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How do drivers overtake cyclists?

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ABSTRACT

In Europe, the number of road crashes is steadily decreasing every year. However, the incidence of bicycle crashes is not declining as fast as that of car crashes. In Sweden, cyclists are the most frequently injured road users. Collisions between bicycles and motorized vehicles are of particular concern because the high speed and large mass of motorized vehicles create a high risk of serious injury to cyclists. In Sweden's urban areas, bicycle lanes keep bicycles separated from motorized vehicles, but on rural roads bicycle lanes are often absent, requiring drivers to interact with cyclists—usually by overtaking them. During this maneuver, drivers regulate speed and lateral position, negotiating with potential oncoming traffic to stay within their comfort zones while approaching and passing cyclists.

In this study an instrumented bicycle recorded 145 overtaking maneuvers performed by car and truck drivers on public rural roads in Sweden. The bicycle was equipped with a LIDAR and two cameras to assess how drivers approached and circumvented the bicycle. The collected data allowed us to identify four overtaking phases and quantify the corresponding driver comfort zones. The presence of an oncoming vehicle was the factor that most influenced the maneuver, whereas neither vehicle speed, lane width, shoulder width nor posted speed limit significantly affected the driver comfort zone or the overtaking dynamics.

1. Introduction

Today, cycling is becoming more and more popular in Europe and the U.S. (Pucher et al., 2011), raising new safety concerns. In 2013, 2019 cyclists died in Europe (CARE, 2015), and in Sweden cyclists are the most frequently injured type of road user (Trafikverket, 2014). The interaction between cyclists and motorists is of particular interest because severe injuries and deaths often occur in collisions between a cyclist and a motorized vehicle (Bil et al., 2010; Chaurand and Delhomme, 2013; Matsui and Oikawa, 2015). Injuries may be more severe on rural than urban roads (Boufous et al., 2012), where the vehicle's higher speed may make overtaking maneuvers particularly dangerous (Stone and Broughton, 2003). On urban roads motorists most commonly encounter cyclists at intersections, while driving at low speed. In contrast, on rural roads drivers are most likely to interact with cyclists during overtaking maneuvers, while driving considerably faster than cyclists (Walker, 2007).

Up to now, research on bicycle-overtaking maneuvers has used the minimum lateral clearance between the cyclist and the vehicle while the vehicle is passing as a surrogate measure for safety (Walker, 2007; Chapman and Noyce, 2012; Love et al., 2012; Mehta et al., 2015). Previous research showed how lateral clearance is influenced by infrastructure design (e.g. presence of bike lanes) (Chapman and Noyce, 2012; Frings et al., 2014; Mehta et al., 2015), the behavior of the cyclist (e.g. speed, steering angle, speed variation control) (Chuang et al., 2013), and the cyclist's appearance (such as outfit, gender and helmet wearing) (Walker, 2007; Chuang et al., 2013; Walker et al., 2014).

Although minimum lateral clearance while passing is definitely a key indicator of safety, an overtaking maneuver is a long and complex process which is not limited to the phase in which the vehicle moves parallel to the bicycle, so the maneuver cannot be fully described by transient lateral clearance alone. Previous research has suggested that overtaking comprises multiple phases. Shamir (2004) and Petrov and Nashashibi (2011) identified three phases in the behavior of the passing driver including diverting from lane, driving straight in the adjacent lane, and returning to the lane. Chuang et al. (2013) also proposed a three-phase classification, but unlike the previous two models mentioned, each phase has a fixed duration. A five-phase division, suggested by (Hegeman et al., 2005), classified phase changes according to the driver's intentions

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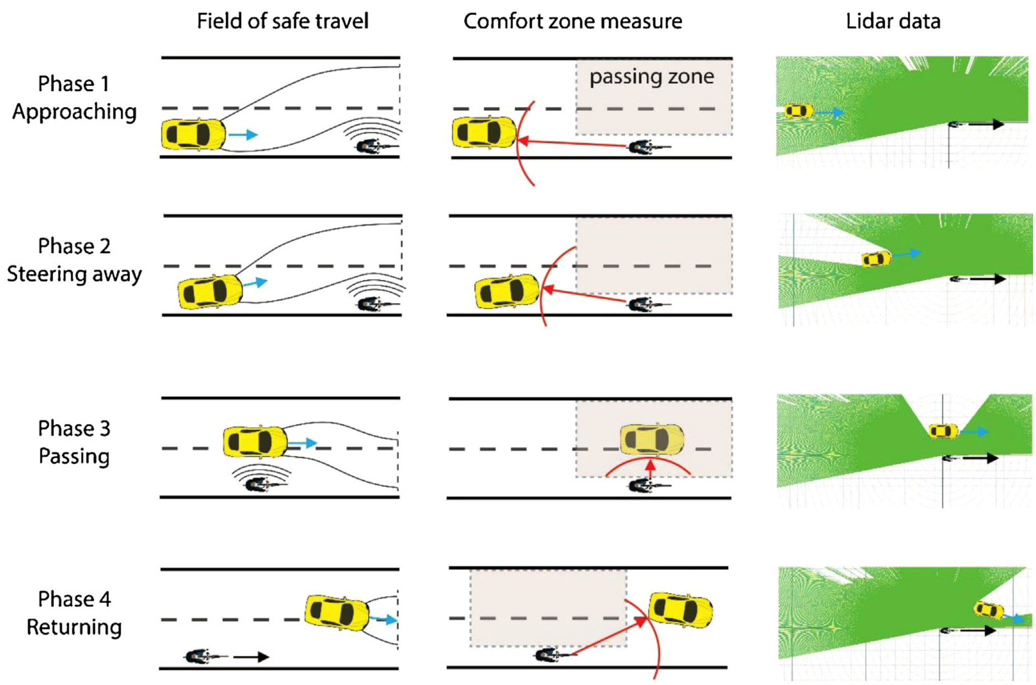

Fig. 1. The four phases in a car-to-bicycle overtaking maneuver. The representation of the field of safe travel was inspired by Gibson and Crooks (1938).

and actions. This division also included a decision and a preparation phase for the overtaking maneuver.

