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Abstract: The interaction of motorists and bicyclists, particularly during passing maneuvers, is cited as one of the primary causes of bicyclist fatalities. This paper reports the results of a driving simulator study, which sought to analyze the effects that three cross-section configurations of a two-lane rural road and four geometric elements of the road have on driver behavior, during the interaction with a cyclist. A two-lane rural road, about 11 km long, was designed and implemented in an advanced-interactive driving simulator. Three different cross-sections (all with same width, but with and without a bicycle lane and for different widths of bicycle lane) were tested. Forty participants carried out three driving sessions (one for each road alignment with different cross-section) and were exposed to the condition of bicycle traffic along four geometric elements of the alignment (2 tangents with different lengths, right curve and left curve). The driving simulator experiments were designed in such a way that, along the sections where the driver - cyclist interactions occurred, the oncoming traffic was absent. Overall, 468 speed profiles and 468 lateral position profiles were plotted to obtain the descriptive variables of the driver behavior during the interaction with the cyclist. The influences of cross-sections, geometric elements and bicycle traffic conditions on driver behavior were evaluated by a multivariate variance analysis. The presence of the cyclist determined different levels of influence on driver's trajectory for the three cross-sections. A wider bicycle lane ensured a higher later clearance distance between driver and cyclist, allowing safer overtaking maneuver.
The interferences of the cyclist on driver's behavior depended on the geometric elements. On tangents, the lowest lateral clearances were recorded and no speed reduction was observed, compared to the cyclist absence condition. On the left curve, the higher lateral clearance was recorded, due to the concordant tendencies of the driver to move away from the cyclist and to cut the curve. This determined an excessive and risky displacement of the vehicle to the opposing lane, whose criticality was also emphasized by the high speed adopted by the driver. On the right curve, the lateral clearance was higher than that recorded on the tangents, probably due to the necessity of the driver to perform the

demanding maneuver of entering in the right curve, which also determined a speed reduction compared to the cyclist absence condition.
The obtained results provide suggestions for the most efficient cross-section reorganization of existing two-lane rural roads in order to improve the road safety.

INTERACTION DRIVER – BICYCLIST ON RURAL ROADS: EFFECTS OF CROSS-SECTIONS AND ROAD GEOMETRIC ELEMENTS

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ABSTRACT

The interaction of motorists and bicyclists, particularly during passing maneuvers, is cited as one of the primary causes of bicyclist fatalities. This paper reports the results of a driving simulator study, which sought to analyze the effects that three cross-section configurations of a two-lane rural road and four geometric elements of the road have on driver behavior, during the interaction with a cyclist. A two-lane rural road, about 11 km long, was designed and implemented in an advanced-interactive driving simulator. Three different cross-sections (all with same width, but with and without a bicycle lane and for different widths of bicycle lane) were tested. Forty participants carried out three driving sessions (one for each road alignment with different cross-section) and were exposed to the condition of bicycle traffic along four geometric elements of the alignment (2 tangents with different lengths, right curve and left curve). The driving simulator experiments were designed in such a way that, along the sections where the driver – cyclist interactions occurred, the oncoming traffic was absent. Overall, 468 speed profiles and 468 lateral position profiles were plotted to obtain the descriptive variables of the driver behavior during the interaction with the cyclist. The influences of cross-sections, geometric elements and bicycle traffic conditions on driver behavior were evaluated by a multivariate variance analysis. The presence of the cyclist determined different levels of influence on driver's trajectory for the three cross-sections. A wider bicycle lane ensured a higher later clearance distance between driver and cyclist, allowing safer overtaking maneuver.

The interferences of the cyclist on driver's behavior depended on the geometric elements. On tangents, the lowest lateral clearances were recorded and no speed reduction was observed, compared to the cyclist absence condition. On the left curve, the higher lateral clearance was recorded, due to the concordant tendencies of the driver to move away from the cyclist and to cut the curve. This determined an excessive and risky displacement of the vehicle to the opposing lane, whose criticality was also emphasized by the high speed adopted by the driver. On the right curve, the lateral clearance was higher than that recorded on the tangents, probably due to the necessity of the driver to perform the demanding maneuver of entering in the right curve, which also determined a speed reduction compared to the cyclist absence condition.

