), the values for both locations are combined in one figure. The red vertical line indicates the critical value of 2s. The minimal time headway value for each interaction is taken. It can be seen that the number of interactions that have a time headway that is considered too low is very high. 54% of all interactions without overtaking have a minimal time headway value lower than 2s. 23% of these interactions even have a minimal time headway of less than 1s.

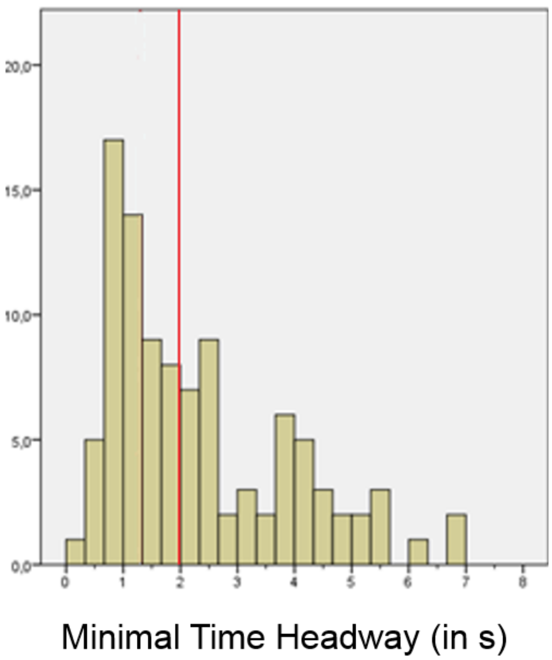

Figure 4 - Distribution of observed Time Headways of interactions without overtaking.

6 Discussion

6.1 Discussion of behavioural aspects and occurring dangerous situations

The road design guidelines in Flanders-Belgium (and a number of other countries) recommend that bus lanes shared with bicyclists are either designed narrow enough to prevent unsafe overtaking manoeuvres within the borders of the bus lanes (≤3.5m), or wide enough to allow buses to safely overtake the bicyclists within the borders of the bus lanes (>4.5m). In the latter case, however, it is argued that a separate bicycle track is to be preferred over a shared use bus lane (Flemish Government, 2014). Therefore, this paper has put an emphasis on comparing the safety of bicyclists at the narrow (recommended) type of bus lane with the safety at the medium-width (3.5m-4.5m) bus lane that is hypothesized to be less safe. Therefore, this paper does not allow to draw any direct conclusions for the widest type of bus lanes shared with bicyclists, which is recommended by road design guidelines in a number of other countries.

When summarizing the results from the analyses of dangerous interactions, it should be concluded that the hypothesis that bus lanes narrower than 3.5m are safer than bus lanes with a width between 3.5 and 4.5m does not hold. Firstly, it is hypothesized by the road design guidelines that the narrower bus lane prevents unsafe overtaking manoeuvres by prohibiting overtaking within the borders of the bus lane itself. The results of the overtaking proximity show however that unsafe overtaking manoeuvres are quite common at the narrow bus lane (33% of all overtaking manoeuvres). The proportion of unsafe overtaking manoeuvres at this bus lane that is designed according to the road design guidelines is not significantly lower than at the bus lane that is not in line with the guidelines. On the contrary, there even is a (non-significant) indication that there are more unsafe overtaking manoeuvres at the recommended narrower bus lane. This finding can be related to the study by Shackel & Parkin (2014), who observed that wider roads generally lead to larger lateral overtaking distances. The median overtaking distance at both bus lanes (1.1m) is similar to the overtaking distance of buses overtaking bicyclists that was recorded by Walker (2007).

This finding could be partly related to the underlying assumption of the space taken up by the bicyclist. It is hypothesized that the bicyclist has a width of one meter, measured from the edge of the road (Flemish Government, 2014). However, the analyses show that bicyclists take up less than one meter from the edge of the road, especially at the moment he/she is being overtaken. The lateral position of a bicyclist (the centroid of the bounding box) while being overtaken is 0.21m and 0.36m at the narrow and at the wider bus lane respectively. Since a bicyclist has a physical width of 0.75m (AASHTO, 2012; CROW, 2004), this means that the bicyclists on average only take up a width of 0.585 and 0.735m from the edge of the road at both bus lanes respectively. At the narrower bus lane, 4 overtaking manoeuvres were registered where the adjacent traffic lane was blocked by car traffic, and the bus could therefore not leave the bus lane for overtaking. These overtaking manoeuvres should theoretically be impossible at this type of bus lane. While these situations are rather infrequent, they all correspond with very low overtaking distances (0.6-0.7m), and therefore these situations are highly undesirable. It is remarkable that even on a bus lane with a width of 3.1m, which is well below the prescribed upper limit of 3.5m and only marginally above the recommended minimal width for all 50 km/h bus lanes of 3.05m, overtaking manoeuvres are still occasionally possible when the adjacent road is blocked. In the majority of situations with an unsafe overtaking distance, however, the adjacent traffic lane is free from traffic, and the bus could easily have kept a larger distance. A reluctance of bus drivers to stay out-of-lane might be one of the causes of this finding (Walker, 2007).