Whether based on three or five phases, classifications from previous research were often tailored to car-to-car overtaking and may not be appropriate to describe vehicle-to-bicycle overtaking. For instance, the use of a fixed phase duration (Chuang et al., 2013) does not seem practical as the lengths of the phases while overtaking a bicycle greatly vary depending on speed and vehicle length. Furthermore, the proposed three-phase classifications fail to consider the approaching phase, in which the driver gets closer to the cyclist and decides whether to overtake immediately (without slowing) or follow the cyclist for a while before overtaking. The five-phase definition from Hegeman et al. (2005) includes the approaching phase; however, since it is focused on improving the design of advanced assistance systems this classification strongly relies on information that is not always readily available such as turn-indicator use, steering angle, and current selected gear as well as on the knowledge of the driver's intention to overtake.

In this study, we used an instrumented electric bicycle equipped with a LIDAR to collect overtaking data on public rural roads in Sweden. Our data analysis validated a new four-phase classification for bicycle overtaking including an approaching, steering away, passing, and returning phase. This new classification extends the measures of clearance—previously only defined for the passing phase—to the entire maneuver. These clearance measures have been used to describe not only the driver comfort zone (Summala, 2007) during overtaking, but also how factors such as speed and oncoming traffic affect driver comfort zone and overtaking dynamics.

2. Materials and methods

2.1. Operational definition of overtaking phases

When overtaking, drivers are required to laterally and longitudinally control their vehicle to safely pass a slower road-user who is on a collision path. A typical overtaking between a motorized vehicle and a bicycle may take several seconds. During this time four consecutive phases may take place (Schindler and Bast, 2015). Overtaking starts with the motorized vehicle reaching the bicycle from behind (*approaching* phase; Fig. 1). When the driver starts to steer away to get out of the collision path, the approaching phase ends and the *steering away* phase starts (Fig. 1). The moment the driver enters the *passing zone* (an area about 5.7 m long, extending from 2 m behind the bicycle to 2 m in front of the bicycle), the steering away phase ends and the *passing* phase begins (Fig. 1). Finally, the driver leaves the passing zone, ending the passing phase and starting the *returning* phase (Fig. 1). The returning phase is over once the vehicle returns to the same lane position it had before the overtaking maneuver. The passing zone length was first provisionally calculated and subsequently verified on the collected data. The 2-m distances behind and in front of the bicycle guaranteed that parameters such as speed and lateral clearance were relatively constant within the phase and that drivers were parallel to the bicycle in the passing phase, while still ensuring that the steering away phase and passing phase had clear identities and reasonable durations. A distance longer than 2 m behind the cyclist could shorten the steering away phase too much, to as little as one data point. In these cases the motorist would still be steering away at the start of the passing phase and not yet driving parallel to the bicycle. A distance shorter than two meters could blend part of the passing phase into the steering away phase. In each of these four phases, the driver comfort zone may be measured as the distance between the bicycle and the vehicle. In this paper, the minimum distance in each overtaking phase was used to define the driver comfort zone boundaries (CZB) in an attempt to approximate key points in the driver's field of safe travel (Gibson and Crooks, 1938).

Three overtaking strategies were considered, according to Matson and Forbes (1938). The *flying* strategy, in which drivers overtake cyclists while keeping their speed relatively constant; the *accelerative* strategy, in which drivers slow down and follow the cyclist for some time before passing; and the *piggy backing* strategy, adopted by drivers who follow the lead driver, so that two or more cars in a row overtake the cyclists. The lead driver may have opted for either a flying or accelerative strategy (Matson and Forbes, 1938).

Fig. 2. Instrumented bicycle. The sensors that provided data for the analyses presented in this paper are highlighted.

2.2. Experimental setup

An instrumented electric bicycle (Fig. 2) was ridden on rural roads to record the overtaking maneuvers of motorized vehicles. This bicycle was previously used in the study by Dozza et al. (2015), and its hardware and software are fully described in Dozza and Fernandez (2014). However, this study only analyzed data from two cameras (one facing forward and one backward; 30 fps full HD), GPS (1 Hz), and a LIDAR system (Hokuyo UXM-30LXH-EWA; 20 Hz). A LIDAR is a sophisticated system consisting of a laser beam rotating at high speed to scan the environment (Olsen et al., 2013). LIDARs are often used to enable autonomous vehicles to detect obstacles and understand the environment (Berman, 2015). Electric bicycles are designed to maintain a constant speed; the bicycle was ridden at a steady 22 km/h, continuously monitored by the researcher from a bicycle computer while riding. Constant speed prevented the results from being confounded by the speed of the bicycle. Further, as electrical bicycles are increasingly common in Sweden and often travel at a constant speed of around 25 km/h (Dozza et al., 2015), this scenario seemed particularly relevant. Two researchers rode the bicycle on two rural roads in Västra Götaland, Sweden, in April 2015. Both roads had two lanes, one for each direction of travel, and no divider. The cyclists maintained a distance of 0.3 m from the curb. Figs. 3 and 4 show the two rural roads (each divided into sections), their main features, and two frames from the front and back cameras while the bicycle is being overtaken. The features lane width, shoulder width, and posted speed limit were recorded to test whether they influenced the CZB. Short sections of both rural roads were excluded from analysis because they either contained an intersection or were affected by temporary construction work; the excluded sections are reported in Figs. 3 and 4. During the rides, the researchers wore bicycle helmets (which is common practice in Sweden for adults, although legally required only for those under 15 years old). Five video clips are attached to this paper and show some representative examples of overtaking maneuvers from this dataset (see Supplementary Appendix).

2.3. Pilot tests

Before data collection, a pilot test was performed to select a position for the LIDAR that could capture as much of the overtaking maneuver as possible without influencing driver behavior. For this purpose, two mounting positions were tested: the back of the bicycle (Fig. 5a) or its left side (Fig. 5b). The first mounting position was expected to have less influence on driver behavior as it was very well disguised and integrated into the bicycle. The second position made better use of the LIDAR field of view, at the expense of being more obvious. The two positions were compared to see whether drivers kept a larger clearance when the bicycle was equipped with the more obvious installation.

