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Influence of oncoming traffic on drivers' overtaking of cyclists

Giulio Francesco Bianchi Piccinini [a,*], Claudia Moretto [b], Huiping Zhou [c], Makoto Itoh [c]

[a] Department of Applied Mechanics, Chalmers University of Technology, Gothenburg, Sweden
[b] Department of Civil Engineering, University of Bologna, Bologna, Italy
[c] Department of Risk Engineering, University of Tsukuba, Tsukuba, Japan

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ABSTRACT

Active transportation - such as cycling - can provide health benefits to the population. However, cycling safety remains a major threat to favour the use of bicycles and, for this reason, more efforts are needed to reduce the number of crashes involving cyclists. One crash scenario which deserves special attention is driver's overtaking of cyclists since it has an increased likelihood to lead to severe injuries. During the overtaking manoeuvre, the monitoring of subjective risk can influence the decision-making process and lead to different outcomes. In this context, the present driving simulator study aims to investigate how the time to collision between oncoming traffic and subject vehicle affected the overtaking strategy, and the minimum safety margins towards the overtaken cyclist. The results show that a decrease in time to collision against the oncoming vehicle significantly affects the drivers' overtaking strategy (accelerative vs. flying), inducing more drivers to choose an accelerative overtaking manoeuvre. The decrease in time to collision also produces a decrease in minimum safety margins to the cyclists for drivers who opt for a flying overtaking strategy. Finally, the current research shows that the minimum lateral safety margins were smaller and the mean speed higher in flying manoeuvres compared to accelerative manoeuvres. Overall, the combination of lower safety margins and higher mean speeds in flying overtaking manoeuvres seems to pose a risk for cyclists' safety. The findings of the study provide some implications for the design of automated driving.

1. Introduction

The promotion of cycling brings health benefits for citizens of all age groups and to further favour the use of bicycles, special attention should be dedicated to cycling safety (Götschi, Garrard, & Giles-Corti, 2016). Although most countries have, over the years, reduced cyclist fatality rates per capita and per kilometre, serious injuries data show smaller declines or even increases in rates per kilometre (Buehler & Pucher, 2017). Those serious injuries are mostly the result of single bicycle crashes or crashes in which a cyclist collides with a motorized vehicle (Björnberg, 2016; Schepers, Stipdonk, Methorst, & Olivier, 2017). With respect to the latter category, situations when a motorist may overtake a slower cyclist have an increased likelihood to lead to severe injuries (Stone & Broughton, 2003). In Japan – which is the country of interest for this paper – the Institute for Traffic Accident Research and Data Analysis (ITARDA) reported 9210 vehicle-cyclist crashes on the

* Corresponding author at: Chalmers University of Technology, Department of Applied Mechanics Department, Division of Vehicle Safety, Crash Analysis and Prevention group, Lindholmspiren 3, Lindholmen Science Park, 41756 Gothenburg, Sweden.
E-mail address: giulio.piccinini@chalmers.se (G.F. Bianchi Piccinini).

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roads, during 2016 (ITARDA, 2018). Among the different crash configurations, crashes during overtaking of cyclists represented 20% of the overall dataset and, therefore, deserve the attention of cycling safety researchers.

In addition to objective risk, the overtaking of a slower vehicle against oncoming traffic also involves subjective risk (Farah, Bekhor, & Polus, 2009; Van der Molen & Bötticher, 1988) which is a key aspect influencing drivers' decision making according to the zero-risk theory (Näätänen & Summala, 1974). During driving, individuals try to minimize their risk by choosing sufficient margins to potential hazards to feel safe and comfortable (Summala, 2007). In other words, drivers strive to remain within comfort zones during the driving task as they do during the interactions with other individuals (Hall, 1966). However, together with other factors, the perception of subjective risk (e.g. risk associated to a possible collision with oncoming traffic) might influence the boundaries of the comfort zones and the corresponding safety margins selected by the drivers (Näätänen & Summala, 1974).

Previous studies about driver's overtaking with oncoming traffic showed that errors during the manoeuvre mainly concern misjudgements of the speed of the approaching vehicle and, partly, of the distance to both the oncoming vehicle and the overtaken vehicle (Hills, 1980). Notably, unsafe overtaking manoeuvres can be caused by the fact that some drivers use the distance to the oncoming vehicle as a control variable for the decision to overtake while temporal variables such as the time to collision (TTC) or the time required to overtake (TRO) would be more meaningful (Gray & Regan, 2005). Previous research also showed that errors in overtaking manoeuvres might be due to unexpected hazards during the overtaking (e.g. oncoming traffic coming into view during overtaking), which can lead to some modifications or even to a drastic change of the initial manoeuvring plan (Clarke, Ward, & Jones, 1999). With respect to that, it was found in a real traffic study that the overtaking driver reduces the longitudinal and lateral safety margins to the overtaken vehicle when an oncoming car is suddenly appearing in the opposite lane with a time headway inferior to 4 s (Papakostopoulos, Nathanael, Portouli, & Marmaras, 2015).