The obtained results provide suggestions for the most efficient cross-section reorganization of existing two-lane rural roads in order to improve the road safety.

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1. INTRODUCTION

In the last years, the environmental cause concerning the use of the motorized transports, the consequences linked to the pollution impact on the human health, the issues of the congested cities are bringing to increase the use of the bicycle as alternative to the traditional transport systems (e.g. Heinen et al., 2010. Health Organization, 2014; Fruhen and Flin, 2015; Shackel and Parking, 2014; Zeuwts, et al. 2016). However, the expansion of the bike mobility both in urban and suburban environment had to struggle with the lack of adequate infrastructure and, thus, with the interferences between vehicles and bikes in the same roads. For the cyclists, in fact, the riskiest situation is the interaction with a motorized vehicle (Chaurand and Delhoomme, 2013; Schepers et al., 2014; Hamann and Peek-Asa, 2013; Frings et al., 2014). Due to the use of the same infrastructure with motorized road users, the cyclists are more vulnerable because their vehicles do not protect them if an accident occurs (Vanparijs et al., 2015) (Wegman et. al., 2012).

The statistics clearly highlight the critical issues of the cyclist safety. In the United States a total of 720 bicyclists were killed in crashes with motor vehicles in 2014 (with an increase of 16% compared to 2010); 32 % of bicyclists were killed in rural areas (Insurance Institute for Highway Safety, 2015). European statistics show that about 2.000 people riding bicycles were killed in road accidents in 2013 in the EU countries; the share of bicycle fatalities of all road fatalities in the EU countries increased from about 6% to almost 8% between 2004 and 2013. 45% of the cyclist fatalities occurred outside urban areas (European Commission, 2015). Italian national statistics (ISTAT, 2015) show that in 2014 the number of fatalities related to the bicycles users (273 fatalities) is increased by 8.8 % compared to the previous year and about of 3% compared to the 2010. About 42% of the cyclist injuries occur outside urban areas; in addition, for rural roads, the severity index (ratio between number of fatalities and number of fatalities and injuries) is almost six times higher (ACI-ISTAT, 2012).

In the rural roads, a determinant factor is the difference between the speed of vehicle and the speed of bicycle, which is positively associated with the increase of the severity of crashes (Kim et al., 2007, Boufous et al., 2012, Chen et al., 2016; Bil et al., 2010).

On rural roads, the interaction between driver and cyclist, which is often realized with an overtaking maneuver, mostly occurs far from the intersections where drivers travel considerably faster than cyclists (Walker, 2007). Stone and Broughton (2003) report that the collisions that occur out of the intersections are more dangerous than those at the intersections, where the drivers have to slow to maneuver.

However, despite the severity of the collisions that occur in rural roads is much higher than that in urban areas due to higher speeds, there have been few studies that investigated the interaction between vehicle and cyclist during a passing maneuver in rural roads.

Parkin and Meyers (2010) analyzed the effect of the bicycle lane on the passing distance of the vehicles on different roads with same overall road width (about 9.50m), different posted speed limits (48km/h, 64km/h and 80km/h) and with and without cycle lane (the width was 1.45 m on roads with speed limit 64km/h and 80km/h, and 1.30 m on roads with speed limit 48km/h). Significantly wider lateral clearances were adopted by drivers in the condition without a 1.45m cycle lane, with posted speed limits of 64km/h and 80km/h. This result was not obtained for the road with a posted speed limit of 48km/h and a 1.3 m cycle lane. The authors concluded that cycle lanes do not appear to provide greater space for cyclists in all conditions.

Savolainen et al. (2012) assessed the lateral placement of motor vehicles as they passed bicyclists through field studies on two segments (with and without centerline rumble strips) of a high-speed (55-mph speed limit) rural two-lane highway (lane width 11ft and shoulder width 4ft). The lateral position of the bicyclists (within the center of the shoulder, on the left edge of the shoulder, and on the right edge of the travel lane) affected the lateral position of the motor vehicles. Drivers were more likely to contact or cross the centerline the nearer the bicyclists were to the travel lane.