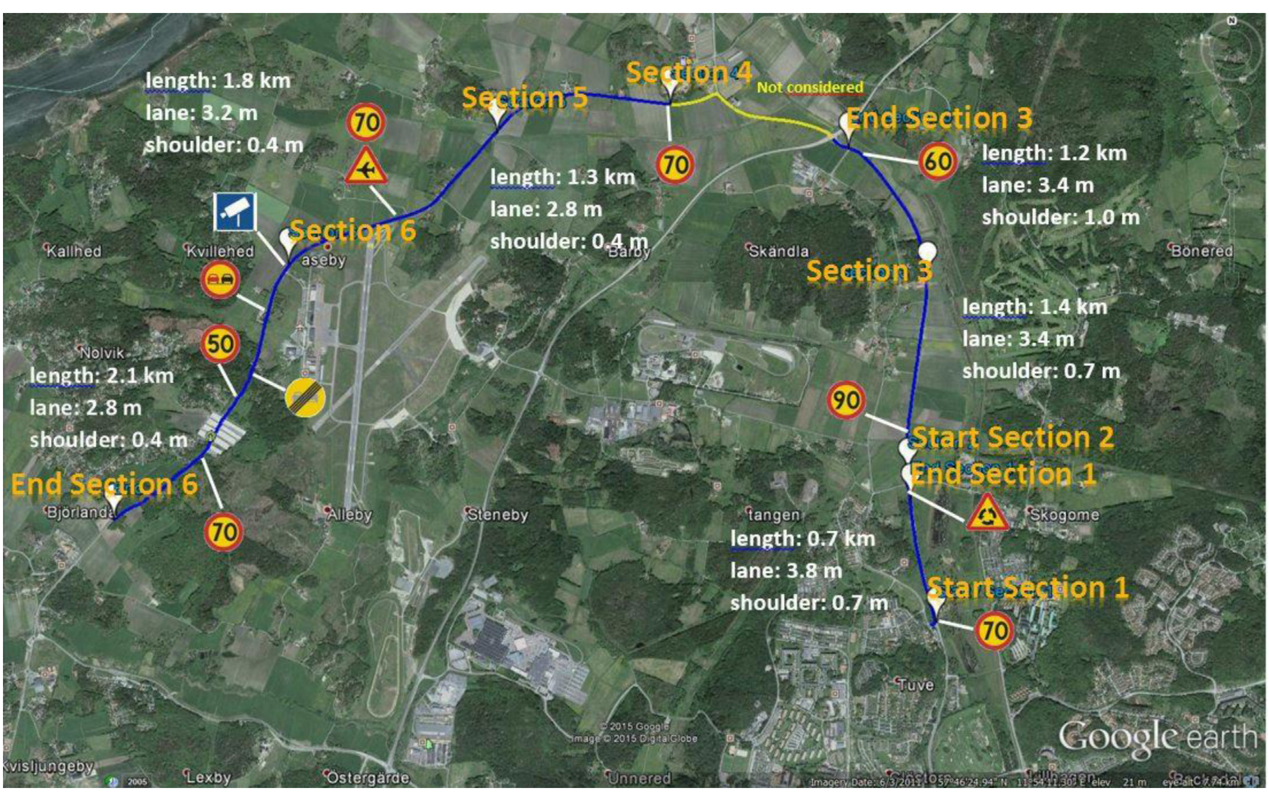

Fig. 3. Test road in Göteborg. Map from Google Earth provided by DigitalGlobe and Lantmäteriet/Metra. 0.3 km between section 1 and section 2 as well as 1.3 km between sections 3 and 4 were excluded from analysis.

Fig. 4. Test road in Vårgårda. Map from Google Earth provided by DigitalGlobe and Lantmäteriet/Metra. A view from the back and front cameras (left and right, respectively) of the instrumented bicycle is also presented. 0.2 km between section 4 and section 5 were excluded from analysis.

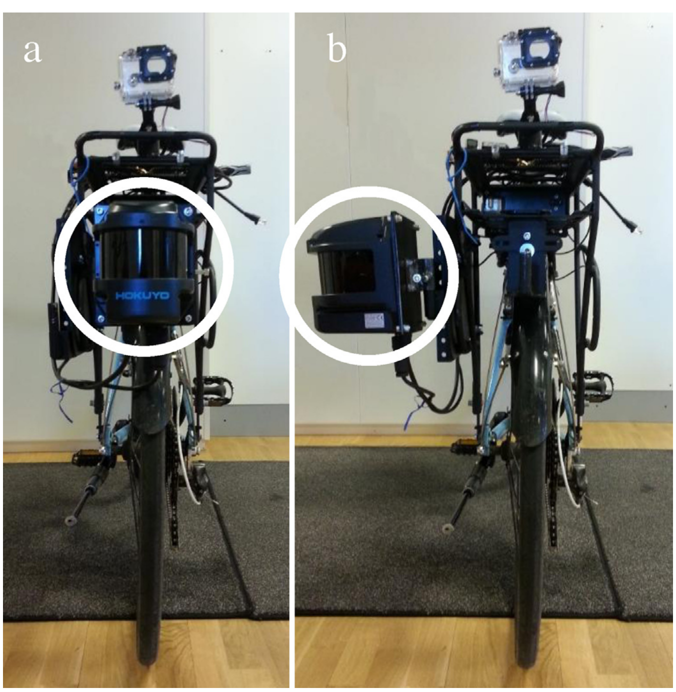

Fig. 5. Pilot test set-up with two different LIDAR mounting positions.

t-Tests verified that the lateral clearance during the passing phase for 47 overtaking maneuvers was not significantly different between the configurations in Fig. 5a and b (1.85 ± 0.47 vs 1.92 ± 0.51 m, respectively; $t = 0.48$ and $p = 0.63$). Therefore, the mounting position in Fig. 5b was selected because it made better use of the LIDAR field of view.