To the knowledge of the authors, there is a lack of similar studies focusing on drivers' overtaking of cyclists. As a matter of fact, previous research has investigated safety margins during overtaking of cyclists (Chapman & Noyce, 2012; Dozza, Schindler, Bianchi Piccinini, & Karlsson, 2016; Feng, Bao, Hampshire, & Delp, 2018; Llorca, Angel-Domenech, Agustin-Gomez, & Garcia, 2017; Mehta, Mehran, & Hellinga, 2015; Walker, 2007) but no study has been conducted to investigate the influence of oncoming traffic on the decision-making process and on the selection of safety margins in such manoeuvres. The present study aims to investigate the matter in Japan, through a driving simulator study.

2. Material and methods

2.1. Apparatus

The study was conducted during November-December 2015 in the driving simulator at the University of Tsukuba (Fig. 1). The driving simulator was equipped with steering wheel, accelerator pedal, brake pedal and gearshift, although the participants were not requested to change gear since the vehicle worked on automatic transmission modality. The driving scene was shown on five screens covering about 180 degrees field of view: the angle between the front monitor and the left/right monitors was 45 degrees. The driver eyes' were located about 140 cm from the front screen and the image of the rear field of view was displayed to the driver through the center mirror and the side mirrors. During the experiment, two video cameras were activated to record the driver's face and the forward roadway.

Fig. 1. Image of the driving simulator used for the experiment.

2.2. Procedure

Once arrived at the site of the driving simulator study, the participants were given general information about the research conducted and the tasks they had to perform. They were communicated that the participation is voluntary and that they were free to withdraw from the driving simulator study at any moment, without the need to present explanations to the research team. They were also informed about the use of personal data collected during the experiment and images recorded with the video cameras. After the introductory session, the participants were requested to sign a form to confirm their understanding of the information provided and to consent the use of the collected data. As well, they were requested to fill a questionnaire to acquire demographic data (e.g. age, gender, driving experience).

The overall experiment was planned to create a driving environment as similar as possible to the field study conducted by Dozza et al. (2016) on a Swedish rural road outside Gothenburg. Therefore, we designed the layout of the simulated route using stretches of the road where Dozza et al. (2016) performed their field test. The resulting driving environment included three drives on three different routes named *Trial route*, *Route 1* and *Route 2*. All the three drives were conducted on a two-lanes rural road (one for each direction of travel), without divider, with lane width equal to 3.2 m and shoulder of 0.4 m. Since the average driving speed of cars during flying overtaking manoeuvres was 69.6 km/h in Dozza et al. (2016), the participants of our driving simulator study were requested to keep the speed of the vehicle as close as possible to 70 km/h. Besides, the vehicle speed was limited to 80 km/h during the whole experiment to avoid overspeeding. Once the participants had completed the 3 drives, the experimenter had a briefing with the subjects and, after that, the participants were sent out.

The *Trial route* was long about 12 km and its main purpose was to make the participants comfortable in the driving simulator, to make them used to maintain the speed at 70 km/h, and to familiarise with the scenery and the overtaking of cyclists: the subjects experienced eight overtaking manoeuvres of cyclists, four with oncoming traffic and four without oncoming traffic.

The *Route 1* was long about 9 km and required the drivers to perform four overtaking manoeuvres of cyclists without oncoming traffic: during this route, the drivers could complete the overtaking manoeuvre without any restrictions from the external environment.

Finally, *Route 2* – which will be the focus of this paper – was long about 16 km and included eight overtaking manoeuvres with oncoming traffic (Fig. 2). All overtaking manoeuvres occurred in straight stretches of road with good visibility and in presence of broken centre line. Also, all the participants experienced the eight overtaking situations in the same order to control for confounding factors associated to the road characteristics (e.g. length of the straight stretches of the road during the overtaking manoeuvre). Since the participants had already driven along *Trial route* and *Route 1*, we expected marginal changes in participants' behaviour due to the lack of counterbalance in the order of the manoeuvres of *Route 2*.

The cyclists to be overtaken by the participants were standing still until the vehicle driven by the participant had reached a longitudinal distance of 100 m from the bicycle: in that moment, the bicycles started to move with constant speed of 22 km/h and maintained a constant distance of 0.3 m from the curb of the road. Besides, the oncoming vehicle was standing still until the distance between the subject and oncoming vehicles reached a given value (Table 1), chosen after conducting several pilot tests. Once the oncoming vehicle started moving, its speed varied according to the speed of the subject vehicle to ensure a specific TTC – hereafter named 'nominal TTC' – when the subject vehicle was 50 m distant from the bicycle