Kay et al. (2014) analyzed the effect of the “Share the Road” sign on driver behavior during the overtaking maneuver on two segments of a high-speed rural two-lane highway (55-mph speed limit; lane width 11 ft and shoulder width 4 ft). The study highlighted that the sign contributed to shift away motor vehicles from the right edge of the lane and to reduce (on average about 4 km/h) the speed of the vehicles during the overtaking maneuver. However, no significant effects were found on the mean lateral distance between the bicyclists and passing motorists.

Chapman and Noyce (2012, 2014) analyzed the influence of several features of rural roads on drivers' behavior during the overtaking of cyclists. They found that a significant factor influencing positively the lateral clearance distance from the bicycle was the presence and the width of the shoulder.

Walker et al. (2014) recorded the amount of space left by motorists as they overtook a bicycle on different types of roads (rural roads were 44% of the sample) in order to study whether drivers overtaking a bicyclist changed the proximities of their passes in response to the bicyclist's appearance. Seven outfits were tested. Walker et al. found that the overall lateral clearance was 117.50 cm, which is lower than the mean of 133 cm found by Walker in a previous study carried out on urban roads (Walker, 2007). The authors deduced that this result was due to the different types of the examined roads. Approximately 1–2% of overtakes came within 50 cm, no matter what outfit the cyclist was worn. The authors observed that the possibility for the rider to avoid close overtaking by altering their appearance is not enough; on the other side, the infrastructural, educational or legal measures may be more effective in preventing close overtaking, and thus, dangerous situation for the cyclist.

Llorca et al. (2014) analyzed the speed and the lateral clearance left by motor vehicles during the passing maneuver of a cyclist along seven rural roads segments in Spain to evaluate as such variables affect the risk perception of the cyclist. They found that lateral clearance was not the only factor that influenced rider's risk perception. On the contrary, a combined factor of lateral clearance, vehicle type and vehicle speed had a more significant correlation with it. Afterwards, Garcia et al. (2015) analyzed the overtaking maneuver (a vehicle that overtakes a cyclist) on two – lane rural highways. Results showed that the passing lateral clearance between vehicle and cyclist increased with road width. Moreover, it was higher on left curve and lower on right curve, compared with the tangent elements. It was also found that, although the interaction with the cyclist lead to a speed reduction trend, in some road segments the speed was comparable to that in the condition of free-flow on the same locations.

Dozza et al. (2016) collected data about the interaction driver-cyclist on rural roads in Sweden. The authors identified four overtaking phases and found that 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 overtaking dynamics.

Although results of urban safety cannot be transferred to overtaking maneuvers of motor vehicles and bicycles on rural roads (Llorca, 2014), useful trends can be obtained from some studies on the interaction between driver and cyclist in urban areas (Love et al. ,2012; Mehta et al. ,2015; Chuang et al., 2013).

Love et al. (2012) measured the distance between overtaking motor vehicles and cyclists in order to assess compliance with the three-foot law (that requires motor vehicles to pass cyclists with a clearance of greater than three feet) and to examine risk factors associated with close vehicle passes. They found that vehicle passes three feet or less were common in standard lanes and lanes with a shared lane marking but not in bicycle lane streets (all the bicycle lanes were 5 ft wide). Similar results were obtained by Mehta et al. (2015) and Chuang et al. (2013), which also revealed that longitudinal markings (for lane separation or slow traffic separation) can encourage greater passing distances when motorized vehicles pass bicyclists.

Such studies (with exeption of Kay et al., 2014, LLorca et al., 2014 and Garcia et al., 2015) involve only the lateral clarence, ignoring the speed analysis of the overtaking vehicle. It should be noted that some authors (Walker et al., 2014) highlighted, among the purposes of further studies on the driver – cyclist interaction, the analysis of the passing speed. That variable, determining important dynamic effects on the cyclist, plays, together with the space left by motorist during the overtake of a cyclist, a crucial role on the collision risk (Ata and Langlois, 2011) and on the bicyclists’ perceived level-of-service on road segments (Jensen, 2007).