2.4. Data analysis

After data collection (51.0 km in Göteborg and 33.6 km in Vårgårda), all recorded overtaking maneuvers were reviewed to (1) define when each of the four phases started and ended; (2) calculate the CZB; and (3) visually code for the following variables: vehicle type (car, truck, bus, van, car with trailer), overtaking strategy (flying, accelerative, piggy backing), presence of oncoming traffic (yes, no), center line type (solid, dashed, warning[2]) and road section (numbered as illustrated in Figs. 3 and 4).

Maneuvers were coded as "flying" when there was no acceleration (positive or negative) of the vehicle distinguishable from the LIDAR or video data. If a significant change in speed during the approaching phase was observed, the maneuver was coded as "accelerative". The maneuver was coded as "piggy backing" when at least two vehicles in a row overtook the cyclist, and the longitudinal distance between the two vehicles was less than 60 m (corresponding to a time headway of approximately 2 s).

LIDAR data was used to identify the four phases for all overtaking maneuvers. Specifically, the approaching phase started when an overtaking vehicle entered the LIDAR field of view. At first, only the front of the vehicle appeared in the LIDAR data; when the side of the vehicle first became visible, it signaled the end of the approaching phase, since the vehicle had started steering away and was no longer on a collision path with the bicycle. This annotation was practical and did not require extensive manual annotation. However, it resulted in a slight, systematic overestimation of the approaching phase. Some of the overtaking maneuvers were analyzed in detail to determine the size of this exaggeration. It was found that a lateral displacement of about 0.2 m with a lateral

[2] A warning line (longer dashed lines) is often used in Sweden to signal areas with poor sight conditions; it is a recommendation to drive carefully and possibly not overtake.

Table 1
Timeline, duration, distances, and CZB for car accelerative overtaking (mean ± standard deviation). * indicates statistically significant difference ($p < 0.05$) with respect to the results for car flying overtaking in Table 2.

($n = 8$)	Start 1	1	1 → 2	2	2 → 3	3	3 → 4	4	End 4
Description	Vehicle detected by LIDAR	Vehicle approaching the bicycle from behind	Side of vehicle detected by LIDAR	Vehicle steering away from the curb	Vehicle entering passing zone	Vehicle passing the bicycle	Vehicle leaving passing zone	Vehicle returning to the initial lane position	Vehicle no longer detected by LIDAR
Timeline [s]	−12.60 ± 4.15		−2.51 ± 0.49		−0.81 ± 0.36	0	0.84 ± 0.26		3.69 ± 1.14
Duration [s]		10.09* ± 4.01		1.70* ± 0.52		1.65* ± 0.61		2.85 ± 0.95	
Distance [m]	70.66 ± 19.90		10.94 ± 4.34		2.80 ± 0.23		2.67 ± 0.27		27.84 ± 7.71
CZB [m]		10.94* ± 4.34		2.80 ± 0.23		2.03* ± 0.28		2.67 ± 0.27	

Table 2
Timing, duration, distances, and CZB for car flying overtaking (mean ± standard deviation). * indicates statistically significant difference ($p < 0.05$) with respect to the results for car accelerative overtaking in Table 1.

($n = 127$)	Start 1	1	1 → 2	2	2 → 3	3	3 → 4	4	End 4
Timeline [s]	−6.18 ± 2.22		−1.49 ± 0.43		−0.38 ± 0.11	0	0.45 ± 0.11		3.20 ± 1.28
Duration [s]		4.69* ± 2.06		1.11* ± 0.37		0.83* ± 0.22		2.75 ± 1.25	
Distance [m]	76.38 ± 21.07		16.14 ± 4.90		2.66 ± 0.35		2.54 ± 0.31		38.58 ± 15.67
CZB [m]		16.14* ± 4.90		2.66 ± 0.35		1.60* ± 0.49		2.54 ± 0.31	

velocity around 2.6 km/h may take place between the moment the vehicle steers away and the moment its side is visible from the LIDAR, resulting in overestimating the approaching phase duration by approximately 0.28 s. This small inaccuracy was not sufficient to justify the extra effort of a more precise annotation; nevertheless it should be considered when calculating safety-critical measures, such as time to collision.

Due to the relatively slow 20-Hz sample rate of the LIDAR, the exact moments in which the vehicle entered and exited the passing zone were rarely captured. In order to improve estimates of the passing phase's start and end, a linear interpolation of the vehicle's path was performed between the two points before and after the entry point and those before and after the exit point. For coding oncoming traffic, an area covering the opposite lane extending from 20 m behind the bicycle to 120 m in front of it was considered. Whenever a motorized vehicle was present in this area during the overtaking maneuver, oncoming traffic was coded as present.

Piggy backing maneuvers, maneuvers that were clearly influenced by unusual environmental factors (e.g. holes in the road, parked cars, intersections, other cyclists present), and maneuvers performed by driving school vehicles were excluded from the analyses.

t-Tests verified whether the coded variables significantly influenced phase duration and CZB. Correlation analyses tested whether (1) CZB measures were correlated across phases and (2) vehicle speed correlated to CZB.

3. Results

3.1. Vehicle type and overtaking strategy

Overall, 235 overtaking maneuvers were recorded during 5 h of data collection (84.6 km of cycling). Based on the criteria defined above, 67 maneuvers were excluded from the analysis, most of which (51) were piggy backing. Another 20 maneuvers by other, miscellaneous vehicles (buses, vans, and cars with trailers) were excluded because there were too few to constitute a statistically useful sample size. Finally, three accelerative overtaking maneuvers by trucks were excluded because such a small sample size would not provide any meaningful results. After exclusions 145 maneuvers remained for analysis, in three categories: 127 flying overtakes by cars, eight accelerative overtakes by cars, and ten flying overtakes by trucks. The timeline (time difference between a phase change and the time when the vehicle is next to the cyclist in the passing phase), the duration (time from start to end of a phase), the mean values for distance (distance from the closest point of the vehicle to the bicycle), and the comfort zone boundaries for each phase are reported in Tables 1–3 for car accelerative, car flying, and truck flying overtaking, respectively. It is worth noting that three of the values in each table are redundant across the last two rows: the CZBs in the approaching, steering away, and returning phases correspond to the distances at phase changes between (1) approaching and steering away, (2) steering away and passing, and (3) passing and retuning phase, respectively.