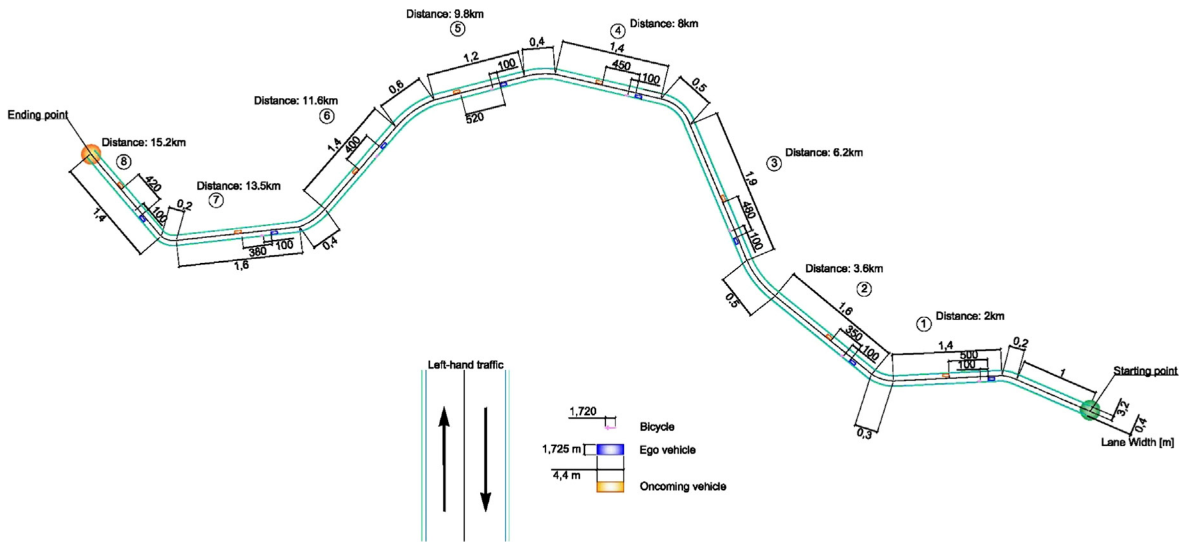

Fig. 2. Layout of the experimental route, including the start and end of the route and the positions of the bicycles and the oncoming vehicles at the time when they started moving (N.B.: vehicles in Japan travel according to left-hand traffic).

Table 1
Distance and nominal TTC between oncoming and subject vehicle in the eight overtaking manoeuvres of *Route 2*.

Overtaking number	1	2	3	4	5	6	7	8
Distance between oncoming and subject vehicle [m]	500	350	480	450	520	400	380	420
Nominal TTC [s]	9.0	6.0	8.5	8.0	9.5	7.0	6.5	7.5

Fig. 3. Image of the virtual environment during overtaking manoeuvre.

(Table 1). Although not optimal with respect to the realism of the driving environment, the decision to have both the bicycle and the oncoming vehicle standing still when the subject vehicle was approaching was made to guarantee more experimental control.

An image of the virtual environment is reported in Fig. 3 and shows both the bicycle travelling on the left side and the oncoming vehicle travelling in the other lane. During the trial, the drivers could decide to slow down and let the oncoming vehicle leave the overtaking zone (shown in Fig. 4) before performing the overtaking (*accelerative* overtaking strategy) or to complete the manoeuver while keeping their speed relatively constant and before the oncoming vehicle left the overtaking zone (*flying* overtaking strategy).

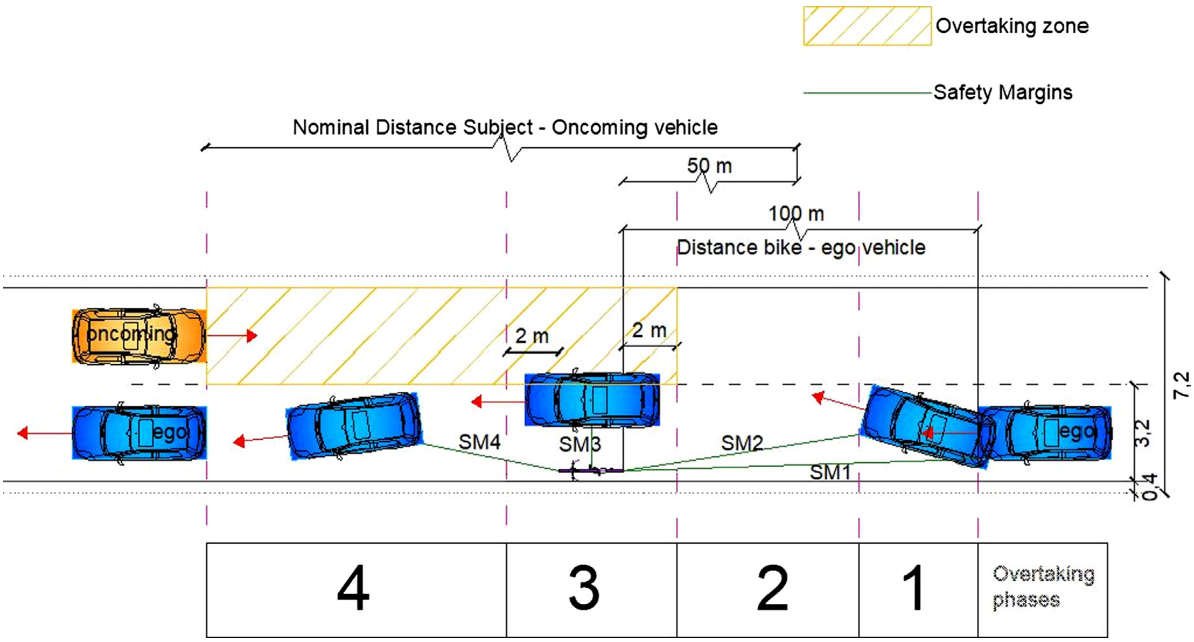

Fig. 4. Phases and safety margins during the overtaking manoeuvre.

2.3. Participants

The participants were recruited through an external agency which looked for participants meeting the following requirements:

- Be a Japanese national.
- Own a driving license.
- Be in one of the following age ranges: 25–40 years old or 65–75 years old.