In addition, most of the studies were conducted on tangents, while only a few times (Llorca et al., 2014 and Garcia et al., 2015) the driver’s behavior during overtaking of the cyclist was also analyzed on other more demanding geometric elements of the road alignment. On such elements the complexity of the road geometry can determine additional effects compared to those due to the only interaction with the cyclist.

Finally, all the reported studies were conducted on field and with the use of instrumented bicycles, which had sensors and cameras that allowed the measurement of the lateral distance of the overtaking vehicles. Such field studies have the advantage of allow the tracking of the driver behavior in the real driving conditions. However, these studies are generally characterized by the impossibility of conducting controlled experiments in terms of road geometry (cross-section, features of the alignment) cyclist dynamics (different speeds or different positions of the cyclist) and interferences of the traffic (in the same lane and in the opposing lane). In other words, such field studies are generally influenced by confounding factors that can alter the analysis of the effects on the driver – cyclist interaction due to specific factors. The results of these studies, thus, must be specifically referred to the particular experimental conditions and cannot be strictly compared to those obtained in other experimental conditions.

Because of this, the objective of this paper was to assess the effects of several two-lane rural road configurations (three cross-section configurations with and without bicycle lane with different widths) and of four geometric elements of the road (tangents with different lengths, right curve and left curve) on driver behavior (in terms of lateral position and speed) during the overtaking maneuver of a bicyclist by the use of an advanced driving simulator, which ensures controlled experimental conditions. In particular, the driving simulator experiments were designed in such a way that, along the sections where the driver – cyclist interactions occurred, the oncoming traffic was absent.

2. METHODS

This study was conducted using the advanced driving simulator of the Department of Engineering – Roma Tre University. Several studies have demonstrated that driving simulators are useful tools for the evaluation of the driver's behavior as induced by the road configuration and traffic conditions (e.g., Bella 2008a, 2011, 2013, 2014a, 2014b; Bella and Calvi, 2013; Bella et. al., 2014; Bella and Silvestri, 2015, 2016). Moreover, driving simulators are ideal tools for studies whose field survey is made impossible by the implicit high risks that the experimenters would be subjected to and the difficulty of ensuring controlled experimental conditions.

More specifically, concerning the study of the interaction between vehicle and cyclist, Chapman and Noyce (2014) suggested the use of a driving simulator, through which submit the drivers to controlled stimuli to identify what factors make easier or more difficult the overtaking maneuver of a cyclist. In addition, a recent driving simulator study (Duivenvoorden et al., 2015) was carried out to analyze how the number of cyclists, the cyclist's approach direction and the cyclist's action affect the speed and mental workload of drivers approaching rural intersections.

In the present study, a multi – factorial experiment was designed to analyze the effects of bicycle traffic on drivers' behavior during the overtaking maneuver, under several bicycle lane widths and different geometric elements of the alignment.

2.1 Cross-section configurations and driver – bicycle interaction

The experimental road scenario was a two – lane rural road about 11 Km long in which also the bicycle traffic was simulated. In order to assess the effect of the alignment on drivers' behavior, the horizontal curves had radii between 200 m and 600 m, while the tangents length were ranged from 150 m to 650 m. The grade of the alignment was null. The posted speed limit was 90 km/h and the cross-section was 9 m wide formed by two 3.50 m wide lanes and two paved shoulders 1.00 m wide, according to the Italian road design guidelines (Ministry of Infrastructures and Transports, 2001). This configuration represents the baseline condition; in other words, it represents a typical situation in which the cyclist has not a dedicated lane to travel. In addition to the baseline condition, two cross-sections (called countermeasures 1 and 2), in which was present a bicycle lane separated from the vehicle lane by a yellow edge line (D.P.R., 2006), were investigated:

- *countermeasure 1*, in which the bicycle lane was 1.50 m wide; in this configuration, the vehicle lane width was 3.00 m;
- *countermeasure 2*, in which the bicycle lane was 1.75 m wide; in this configuration, the vehicle lane width was 2.75 m.

For both the countermeasures, the cross-section width was 9 m as for the baseline condition.