Car accelerative overtaking took longer (16.3 ± 4.6 s) than car flying overtaking (9.4 ± 2.8 s). Flying overtaking showed a significantly larger CZB in the approaching phase ($t = -2.93$; $p < 0.05$) and a significantly lower CZB in the passing phase ($t = 2.44$; $p < 0.05$) than accelerative overtaking. Phase duration was also significantly longer for accelerative than for flying overtaking in the approaching ($t = 3.78$; $p < 0.01$), steering away ($t = 4.27$; $p < 0.001$) and passing phases ($t = 3.75$; $p < 0.01$; Tables 1 and 2).

Truck flying overtaking maneuvers were 10.1 ± 3.4 s long, and their average speed was 72.3 ± 11.9 km/h (on average 4.6 km/h less than the posted speed limit) whereas car flying overtaking had an average speed of 69.6 ± 11.5 km/h (on average 8.6 km/h slower than the posted speed limit). CZBs were significantly larger for trucks than cars only in the approaching phase ($t = -2.30$; $p < 0.05$). Furthermore, cars spent less time than trucks in the passing phase ($t = -4.90$, $p < 0.001$; Table 3).

For all three types of maneuvers, CZBs in the approaching phase were not correlated to CZBs in the other three phases. However, CZBs in these latter phases were highly correlated with each other (Table 4). This result was the same if only flying maneuvers were considered.

3.2. Oncoming traffic, warning line, section features, and vehicle speed

CZBs were significantly larger when overtaking without oncoming traffic ($n = 99$) than when overtaking with oncoming traffic ($n = 28$) in all four phases ($t = -2.18$, $p < 0.05$; $t = -6.27$, $p < 0.001$; $t = -5.25$, $p < 0.001$; $t = -6.37$, $p < 0.001$; respectively). Fig. 6 shows the CZBs in all phases with and without oncoming traffic.

About one third of the car flying overtaking maneuvers were performed at a warning line. Only one maneuver was performed at a solid line. Only the CZB in the approaching phase showed a significant difference between overtaking with a warning line and

Table 3
Timing, duration, distances, and CZB for truck flying overtaking (mean ± standard deviation). * indicates statistically significant difference ($p < 0.05$) with respect to the results for car flying overtaking in Table 2.

($n = 10$)	Start 1	1	1 → 2	2	2 → 3	3	3 → 4	4	End 4
Timeline [s]	6.18 ± 2.90		2.07 ± 0.74		0.45 ± 0.11	0	−0.96 ± 0.42		−3.92 ± 1.30
Duration [s]		4.11 ± 2.81		1.62 ± 0.76		1.41* ± 0.44		2.96 ± 1.09	
Distance [m]	74.34 ± 22.58		24.65 ± 12.02		2.84 ± 0.31		2.61 ± 0.33		44.72 ± 17.49
CZB [m]		24.65* ± 12.02		2.84 ± 0.31		1.92 ± 0.44		2.61 ± 0.33	

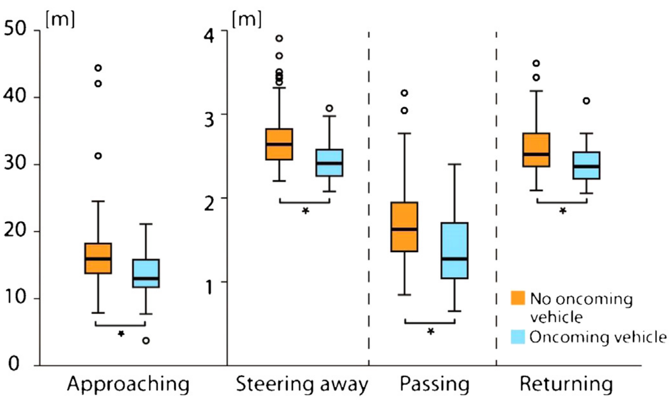

Fig. 6. CZB with respect to oncoming traffic in all overtaking phases. Box plots were generated with SPSS and indicate range (whiskers), first and third quartile (box edges) and median (bar in the middle of the box). Circles designate outliers. * signal statistically significant differences.

Table 4
Correlation coefficients among CZBs for all overtaking maneuvers and flying overtaking. * indicates statistical significance ($p < 0.001$).

r^2	Approaching	Steering away	Passing
Steering away	0.27*/0.31*	–	
Passing	0.18*/0.24*	0.93*/0.95*	–
Returning	0.17*/0.22*	0.78*/0.80*	0.86*/0.88*

overtaking at a dashed line (14.9 ± 3.2 m, and 16.8 ± 5.5 m, respectively; $t = -2.05$, $p < 0.05$).

Vehicle speed and CZB for car flying overtaking were not correlated ($r = 0.31$, $r = 0.13$, $r = 0.03$, $r = 0.12$, respectively for the four phases). However, this analysis could not be performed for car accelerative and truck flying overtaking because of their limited sample size. No effect of lane width, shoulder width, or speed limit was found on CZB.

4. Discussion

4.1. Overtaking dynamics and comfort zone boundaries

On Swedish rural roads, motorists overtake a cyclist in less than 10 s on average at a speed of about 70 km/h, passing the cyclist in less than 2 s. Passing may take a few seconds longer when the vehicle slows down before passing (accelerative overtaking), or when the motor vehicle is a truck (since trucks are longer than cars). In any case, the passing phase leaves little time for a road user to react in a critical situation (if, for instance, the cyclist suddenly changes course to avoid a pothole). Thus, safely passing a cyclist depends on the driver preparing appropriately for the approaching and steering away phases of the overtaking maneuver.