The last requirement was included to perform analyses based on age group which will not be the focus of this paper. Overall, 42 participants took part in the experiment but three subjects were excluded after the ride on the simulator: one participant experienced simulation sickness before concluding the drives and two participants drove with the clear interest to complete the experiment as soon as possible, regardless of the experimental protocol. During the analyses of Route 2, three additional participants were removed from the sample because part or the totality of their data were missing. Hence, the remaining sample included 36 participants whose demographic information is reported in Table 2.

2.4. Analysis

The analyses reported in the next chapter will focus on *Route 2* and exclusively consider the first 7 overtaking manoeuvres described in Table 1, due to missing data in the last part of the recorded route for most of the participants.

In line with Dozza et al. (2016), the phases of the overtaking manoeuvre were divided into *approaching phase*, *steering away phase*, *passing phase* and *returning phase* (Fig. 4). The *approaching phase* (phase 1) starts when the subject vehicle reaches the bicycle from behind and it ends when the subject vehicle starts to steer away from the collision path. At this point, the *steering away phase* (phase 2) starts which ends when the driver enters the passing zone (an area extending from 2 m behind the bicycle to 2 m in front of the bicycle), moment in which the *passing phase* (phase 3) begins. Finally, the driver leaves the passing zone, ending the passing phase and starting the *returning phase* (phase 4). The returning phase is over once the vehicle returns to the same lane position it had before the overtaking manoeuvre. Based on the previous definitions, the end of phase 1 could not be reliably assessed for most participants in our driving simulator study: this is because the subject vehicle was already out of the collision path with the bicycle once it reached the straight stretches of the road where the bicycle was standing still. For this reason, our analyses are limited to the calculation of the minimum safety margins (SMs) in phase 2, 3 and 4. The SM(s) in each overtaking phase were defined as the minimum distance between the vehicle and the bicycle (Fig. 4) and assessed through trigonometric calculations.

Overall, the dependent variables for our analyses were: (1) the overtaking strategies (flying vs. accelerative) chosen by the participants in each overtaking manoeuvre; (2) the minimum safety margins (SMs) in phase 2, 3 and 4 of each overtaking manoeuvre; (3) the average speed of the subject vehicle in each overtaking manoeuvre. The independent variable is the nominal TTC reported in Table 1. For the scope of this paper, TTC has been defined as "the time required for two vehicles to collide if they continue at their present speed and on the same path" (Hayward, 1971). The choice of using the TTC as an independent variable relies on the following considerations:

- TTC is based on visual information (Lee, 1976) which is available during the overtaking manoeuvre;
- TTC is considered being a cue that road users utilize for decision-making in traffic (van der Horst, 1990);
- TTC is a variable which has been already previously used to operationalize safety margins between vehicles (Engstrom & Ljung Aust, 2011).

Table 2
Demographic information about the participants.

Number of participants	36					
Age [years]	48.36 ± 19.53					
Gender	Male 21 (58.33%)			Female 15 (41.67%)		
Driving license ownership [years]	24.50 ± 15.99					
Mileage driven in the last 12 months [km]	Less than 5000 km 8 (22.2%)		5001 km–10,000 km 15 (41.7%)	10,001 km–20,000 km 8 (22.2%)		More than 20,000 km 5 (13.9%)
Mileage driven since getting driving license [km]	Less than 10,000 km 2 (5.5%)	10,001 km–30,000 km 6 (16.7%)	30,001 km–50,000 km 1 (2.8%)	50,001 km–100,000 km 5 (13.9%)	10,001 km–150,000 km 6 (16.7%)	More than 150,000 km 16 (44.4%)
Driving frequence [days per week]	No more than 1 day 1 (2.8%)		1–3 days 6 (16.7%)	4–6 days 8 (22.2%)		Every day 21 (58.3%)

As mentioned earlier, this paper will focus on the analyses of the data collected during *Route 2*. However, the values of the safety margins calculated during *Route 1* have been included in Appendix A, as a basis for comparison.

3. Results

3.1. Overtaking strategy

Table 3 reports the number – and the corresponding percentage – of participants who chose respectively flying and accelerative overtaking strategies in each overtaking manoeuvre.

A correlation analysis was conducted to assess the effect of the nominal time to collision on the overtaking strategy, by performing the Spearman's test. The results show a significant effect ($r_s = 0.821$, $\mathbf{p = 0.023}$), indicating that the number of flying overtaking manoeuvres increased – and the number of accelerative overtaking manoeuvres decreased – with higher nominal values of time to collision: as expected, drivers chose a more cautious overtaking strategy (accelerative manoeuvre) when the objective risk associated to the situation increased.

Looking at Table 3, the data seem to be organized in two clusters (divided by a dashed line in the table), depending on the value of nominal time to collision, with cluster 1 including data for TTC $\leq$ 7 s and cluster 2 including data for TTC $\geq$ 8 s. Those results suggest that the reduction in nominal time to collision from 8 s to 7 s might affect the overtaking strategy, by decreasing the number of participants undertaking a flying overtaking manoeuvre. In order to test this assumption, the X^2-test was performed and the results indicate that a change in nominal time to collision from 8 s to 7 s has a significant effect on the choice of overtaking strategy ($X^2(1) = 3.853$, $\mathbf{p = 0.05}$).

3.2. Safety margins

Table 4 shows the mean values and the standard deviation for the minimum SMs in phase 2, 3 and 4, for each overtaking (the results are jointly reported for flying and accelerative manoeuvres).