Such bicycle lane widths are completely consistent with those suggested by the Italian regulations (Ministero Lavori pubblici, 1999; provincia di Milano, 2006) and by the guidelines for the Development of Bicycle Facilities of the American Association of State Highway and Transportation Official (AASHTO, 2012). When the bicycle lane was present, a bike lane sign and a pavement-marking symbol on the bicycle lane were used to properly inform drivers (D.P.R., 2006).

Concerning the vehicle – bicycle interaction, along the alignment the driver overtakes a cyclist in correspondence of:

- one right curve with radius equal to 200 m

- one left curve with radius equal to 200 m
- one tangent 450 m long
- one tangent 650 m long

For all the cross-sections, the cyclist travelled always on a trajectory that was 0.75 m far from the right edge of the shoulder (fig. 1) and with constant speed equal to 20 km/h, consistent with the speed of the cyclist reported in previous studies in literature (Walker 2007, Llorca et al., 2014; Garcia et al., 2015, Walker et al., 2014; Dozza et al., 2016).

To avoid potential effects due to different roadside features, the roadside configuration along the three road scenarios (i.e. baseline condition and countermeasures 1 and 2) was always the same (it is shown in figure 1).

Figure 1 - Cyclist on cross-section configurations a) baseline condition, b) countermeasure 1, c) countermeasure 2

To limit a potential order effect on the driver's behavior, for each of the three road scenarios 2 different encounter orders (A and B) of the cyclist on the geometric elements of the alignment were implemented in the driving simulator. More specifically, for the encounter order A, the presence of the cyclist along the geometric elements was set as follows: left curve (located about 650 m from the beginning of the alignment); tangent 650 m long (about 2.100 m from the beginning of the alignment); tangent 450 m long (about 8.400 m from the beginning of the alignment); right curve (about 10.000 m from the beginning of the alignment). For the encounter order B, the presence of the cyclist was set as follows: tangent 450 m long (located about 3.400 m from the beginning of the alignment); right curve (about 4.750 m from the beginning of the alignment); left curve (about 5.900 m from the beginning of the alignment); tangent 650 m long (about 7.300 m from the beginning of the alignment).

Each type of geometric element in which the interaction with the cyclist occurred (e.g. tangent 650 m long), although placed – for the two encounter orders - in two different points along the road (the tangent 650 m long was about 2.100 m and 7.300 m from the beginning of the alignment for the encounter orders A and B, respectively), it was preceded by the same geometric configuration of the approach section (for the tangent 650 m long it was a left curve with radius of 500 m). Such specification was used with the aim of avoiding the potential influence on the driver's behavior due to different approach conditions.

2.2 Driving simulator

The driving simulator of the Department of Engineering – Roma Tre University is an interactive fixed-base driving simulator. It was previously tested, calibrated and validated (Bella, 2005, 2008b) as a reliable tool for the study of the driver's speed behavior. The hardware interfaces (wheel, pedals and gear lever) are installed on a real vehicle. The driving scene is projected onto three screens: one in front of the vehicle and one on either side, which provide a 135° field of view. The resolution of the visual scene is 1024x768 pixels with a refresh rate of 30 to 60 Hz. The system is also equipped with a sound system that reproduces the sounds of the engine. The simulator provides many parameters for describing the travel conditions (e.g., relative position of the center of the vehicle with respect to the road axis, local speed and acceleration, steering wheel rotation angle, pitching angle, rolling angle, etc.). Data can be recorded at time or space intervals of a fraction of a second or a fraction of a meter.

2.3 Procedure

The experiment was conducted with the free vehicle in its own driving lane. On the opposing lane, it was present a traffic flow to induce the driver not to drift to the incoming traffic lane and to make the driving experience of the participants closer to the driving experience in the real world. The features of the traffic on the opposing lane were the following: traffic volume equal to 280 v/h; speed of vehicles 70 km/h; heavy vehicles equal to 5%. Such traffic features are representative of the typical traffic condition on the Italian two – lane rural roads, similar to that used in the present study. All the driver – cyclist interactions were designed to occur when in the opposing lane there was not any vehicle. This in order to avoid, during the overtaking maneuver, the influence on the driver behavior of an oncoming vehicle and therefore allow the analysis of the only induced effects by the interaction with the cyclist, the cross – section configuration and the geometric element of the road. The simulated vehicle was a standard medium-class car (width of 1.60 m) and with automatic gears. The data recording system acquired all of the parameters at spatial intervals of 2 m.