Time to collision is an important indicator of criticality in normal driving situations. Time to collision can be estimated by dividing the minimum distance in the approaching phase (Tables 2 and 3) by the relative speed between the car and the bicycle, and adding 0.28 s to take into account a possible overestimation of the approaching phase (as explained in Section 2.4). During flying overtaking, car drivers deviate from the collision path with the cyclist on average 16 m before the collision, corresponding to an average time to collision of approximately 1.6 s, which is critical in normal driving situations. Thus, by the time a motorist starts to steer away to circumvent the bicycle, vehicle dynamics are such that, in an emergency situation (e.g. cyclist falling, swerving toward the middle of the lane, or starting to cross the lane to turn), sudden application of full braking would be necessary to try to avoid the collision. Time to collision was on average 0.6 s longer for trucks than for cars during flying overtaking, probably because the longer the vehicle the more lateral maneuvering is anticipated.

Lateral clearance was larger in accelerative maneuvers possibly because drivers who had larger CZBs were also more likely to slow down before overtaking, especially if there was oncoming traffic. Nevertheless, the presence of oncoming traffic did not prevent overtaking. On the contrary several overtaking maneuvers were performed with oncoming traffic, resulting in narrower CBZs in all phases, making these overtaking maneuvers more critical at least from a cyclist's standpoint. When oncoming traffic was present, drivers often passed the cyclist with a lateral clearance of less than 1.5 m (or even less than 1 m in some cases). Although Swedish law does not set a minimum lateral clearance for overtaking, in most European countries overtaking a cyclist with less than 1.5 m clearance is unlawful. Several states in the U.S. enforce a similar three-foot bicycle-passing law. Thus this study shows that drivers do not always leave an appropriate clearance when passing cyclists, in agreement with other studies from different geographical locations (Mathie et al., 2004; Chuang et al., 2013; Llorca et al., 2014; Walker et al., 2014). Furthermore, this study also shows the drastic influence of oncoming traffic on lateral clearance and other CZBs that previous studies did not address.

The presence of a warning line corresponded with an increase in the driver CZB in the approaching phase only. Since warning lines are painted to indicate areas with lower visibility, this result most likely reflects the effect of visual occlusion on CZB. Decreased visibility would solely affect the decision time and planning of the overtaking, which take place in the approaching phase.

Counterintuitively, lane width, shoulder width, posted speed limit and vehicle speed did not influence CZB. Although lane width was previously found to influence CZB in the passing phase (this is equivalent to lateral clearance; Love et al., 2012), it may be that our study found no significant influence because other factors, such as oncoming traffic, played a much larger role. As for vehicle speed, it seems reasonable that it would correlate with CZB, and it is obviously correlated with the posted speed limit. However, Mehta et al. (2015) have already found that lateral clearance and speed are not related, supporting our finding that neither vehicle speed nor posted speed limit is related to CZB. Taken together, these results suggest that there may be a perception mismatch between different road users during overtaking; drivers do not seem to perceive that higher speeds require larger clearances to maintain comfort, but cyclists clearly have this expectation (Llorca et al., 2014). These results are important because incorrect expectations about the interaction between cyclists and drivers have been shown to cause bicycle accidents (Summala et al., 1996; Räsänen and Summala, 1998; Wood et al., 2009). Moreover, when cyclists do not feel safe they are more likely to adopt cycling avoidance as a coping strategy (Chataway et al., 2014), independently of whether their perception of safety is accurate (Wood et al., 2013). Finally, the discrepancy between perceived and objective safety may result in dangerous behaviors (Chaurand and Delhomme, 2013).

4.2. Methodology

The LIDAR used in this study proved to be a valuable sensor to monitor and analyze overtaking maneuvers. In comparison with previous studies using cameras (Love et al., 2012), ultrasonic sensors (Walker, 2007; Chuang et al., 2013), or laser sensors (Llorca et al., 2014), this study was able to measure the position of the vehicle with accuracy and resolution during the whole overtaking maneuver. In this way, this study could calculate the CZB not only for the passing phase (lateral clearance) as previous studies have done, but also during the rest of the overtaking maneuver.

This study divided the overtaking maneuver into four phases and measured each phase's CZB, providing new insights into how drivers overtake cyclists. It is apparent that the four measures of CZB were sensitive to different factors. Nevertheless three of the CZB measures, corresponding to the steering away, passing, and returning phases, were highly correlated, suggesting that the CZBs in these phases depend on some common factor, which is most likely to be the joint driver-vehicle system (Ljung, Aust & Engström, 2011). This correlation was maintained even when flying overtaking was considered alone.

Motorist-to-cyclist overtaking maneuvers may also be measured with an instrumented car. An instrumented car could provide more reliable information about the maneuver's beginning and end (radar in front and rear, respectively) as well as the transition between the approaching and steering away phases and the passing and returning phases (steering angle). However, the car would still need other sensors (such as the LIDAR used in this study) to cover the vehicle surroundings and measure the CZB. Thus, capturing the same overtaking maneuvers from a drivers' perspective would require a more expensive setup. Future studies could combine instrumented bicycles and motorized vehicles to provide a more complete picture of the overtaking maneuver, including information on driver behavior and demographics.

4.3. Limitations

The main limitation of this study is that it is not known who overtook the bicycle. Even if the drivers overtaking the bicycle were representative of the Swedish population, it is unknown how driver characteristics influenced our results. Not all drivers drive in the same way (Sagberg et al., 2015) and not all drivers overtake in the same way (Wilson and Best, 1982); for instance, safer drivers may have contributed more accelerative maneuvers and sensation seekers may be responsible for the most critical overtaking maneuvers analyzed in this study. In addition, although it was found that the presence of oncoming traffic influences the CZB, the extent to which the speed and distance of oncoming traffic affect a driver's decision to overtake a cyclist was not investigated.

Besides the obvious geographical limitation of this study, some technical issues are worth a mention. Cyclists experience periodic accelerations in the longitudinal and lateral direction while riding (Dozza and Fernandez, 2014). The lateral movement is of particular concern, as tilting the LIDAR up and down results in increasing or reducing the recorded distances, respectively. In fact the greater the distance, the larger the effect of tilting the LIDAR. Fortunately, the CZBs were measured when the vehicle was already so close to the bicycle that the tilt did not result in a large distance error. Nevertheless the transition points between the approaching and passing phases and the passing and returning phases may have been slightly affected, whereas distances in the longitudinal direction were not likely to be affected.