The values reported in Table 4 were used to determine the effect of the nominal time to collision on the minimum safety margins in phase 2, 3 and 4, and the Pearson's test did not identify any significant result ($r = 0.147$, $p = 0.753$ for SM2; $r = 0.148$, $p = 0.752$ for SM3; $r = -0.710$, $p = 0.074$ for SM4). So, looking at the overall data, it is not possible to identify any effect of the nominal time to collision on the choice of minimum safety margins during the overtaking manoeuvre. However, the outcome might have been confounded by the overtaking strategy chosen by the drivers, given that Table 3 showed that drivers modified their overtaking strategy based on the values of nominal time to collision. Therefore, the Pearson's test was also run considering the data filtered by overtaking strategy (Table 5): the results show that the nominal time to collision had a significant effect on the minimum values of safety margins in phase 2 and phase 3 for flying overtaking manoeuvres ($r = 0.816$, $\mathbf{p = 0.025}$ for SM2; $r = 0.859$, $\mathbf{p = 0.013}$ for SM3; $r = -0.238$, $p = 0.608$ for SM4) while the same result was not

Table 3
Overtaking strategy (flying vs. accelerative) during different overtaking manoeuvres.

Nominal TTC [s]	Nominal distance [m]	Overtaking number	Number and (%) of participants who chose flying overtakings	Number and (%) of participants who chose accelerative overtakings
6.0	350	2	18 (50.0%)	18 (50.0%)
6.5	380	7	21 (58.3%)	15 (41.7%)
7.0	400	6	19 (52.8%)	17 (47.2%)
8.0	450	4	27 (75.0%)	9 (25.0%)
8.5	480	3	26 (72.2%)	10 (27.8%)
9.0	500	1	25 (69.4%)	11 (30.6%)
9.5	520	5	29 (80.6%)	7 (19.4%)

Table 4
Minimum values of safety margins for each overtaking manoeuvre.

Nominal TTC [s]	Overtaking number	SM2 [m]	SM3 [m]	SM4 [m]
6.0	2	2.58 ± 0.33	1.32 ± 0.60	2.74 ± 0.38
6.5	7	2.60 ± 0.37	1.35 ± 0.63	2.74 ± 0.40
7.0	6	2.43 ± 0.16	1.36 ± 0.55	2.79 ± 0.33
8.0	4	2.58 ± 0.28	1.33 ± 0.51	2.72 ± 0.31
8.5	3	2.54 ± 0.27	1.27 ± 0.50	2.48 ± 0.10
9.0	1	2.52 ± 0.18	1.27 ± 0.40	2.70 ± 0.23
9.5	5	2.63 ± 0.24	1.46 ± 0.42	2.48 ± 0.32

Table 5
Minimum values of safety margins by overtaking strategy for each overtaking manoeuvre.

	SM2 [m]		SM3 [m]		SM4 [m]	
Nominal TTC [s]	Flying	Accel.	Flying	Accel.	Flying	Accel.
6.0	2.39 ± 0.15	2.77 ± 0.36	0.93 ± 0.27	1.71 ± 0.59	2.50 ± 0.11	2.99 ± 0.39
6.5	2.41 ± 0.21	2.86 ± 0.41	1.02 ± 0.39	1.82 ± 0.60	2.52 ± 0.18	3.05 ± 0.41
7.0	2.38 ± 0.11	2.48 ± 0.19	1.09 ± 0.44	1.66 ± 0.53	2.61 ± 0.22	2.99 ± 0.39
8.0	2.52 ± 0.23	2.78 ± 0.33	1.21 ± 0.42	1.71 ± 0.59	2.62 ± 0.20	3.00 ± 0.40
8.5	2.46 ± 0.17	2.74 ± 0.38	1.12 ± 0.38	1.65 ± 0.57	2.47 ± 0.60	2.50 ± 0.16
9.0	2.46 ± 0.15	2.65 ± 0.16	1.13 ± 0.36	1.57 ± 0.31	2.61 ± 0.14	2.91 ± 0.26
9.5	2.59 ± 0.22	2.82 ± 0.23	1.37 ± 0.36	1.86 ± 0.41	2.39 ± 0.17	2.83 ± 0.52

Table 6
Values of safety margins by overtaking strategy in manoeuvre 2.

	Flying Manoeuvre (N = 18)	Accelerative Manoeuvre (N = 18)	Wilcoxon rank-sum test	Effect size (Rosenthal, 1991)
SM2 [m]	2.39 ± 0.15	2.77 ± 0.36	W_s = 222.5, z = −3.45, **p < 0.001**	r = −0.58
SM3 [m]	0.93 ± 0.27	1.71 ± 0.59	W_s = 207.0, z = −3.99, **p < 0.001**	r = −0.66
SM4 [m]	2.50 ± 0.11	2.99 ± 0.39	W_s = 208.0, z = −3.96, **p < 0.001**	r = −0.66

found for accelerative overtaking manoeuvres (r = 0.032, p = 0.945 for SM2; r = −0.073, p = 0.876 for SM3; r = −0.534, p = 0.217 for SM4). Hence, drivers who performed a flying overtaking manoeuvre, reduced their safety margins to the bike when the objective risk associated to the situation increased (decrease in time to collision to the oncoming traffic): the possible risk of a collision with the oncoming traffic brought the drivers closer to the bike during the steering away and passing phases, being the minimum average lateral distance equal to 0.93 m. On the other hand, drivers who performed an accelerative overtaking manoeuvre, had similar values of safety margins towards the bike during all manoeuvres: since the drivers waited for oncoming traffic to pass, they could freely perform the overtaking manoeuvre without any risk associated to the oncoming traffic.