The driving procedure consisted of the following steps: (a) communicating to the driver about the duration of the driving and the use of the steering wheel, pedals, and automatic gear; (b) training at the driving simulator on a specific alignment with a length of approximately 15 Km in order to become familiar with the driving simulator and experience numerous interaction conditions such as car-following condition, overtaking, braking, acceleration and so on with other vehicles (among these also bicycles) both on the driving lane and on the opposing lane; (c) filling in a form with personal data, years of driving experience, average annual distance driven; (d) driving the three road scenarios with the specific configuration (baseline condition and countermeasures 1 and 2). Between each scenario the driver waited about 5 minutes to restore his/her psychophysical conditions and filled in of a questionnaire about the interaction with the cyclist; (e) filling in of a questionnaire about the perceived discomfort during driving, to eliminate from the sample the driving performed under anomalous conditions. This questionnaire consisted of 5 questions, with each question addressing a typed of discomfort: nausea, giddiness, daze, fatigue, other. Each question could be answered by a score of 1–4 in proportion to the level of discomfort experienced: null, light, medium, and high. The null and light level for all five types of discomfort is considered to be the acceptable condition for driving. Drivers were instructed to drive as they normally would in the real world.

2.4 Participants

Forty drivers (24 men and 16 women), whose ages ranged from 23 to 62 (average 29) and who had regular European driving licenses for at least three years, were selected to perform the driving in the simulator. They were chosen from students, faculty, staff of the University and volunteers from outside of the University. The drivers had no prior experience with the driving simulator and had an average annual driven distance on rural roads of at least 2500 km. The average number of years of driving experience was approximately 9.

The sample was divided into 2 groups; each group drove the three road scenarios with a sequence of the encounters of the cyclist along the alignment (encounter order A or B). The sequence of the three scenarios was counterbalanced to avoid influences due to the repetition of the same order in the experimental conditions.

According to the questionnaire on perceived discomfort, one of forty drivers experienced a high level of discomfort during the simulated drive and was excluded from the sample. Thus, the size of the sample used for the following analysis consisted in 39 drivers.

3. DATA PROCESSING

In order to analyze how drivers behave in the interaction with the cyclist under the three different configurations of the cross–section and the four geometric elements (right curve and left curve with radius equal to 200 m, tangents 450 m and 650 m long) the following variables were collected:

- *d*: the lateral position, i.e. the distance between the vehicle axis and the centerline in the point along the alignment where the vehicle overtakes the cyclist; it should be noted that such variable is not the lateral clearance between vehicle and cyclist used in previous studies in literature. Considering the bicycle lane width and the position of the longitudinal axis of the bicycle (0.75 m from the right edge of the shoulder), the lateral clearance is obtained from the following equation:

  $$lateral\ clearance = 4.50-(0.75+lh)-(d + \mathrm{w}/2) \quad (1)$$

  where *lh* is the width of the leftbicycle handlebar and *w* is the width of the vehicle;
- d_{av}: the average lateral position from the beginning to the finish of the overtaking maneuver; the beginning and the ending points of the overtaking maneuver were located by the plotting of the lateral position profile that was adopted by driver. The beginning point was the point in which the driver started to modify his/her trajectory (moving to the centerline of the road, i.e. changing the steering wheel rotation angle) to overtake the cyclist. The ending point of the overtaking maneuver was the point in which the driver, returned on the right after the overtake, took a lateral position that remained constant (i.e. the steering wheel rotation angle remained constant);
- *V*: the overtaking speed, i.e. the speed at the point in which *d* is recorded;
- V_{av}: the average overtaking speed, i.e. the average speed of the entire overtaking maneuver.

The lateral position (*d*) and the speed (*V*) were recorded to study the driver behavior at the point along the alignment where the vehicle overtakes overtook the cyclist. The variables d_{av} and V_{av} were also considered to analyze the average driver behavior during the entire overtaking maneuver of the cyclist. The figure 2 shows all the described variables.