Additional to the issue of unsafe overtaking manoeuvres, there also seems to be an issue of unsafe bicycle-following situations. More than half of all interactions without overtaking have a time headway of less than 2s, and nearly one in four interactions without overtaking even have a time headway less than 1s. At both locations, a very high proportion of bus-bicycle interactions lead to overtaking. This proportion is however even slightly higher at the wider bus lane. Or, in other words, the problem of unsafe bicycle-following situations could be more pronounced at the narrower bus lane. Since the traffic volumes on the adjacent traffic lanes are highly comparable between both locations, it is justified to argue that this difference in overtaking probability is mostly due to the difference in width of both bus lanes. This also means that the issue of dangerous interactions without overtaking is more pronounced at the narrower bus lane. One could therefore question whether it is desirable to limit the possibilities for buses to overtake bicyclists.

While the frequency of dangerous situations therefore generally seems to be higher at the narrower bus lane, it must be mentioned that the overtaking speed of the bus is significantly higher at the wider bus lane. This finding is in line with Shackel & Parkin (2014). The higher overtaking speed poses a safety threat to bicyclists as well, since the consequences in case a collision would take place are likely to be higher.

A comparison between the riding speed of bicyclists that are in interaction with a bus and the riding speed of free flow bicyclists shows mixed results. At the narrower bus lane, only bicyclists involved in an interaction without overtaking have a significantly higher riding speed than the control group of free flow bicyclists. At the wider bus lane on the other hand, only bicyclists that get overtaken ride significantly faster than free flow bicyclists. It should however been added that slower bicyclists theoretically have a higher chance of getting involved in an interaction because they linger a longer time in the observation area. Therefore, slower bicyclists might be slightly overrepresented in the sample of bicyclists that are in interaction with buses compared to the control group of free flow bicyclists. While the patterns are not fully clear and unequivocal, it can be suggested that there are some indications that the presence of a bus may lead to an increase in cycling speed. This is confirmed by a small-scale follow-up survey, for which we stopped 101 bicyclists at both research locations and asked whether they adapt their speed to the presence of a bus. 33% of all bicyclists state that they increase their speed when they notice that a bus is approaching. At the narrower bus lane, the proportion of respondents stating that they increase their speed is higher than at the wider bus lane (40% and 25%, respectively). 46% of respondents state that they do not change their riding speed, 17% state that they reduce their speed and 4% state that they stop completely. This increased riding speed could indicate a feeling of discomfort of the bicyclist, which would be in line with Baumann et al. (2012).

The presence of a bus has an influence on the lateral position of the bicyclist. Mainly bicyclists who get overtaken by a bus ride more closely to the edge of the road. This could indicate that some bicyclists, either consciously or unconsciously, ride more closely to the edge of the road when in interaction with a bus. If this is a conscious behaviour, it could possibly indicate that bicyclists do not like having a bus driving behind them, and hope that they get overtaken more easily when they are riding more closely to the edge of the road. Respondents from the small-scale survey were also asked whether they adjust their lateral position when they notice that a bus is approaching. 57% of the respondents state that they move more towards the edge of the road, 39% state that they keep the same lateral position, and 4% indicate that they will leave the bus lane altogether. No respondents state that they will take a position further towards the middle of the road. This suggests that some bicyclists deliberately take a position closer to the edge of the road when they get involved in an interaction with buses to facilitate overtaking. No significant difference was found between free-flow bicyclists and bicyclists that are involved in an interaction with a bus regarding the SDLP. Therefore, the finding by Chuang et al. (2013) that bicyclists have a weaker lateral control while being overtaken by a bus cannot be confirmed.

6.2 Strengths, limitations and further research

Research into the safety of bus lanes is relatively limited, and to the best of our knowledge this is the first study to explicitly address the issue of shared use of bus lanes with bicyclists. An additional strength is the use of observed (revealed) behaviour and interactions. The detailed analysis of interactions on video footage has provided a better insight into the behaviour of bicyclists and buses on bus lanes shared with bicyclists, as well as in patterns of unsafe situations that take place at bus lanes shared with bicyclists.