The last analysis aimed to assess the influence of the overtaking strategy on the minimum safety margins preferred by the drivers. This test was run for the second overtaking manoeuvre because it represents the most difficult scenario, being the nominal time to collision at its minimum value. The results are reported in Table 6 and show a significant influence of the overtaking strategy on the minimum safety margins in all the three phases considered. As before, the risk associated to oncoming traffic induced the drivers who chose a flying manoeuvre to reduce the safety margins to the bike compared to drivers who chose an accelerative manoeuvre, with possible negative effects on cyclists' safety.

Table 6 also shows that phase 3 is the most critical for cyclists' safety, because it is the one with smallest safety margins between the subject vehicle and the bicycle. For this reason, a more detailed analysis was conducted for this phase: the results are graphically displayed in the boxplots of Fig. 5 and the statistical analyses are reported in Table 7. From those

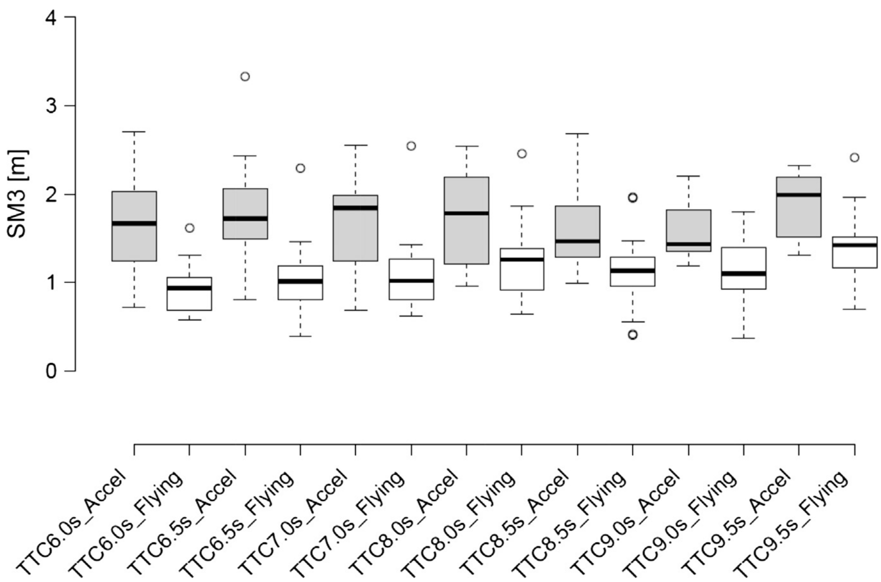

Fig. 5. Minimum values of safety margins in phase 3 for flying and accelerative manoeuvres.

Table 7
Values of safety margins in phase 3 by overtaking strategy, in manoeuvre 2.

Nominal TTC [s]	SM3 [m] Flying manoeuvre (N = 18)	SM3 [m] Accelerative manoeuvre (N = 18)	Wilcoxon rank-sum test	Effect size (Rosenthal, 1991)
6.0	0.93 ± 0.29	1.71 ± 0.68	$W_s = 207.0$, $z = -3.99$, $\mathbf{p < 0.001}$	$r = -0.66$
6.5	1.02 ± 0.51	1.82 ± 0.57	$W_s = 262.0$, $z = -4.06$, $\mathbf{p < 0.001}$	$r = -0.68$
7.0	1.09 ± 0.56	1.66 ± 0.47	$W_s = 254.5$, $z = -3.07$, $\mathbf{p = 0.002}$	$r = -0.51$
8.0	1.21 ± 0.38	1.71 ± 0.59	$W_s = 445.0$, $z = -1.99$, $\mathbf{p = 0.046}$	$r = -0.33$
8.5	1.12 ± 0.46	1.65 ± 0.57	$W_s = 413.5$, $z = -3.14$, $\mathbf{p = 0.002}$	$r = -0.52$
9.0	1.13 ± 0.38	1.57 ± 0.31	$W_s = 370.5$, $z = -3.16$, $\mathbf{p = 0.002}$	$r = -0.53$
9.5	1.37 ± 0.35	1.86 ± 0.41	$W_s = 469.0$, $z = -2.70$, $\mathbf{p = 0.007}$	$r = -0.45$

Table 8
Values of average speed of the subject vehicle in flying and accelerative manoeuvres for each overtaking.