The definition of the passing zone influenced the CZB, which also explains why some of the results in Tables 1–3 are redundant across the last two rows. The shorter the passing zone, the smaller the CZB in the steering away and returning phases, and vice versa. In this study we found that a 2-m distance behind and in front of the bicycle was the best compromise in terms of defining the passing zone because (1) it made it possible to identify steering away and passing zones that had reasonable durations for all overtaking maneuvers (accelerative and flying, for cars and for trucks) and (2) the steering away phase captured the period in which the motor vehicle was not moving in a purely longitudinal direction, while the passing phase included the period of time when the vehicle was moving essentially parallel to the cyclist. New studies addressing urban roads or non-moving cyclists may need to adjust the definition of the passing zone accordingly.

In this study, multiple tests were performed without correcting the threshold for statistical significance. A conservative approach would be to decrease the threshold for significance as the number of tests increases, for instance by dividing it by the number of tests (Holm, 1979). However, this procedure may not be appropriate when variables are correlated and multiple tests are not independent, which is the case in this paper. In addition, most of the p values in this study were well below 0.01, making these results robust to correction for multiple tests.

5. Conclusions

Maneuvers in which a driver overtakes a cyclist on a rural road are indeed critical; they happen at high speed (approx. 70 km/h), in a short time (10–16 s), and with little time to avoid a collision (usually less than 2 s) if unforeseen events occur. In addition, the safety of overtaking depends on proper planning and correct anticipation of potential critical situations from the driver side.

Understanding the effect of oncoming vehicles is critical to understanding the dynamics of overtaking maneuvers. When an oncoming vehicle is present, drivers change their CZB, driving significantly closer to the cyclist not only when passing her/him but also when approaching and circumventing the cyclist.

Driver CZBs are also influenced by visibility, but not by vehicle speed. This latter result shows that drivers' and cyclists' perceptions of the same situation may be different, as a cyclist would expect a larger clearance when overtaken faster. As a safe interaction between cyclists and motorists is largely based on common understanding and expectation of the traffic situation, this result clearly exemplifies a particularly challenging cyclist–motorist interaction with great implications for safety and mobility.

In light of these results, policies, campaigns, and training programs should help drivers understand that how cyclists perceive safety while being overtaken depends on clearances (both lateral and longitudinal) and speed. As posted speed increases infrastructure design should incorporate larger clearances for overtaking cyclists on urban roads, possibly recommending a minimum clearance that depends on the posted speed. Additionally, designers of advanced driving assistance systems should take the findings of this paper into account to support drivers while overtaking (Hegeman, 2004). These systems could use proximity sensors around the vehicle to help drivers keep an appropriate distance from cyclists in all phase of the overtaking maneuver especially when oncoming traffic is present.

A LIDAR sensor mounted on an instrumented bicycle provided continuous and high-resolution information about the whole overtaking maneuver, making it possible to identify and analyze four critical phases of the overtaking maneuver along with their corresponding CZBs. Thanks to the use of the LIDAR, this work extended previous studies, which were limited to measuring lateral clearance in the passing phase, by providing a more accurate and complete picture of the overtaking maneuver.

The definition of a four-phase overtaking, together with the quantification of the corresponding timing, dynamics, and CZBs presented in this paper, can guide the development of advanced driving assistance systems and autonomous driving. In fact, the results presented in this paper can be used to determine whether a maneuver is more or less comfortable for a driver (by the size of the comfort zone) and the extent to which the surroundings determine which strategy (i.e. accelerative or flying) is employed.

Future studies should investigate the extent to which driver characteristics (such as gender, age, driving style, etc.), driver behaviors (such as gaze, secondary tasks, etc.), and speed and distance of the oncoming traffic may influence CZBs and overtaking dynamics. Using an instrumented car, with sensors such as lane and gaze trackers, in combination with the instrumented bicycle may help validate the data from the instrumented bicycle, and complete the picture by providing more data on driver characteristics and behavior.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.aap.2015.12.008.

References

Berman, B., 2015. Lower-cost lidar is key to self-driving future. Automotive Engineering Magazine, SAE.

Bil, M., Bilova, M., Muller, I., 2010. Critical factors in fatal collisions of adult cyclists with automobiles. Accid. Anal. Prev. 42 (6), 1632–1636.

Boufous, S., De Rome, L., Senserrick, T., Ivers, R., 2012. Risk factors for severe injury in cyclists involved in traffic crashes in Victoria, Australia. Accid. Anal. Prev. 49, 404–409.

Care, 2015. Fatalities by Transport Mode (No Cars) in 2013, Available at http://ec.Europa.Eu/transport/road_safety/pdf/statistics/2013_transport_mode_except_cars.Pdf (accessed August 2015).

Chapman, J.R., Noyce, D.A., 2012. Observations of driver behavior during overtaking of bicycles on rural roads. Transp. Res. Rec. (2321), 38–45.

Chataway, E.S., Kaplan, S., Nielsen, T.A.S., Prato, C.G., 2014. Safety perceptions and reported behavior related to cycling in mixed traffic: a comparison between Brisbane and Copenhagen. Transp. Res. Part F: Traffic Psychol. Behav. 23, 32–43.

Chaurand, N., Delhomme, P., 2013. Cyclists and drivers in road interactions: a comparison of perceived crash risk. Accid. Anal. Prev. 50, 1176–1184.

Chuang, K.H., Hsu, C.C., Lai, C.H., Doong, J.L., Jeng, M.C., 2013. The use of a quasi-naturalistic riding method to investigate bicyclists' behaviors when motorists pass. Accid. Anal. Prev. 56, 32–41.

Dozza, M., Fernandez, A., 2014. Understanding bicycle dynamics and cyclist behavior from naturalistic field data (November 2012). IEEE Trans. Intell. Transp. Syst. 15 (1), 376–384.