The use of indicators such as overtaking proximity and time headway and their link to traffic safety could be debated. The validity of these indicators as surrogate measures of safety is not sufficiently investigated by research. It is therefore uncertain how strongly these indicators correlate with the prevalence of actual accidents. A major disadvantage of accident data is however that they are a very coarse indicator. Accidents are rare events, which often makes it difficult to draw statistically meaningful conclusions, there is a well-known problem of underreporting, and the limited information about behavioural and situational aspects preceding the accident data makes it difficult to get insight in the actual causes of the accident (Laureshyn et al., 2010). Due to the limited number of bus lanes shared with bicyclists, analyses of accidents on these bus lanes would not allow to gain much insight into this subject. The use of surrogate safety measures does have however, despite these limitations, allowed to get some insights into the safety of bicyclists at bus lanes shared with bicyclists.

A limitation of the study is the low number of research locations. Only short stretches of two bus lanes were analysed in this study. Two full weeks of video were analysed at both locations, which should be considered a rather extensive observation period. While there are no reasons to believe that the observed bus lanes are atypical in any way, generalizability of the results cannot be guaranteed. This study should be seen as an exploratory study on the subject that provides some first indications and raises some points for discussion that should be further investigated in future research.

Further research is needed to clarify which policy recommendations should be made regarding bus lanes shared with bicyclists. While this study indicates that the hypothesis that bus lanes narrower than 3.5m are safer than bus lanes with a width of 3.5-4.5m does not hold, it is still unclear what the recommendation should be then. Should it be recommended that the design guidelines of the narrow design should be even narrower to prevent unsafe overtaking? Or should only a wider design be recommended that facilitates overtaking, as is recommended in a few countries such as the UK, Australia and Denmark? Alternatively, raising awareness for this problem with bus drivers might be considered as a mediating measure. This could improve the distance they keep when following or overtaking bicyclists.

It can be concluded that dangerous interactions seem quite frequent at both analysed types of bus lanes. Based on these results, it seems that there are some issues regarding bicyclists' safety at bus lanes shared with bicyclists. The design guidelines in some countries implicitly seem to acknowledge that bus lanes shared with bicyclists are a suboptimal solution. Some of the national road design guidelines explicitly state that separate bicycle lanes are to be preferred, or that shared use of bus lanes with bicyclists should only be implemented for short distances (e.g. Flemish Government, 2014; Forschungsgesellschaft für Straßen- und Verkehrswesen, 2010). The results of this study seem to confirm that bus lanes shared with bicyclists are a compromise that may have a negative effect on bicyclists' safety.

7 Conclusions

Observations at two bus lanes shared with bicyclists found that dangerous interactions between bicyclists and buses are relatively frequent at both locations. Dangerous overtaking manoeuvres (a bus overtakes a bicyclist with an insufficient lateral distance) as well as dangerous bicycle-following situations (a bus drives behind a bicyclist with a small time headway) are quite common at both observed bus lanes.

The analyses could not confirm the hypothesis that is made in a number of national road design guidelines that a sufficiently narrow bus lane (<3.5m) is safer than a medium-wide bus lane (3.5-4.5m). On the contrary, unsafe interactions even seem slightly more common at the narrow bus lane. Somewhat more dangerous overtaking manoeuvres seem to place at the narrower bus lane (33% of all overtaking manoeuvres, versus 21% of overtaking manoeuvres at the wider bus lane), but the difference is not statistically significant. Additionally, more interactions without overtaking (i.e., situations where a bus is driving behind a bicyclist but does not overtake) take place at the narrower bus lane. The results show that buses often maintain unsafe time headways in these situations; in 54% of these situations the time headway is less than 2s, and in 23% of the situations the time headway is even less than 1s.

The presence of a bus has an influence on the behaviour of the bicyclists. Bicyclists that get overtaken by a bus ride more closely to the edge of the road than bicyclists that are not in interaction with a bus. While the road design guidelines assume that bicyclists take up a width of one meter from the edge on bus lanes shared with bicyclists, the observations show that bicyclists take up much less space while being overtaken. The presence of a bus does not have a significant influence on the lateral stability of the bicyclist. There are also some indications that bicyclists who are involved in an interaction with a bus ride faster than bicyclists who are not involved in an interaction with a bus.

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