Nominal TTC [s]	Speed in flying manoeuvre [km/h]	Speed in accelerative manoeuvre [km/h]	Wilcoxon rank–sum test	Effect size (Rosenthal, 1991)
6.0	67.92 ± 7.58	47.15 ± 7.95	$W_s = 179.0$, $z = -4.87$, $\mathbf{p < 0.001}$	$r = -0.81$
6.5	69.94 ± 7.44	47.53 ± 6.87	$W_s = 126.0$, $z = -4.86$, $\mathbf{p < 0.001}$	$r = -0.81$
7.0	68.85 ± 7.56	51.20 ± 9.04	$W_s = 184.0$, $z = -4.13$, $\mathbf{p < 0.001}$	$r = -0.69$
8.0	68.01 ± 7.72	44.88 ± 6.76	$W_s = 48.0$, $z = -4.33$, $\mathbf{p < 0.001}$	$r = -0.72$
8.5	66.76 ± 8.69	45.86 ± 5.45	$W_s = 68.0$, $z = -4.133$, $\mathbf{p < 0.001}$	$r = -0.69$
9.0	66.92 ± 8.47	44.47 ± 6.59	$W_s = 76.0$, $z = -4.38$, $\mathbf{p < 0.001}$	$r = -0.73$
9.5	69.83 ± 6.01	43.17 ± 6.57	$W_s = 28.0$, $z = -4.06$, $\mathbf{p < 0.001}$	$r = -0.68$

analyses, it emerged that the minimum safety margins in phase 3 significantly differed between flying and accelerative manoeuvres in all overtakings. This outcome stresses that drivers who chose a flying manoeuvre adopted a smaller lateral distance to the bike compared to drivers who chose an accelerative manoeuvre, in all overtaking manoeuvres.

3.3. Speed

Table 8 reports the mean values of the subject vehicle speed in flying and accelerative manoeuvres for each overtaking. The statistic analyses conducted with the Wilcoxon rank-sum test show that the mean speed was significantly higher in flying manoeuvres compared to accelerative manouvres, and the results are valid for all overtakings. The Pearson's test was also run to determine the effect of nominal TTC on the average speeds: the results show that the nominal time to collision does not significantly influence the average speeds in flying overtaking manoeuvres ($r = -0.205$, $p = 0.659$) and in accelerative overtaking manoeuvres ($r = -0.728$, $p = 0.064$).

More detailed analyses were conducted on the mean speed in phase 3 for accelerative and flying overtaking manoeuvres, given that this phase is the most critical for cyclists' safety. The results are reported in Table 9 and show that the mean speed was significantly higher in flying manoeuvres compared to accelerative manouvres, in five of the seven overtakings. However it should be noted that the effect sizes are higher in Table 8 compared to Table 9: this result suggests that the larger difference in mean speed between flying and accelerative strategies occur in other phases, probably in phase 1 and phase 2, where the driver choosing an accelerative strategy would decrease its speed compared to a driver choosing a flying strategy.

The Pearson's test was run to determine the effect of nominal TTC on the mean speed in phase 3: the results show that the nominal TTC does not significantly influence the mean speeds in phase 3 in flying ($r = 0.599$, $p = 0.155$) and accelerative overtaking manoeuvres ($r = -0.274$, $p = 0.552$).

4. Discussion

4.1. Summary of findings

The overtaking is a complex driving manoeuvre which requires the driver to acquire several visual information from the surrounding environment, such as the speed of the oncoming vehicle as well as the distance and the time to collision to the same. This perceptual process (Gray & Regan, 2005), together with incongruous expectations (Hills, 1980) and unexpected

Table 9
Values of average speed of the subject vehicle in phase 3 in flying and accelerative manoeuvres for each overtaking.

Nominal TTC [s]	Speed in flying manoeuvre [km/h]	Speed in accelerative manoeuvre [km/h]	Wilcoxon rank-sum test	Effect size (Rosenthal, 1991)
6.0	66.42 ± 12.87	61.11 ± 10.23	W_s = 293.0, z = −1.27, p = 0.206	r = −0.21
6.5	69.27 ± 9.75	60.35 ± 10.62	Ws = 203.0, z = −2.39, **p = 0.017**	r = −0.40
7.0	68.67 ± 12.21	60.36 ± 8.71	Ws = 238.0, z = −2.42, **p = 0.015**	r = −0.40
8.0	70.82 ± 11.23	63.91 ± 12.67	W_s = 127.0, z = −1.44, p = 0.149	r = −0.24
8.5	68.02 ± 14.43	59.04 ± 9.41	W_s = 127.0, z = −2.05, **p = 0.041**	r = −0.34
9.0	69.13 ± 13.97	58.66 ± 10.41	W_s = 139.0, z = −2.21, **p = 0.027**	r = −0.37
9.5	70.65 ± 9.76	60.28 ± 8.66	W_s = 73.0, z = −2.61, **p = 0.024**	r = −0.43

hazards (Clarke et al., 1999), can result in errors during the overtaking manoeuvre which might cause crashes or reduced longitudinal and lateral safety margins to the overtaken or oncoming vehicles (Papakostopoulos et al., 2015). The monitoring of subjective risk – which is a key factor in driving expectations (Näätänen & Summala, 1974) – can therefore influence the decision-making process during the overtaking manoeuvre and lead to different outcomes related to both the overtaking strategy (accelerative vs. flying) and to the minimum safety margins towards other road users. During overtaking manoeuvres, a vehicle approaching from the opposite direction and the associated time to collision can influence the monitoring of subjective risk, for example by increasing fear if the vehicle is approaching unexpectedly fast (Näätänen & Summala, 1974). In this context, the present driving simulator study aimed to investigate how the time to collision between oncoming traffic and subject vehicle affected the overtaking strategy, the minimum safety margins towards the overtaken cyclist and the mean speed.