Dozza, M., Piccinini, G.F.B., Werneke, J., 2015. Using naturalistic data to assess e-cyclist behavior. Transp. Res. Part F: Traffic Psychol. Behav.

Frings, D., Parkin, J., Ridley, A.M., 2014. The effects of cycle lanes, vehicle to kerb distance and vehicle type on cyclists' attention allocation during junction negotiation. Accid. Anal. Prev. 72, 411–421.

Gibson, J.J., Crooks, L.E., 1938. A theoretical field-analysis of automobile-driving. Am. J. Psychol. 51, 453–471.

Hegeman, G., 2004. Overtaking frequency and advanced driver assistance systems. In: 2004 IEEE Intelligent Vehicles Symposium, pp. 431–436.

Hegeman, G., Brookhuis, K., Hoogendoorn, S., 2005. Opportunities of advanced driver assistance systems towards overtaking. Eur. J. Transp. Infrastruct. Res. 5 (4).

Holm, S., 1979. A simple sequentially rejective multiple test procedure. Scand. J. Stat. 6 (2), 65–70.

Ljung Aust, M., Engström, J., 2011. A conceptual framework for requirement specification and evaluation of active safety functions. Theoret. Iss. Ergon. Sci. 12 (1), 44–65.

Llorca, C., Angel-Domenech, A., Agustin-Gomez, F., Ferrer, V., Garcia, A., 2014. Motor vehicles overtaking cyclists on two-lane rural roads: Analysis on speed and lateral clearance. In: International Cycling Safety Conference 2014, Göteborg, 18–19 November.

Love, D.C., Breaud, A., Burns, S., Margulies, J., Romano, M., Lawrence, R., 2012. Is the three-foot bicycle passing law working in Baltimore, Maryland? Accid. Anal. Prev. 48, 451–456.

Mathie, M.J., Coster, A.C., Lovell, N.H., Celler, B.G., 2004. Accelerometry: providing an integrated, practical method for long-term, ambulatory monitoring of human movement. Physiol. Meas. 25 (2), R1–R20.

Matson, T., Forbes, T., 1938. Overtaking and passing requirements as determined from a moving vehicle. In: Proceedings of the Highway Research Board Proceedings, pp. 100–112.

Matsui, Y., Oikawa, S., 2015. Features of Fatal Cyclist Injuries in Vehicle-Versus-Cyclist Accidents in Japan. SAE Technical Paper.

Mehta, K., Mehran, B., Hellinga, B., 2015. Analysis of lateral distance between motorized vehicles and cyclists during overtaking maneuvers. In: Proceedings of the Transportation Research Board 94th Annual Meeting.

Olsen, M.J., Roe, G.V., Glennie, C., Persi, F., Reedy, M., Evans, D., Hurwitz, D., Williams, K., Tuss, H., Sequellati, A., Knodler, M., 2013. In: Board, T.R. (Ed.), NCHRP Report 748, Guidelines for the Use of Mobile Lidar in Transportation Applications. , Appendix A.

Petrov, P., Nashashibi, F., 2011. Planning and nonlinear adaptive control for an automated overtaking maneuver. In: 2011 14th International IEEE Conference on Intelligent Transportation Systems (ITSC), pp. 662–667.

Pucher, J., Buehler, R., Seinen, M., 2011. Bicycling renaissance in north america? An update and re-appraisal of cycling trends and policies. Transp. Res. Part A: Policy Pract. 45 (6), 451–475.

Räsänen, M., Summala, H., 1998. Attention and expectation problems in bicycle–car collisions: an in-depth study. Accid. Anal. Prev. 30 (5), 657–666.

Sagberg, F., Piccinini, G.F.B., Engström, J., 2015. A review of research on driving styles and road safety. Hum. Fact., 0018720815591313.

Schindler, R., Bast, V., (Master thesis) 2015. Drivers' Comfort Boundaries When Overtaking a Cyclist: Set-up and Verification of a Methodology for Field Data Collection and Analysis. Technology, C.U.O., Gothenburg.

Shamir, T., 2004. How should an autonomous vehicle overtake a slower moving vehicle: design and analysis of an optimal trajectory. IEEE Trans. Autom. Control 49, 607–610.

Stone, M., Broughton, J., 2003. Getting off your bike: cycling accidents in Great Britain in 1990–1999. Accid. Anal. Prev. 35 (4), 549–556.

Summala, H., 2007. Towards understanding motivational and emotional factors in driver behaviour: comfort through satisficing. In: Cacciabue, P.C. (Ed.), Modelling Driver Behaviour in Automotive Environments. Springer, London, pp. 189–207.

Summala, H., Pasanen, E., Rasanen, M., Sievanen, J., 1996. Bicycle accidents and drivers' visual search at left and right turns. Accid. Anal. Prev. 28 (2), 147–153.

Trafikverket, 2014. Säkrare cykling –gemensam strategi för år 2014-2020. PN Trafikverket.

Walker, I., 2007. Drivers overtaking bicyclists: objective data on the effects of riding position, helmet use, vehicle type and apparent gender. Accid. Anal. Prev. 39 (2), 417–425.

Walker, I., Garrard, I., Jowitt, F., 2014. The influence of a bicycle commuter's appearance on drivers' overtaking proximities: an on-road test of bicyclist stereotypes, high-visibility clothing and safety aids in the United Kingdom. Accid. Anal. Prev. 64, 69–77.

Wilson, T., Best, W., 1982. Driving strategies in overtaking. Accid. Anal. Prev. 14 (3), 179–185.

Wood, J.M., Lacherez, P.F., Marszalek, R.P., King, M.J., 2009. Drivers' and cyclists' experiences of sharing the road: incidents, attitudes and perceptions of visibility. Accid. Anal. Prev. 41 (4), 772–776.

Wood, J.M., Tyrrell, R.A., Marszalek, R., Lacherez, P., Carberry, T., 2013. Bicyclists overestimate their own night-time conspicuity and underestimate the benefits of retroreflective markers on the moveable joints. Accid. Anal. Prev. 55, 48–53.