The results of the study show that the nominal time to collision significantly affects the overtaking strategy chosen by the driver. The increase in subjective risk associated to the overtaking manoeuvre – due to a decrease in time to collision – induced a significant number of drivers to adopt an accelerative strategy. In particular, the results denote a significant change in strategy from flying to accelerative when the nominal time to collision decreases from 8 s to 7 s.

During the analyses, the safety margins towards the bicycle were assessed in three different phases, defined according to Dozza et al. (2016): the steering away phase, the passing phase and the returning phase. Looking at the overall dataset, the results did not show any significant effect of the time to collision between subject vehicle and oncoming traffic on the choice of minimum safety margins towards the bicycle. However, analysing the data by overtaking strategy (flying vs. accelerative), a decrease in minimum safety margins was found for drivers who opted for a flying overtaking strategy, in the steering away and passing phases: the drivers who completed the overtaking manoeuvre without waiting for oncoming traffic to pass reduced their minimum safety margins in the steering away and passing phases, when the time to collision decreased. This outcome suggests that the subjective risk associated to the fast approaching vehicle in the oncoming lane induced drivers to reduce the safety margins towards the overtaken bicycle, confirming the results found by Papakostopoulos et al. (2015) for car-to-car overtaking.

Besides, the current research showed that the lateral minimum safety margins – calculated for the passing phase – were overall larger in accelerative manoeuvres compared to flying manoeuvres, confirming the results reported in Dozza et al. (2016). In the overtaking manoeuvre with smallest time to collision, the average lateral safety margin maintained by drivers in flying overtaking manoeuvres (0.93 m) was about 40% lower than the value of 1.5 m recommended for rural roads or for speed higher than 60 km/h in some European countries (Irish Road Safety authority, 2018; Llorca et al., 2017), in some Australian states (Queensland Government, 2018), in New Zealand (New Zealand Transport Agency, 2018) and in some Japanese prefectures (Ehime Prefectural Government, 2018).

Finally, the mean speed was significantly higher in flying compared to accelerative overtaking manoeuvres because drivers decreased their speed in accelerative manoeuvres to let the oncoming vehicle pass. However, drivers kept a higher speed in flying overtaking manoeuvres also during the passing phase, when the vehicle is travelling parallel to the cyclist in the passing zone (an area extending from 2 m behind the bicycle to 2 m in front of the bicycle). Previous research reported that lateral clearance and vehicle speed significantly affect the cyclists' perceived risk during overtaking manoeuvres (Llorca et al., 2017). Then, the flying overtaking manoeuvres recorded in this study seem to pose a risk for cyclists' safety due to the combination of lower safety margins and higher mean speeds. Also, the values of mean speed recorded in flying overtaking manoeuvres – ranging between 66.42 km/h and 70.82 km/h – do not substantially differ from the speed (70 km/h) that experimenters requested the drivers to keep during the study. This finding indicates that the presence of the cyclist did not induce the drivers to reduce their speed, supporting the results reported by Bella and Silvestri (2017).

4.2. Practical applications

Overall, the current study provides interesting insights for the design of automated driving. A nominal TTC higher than 8 s induced a significant number of drivers to choose a flying rather than an accelerative overtaking manoeuvre. In the future, the design of automated vehicles could consider the nominal TTC or a similar variable to assess the appropriate timing for starting the overtaking manoeuvre. Besides, the values of average minimum safety margins and average speeds recorded in this study provide indications about how drivers perform respectively an accelerative and a flying overtaking manoeuvre. Those inputs could be taken into account to design automated vehicles that reproduce as much as possible human behaviour. In this regard, it is worth noticing that the smaller minimum lateral safety margins and the higher speeds measured during flying overtaking manoeuvres constitutes an important challenge for automated vehicles: designers will have to ensure that the requirements on both cyclist' safety and driver's comfort will have to be met.

5. Study limitations

The current study presents some limitations. First, the experiment was conducted in a simulated environment and drivers' behaviour might differ for on road driving (Mullen, Charlton, Devlin, & Bedard, 2011): the absence of motion cues and the limited resolution of the screen might have affected the perception of relevant cues to estimate the distance of oncoming traffic and the corresponding time to collision (Kemeny & Panerai, 2003). Besides, the sample included only drivers aged either 25–40 years old or 65–75 years old and this control on the age of participants might have had an influence on the final results, considering that age was shown to influence the overtaking manoeuvre with respect to time duration, following distances, critical overtaking gaps, and desired driving speeds (Farah, 2011). Finally, the sample size – including only 36 participants – was limited and, therefore, the conclusions cannot be extended to the overall population of Japanese drivers. Further research should consider this caveat during the planning of experiments to have more conclusive results on the topic.

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Appendix A

SMs during overtaking manoeuvres in Route 1

This section provides the results of SMs calculated during the four overtaking manoeuvres without oncoming traffic in *Route 1* (Table A1).

Table A1
Values of safety margins assessed during overtaking manoeuvres without oncoming traffic in *Route 1*.[a]

Overtaking number	SM2 [m]	SM3 [m].	SM4 [m]
1	2.61 ± 0.42	1.75 ± 0.58	2.79 ± 0.41
2	2.67 ± 0.33	1.73 ± 0.43	2.70 ± 0.29
3	2.61 ± 0.40	1.72 ± 0.57	2.74 ± 0.40
4	2.62 ± 0.33	1.77 ± 0.47	2.73 ± 0.23

[a] The SMs reported in table refers to 39 participants.

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