Figure 2 - Variables of the driver-cyclist interaction

To obtain these variables when vehicle – bicycle interactions occurred, the lateral position profiles and the speed profiles were plotted for each driver, cross–section configuration and geometric element. Overall 468 lateral position profiles and 468 speed profiles were plotted (39 drivers x 3 cross-section configurations x 4 geometric elements). When the cyclist was not present, the variables were recorded at the same points and sections in which there would be the vehicle – bicycle interaction.

4. DATA ANALYSIS AND RESULTS

A multivariate variance analysis (MANOVA) procedure was conducted to investigate all of the interaction and main effects on the dependent variables (*d*, d_{av}, *V* and V_{av}) due to three factors: configuration of the cross-section (baseline, countermeasures 1 and 2), presence/absence of cyclist, and geometric element of the alignment. For every combination of the three independent factors, the table 1 shows the descriptive statistics of the dependent variables and the values of lateral clearance obtained by the equation (1), assuming the vehicle width (*w*) equal to 1.60 m and the leftbicycle handlebar width (*lh*) equal to 0.20 m.

Table 1 - Descriptive statistics.

The interaction and the main effects on driver behavior due to independent factors were analyzed with MANOVA. A Bonferroni correction was used for multiple comparisons. MANOVA revealed (tab. 2) a significant main effect for cross-section ($F_{(8,31)}$ = 36.290, P = 0.000, Wilk's Λ = 0.096, partial Eta squared = 0.904, observed power = 1.000) for the presence/absence of cyclist ($F_{(4,35)}$ = 49.774, P = 0.000, Wilk's Λ = 0.150, partial Eta squared = 0.850, observed power = 1.000), and for geometric element ($F_{(12,27)}$ = 19.483, P = 0.000, Wilk's Λ = 0.104, partial Eta squared = 0.896, observed power = 1.000). A significant interaction effect was found for cross-section by presence/absence of cyclist ($F_{(8,31)}$ = 9.222, P = 0.000, Wilk's Λ = 0.296, partial Eta squared = 0.704, observed power = 1.000) and geometric element by presence/absence of cyclist ($F_{(12,27)}$ = 11.318, P = 0.000, Wilk's Λ = 0.166, partial Eta squared = 0.834, observed power = 1.000).

Table 2 – Statistically significant main and interaction effects

Tests of between-subject effects (tab. 3) revealed that only the spatial variables (d and d_{av}) were statistically significantly affected by the cross-section and the presence/absence of cyclist, while all the dependent variables (d, d_{av}, V and V_{av}) were affected by the geometric elements. Cross-section by presence/absence of cyclist affected only d and d_{av}, while geometric element by presence/absence of cyclist affected d_{av}, V and V_{av}.

Table 3 –Main and interaction effects on dependent variables

4.1 Effects of the cross-section configurations

The effect of the cross-section on the lateral position (d) was statistically significant ($F_{(1.359,51.627)}$ = 9.004; P = 0.002) (tab. 3); post – hoc analysis showed that the lateral position for the baseline condition (1.79 m) was statistically significantly higher than that for the countermeasure 2 (mean difference = 0.19 m; P = 0.000; d = 1.60 m) and not statistically significantly different than that for the countermeasure 1 (mean difference = 0.08; P = 0.411; d = 1.71 m). No other mean difference of d was statistically significant.

The effect of the cross-section was statistically significant also for the average lateral position (d_{av}) ($F_{(1.708,\ 64.918)}$ =112.055; P = 0.000) (tab. 3); post hoc – analysis showed that the average lateral position was statistically significantly higher for the baseline condition (2.00 m) than that for the countermeasure 1 (mean difference = 0.18 m; P = 0.000; d_{av}= 1.82 m) and for the countermeasure 2 (mean difference = 0.26 m; P = 0.000; d_{av}= 1.74 m). Also the difference between the countermeasure 1 and 2 was statistically significant (mean difference = 0.08 m; P = 0.000).

The effect of the cross-section was not statistically significant on the overtaking speed (*V* ranged between 25.5 m/s for countermeasure 2 and 25.9 m/s for baseline condition) and the average overtaking speed (V_{av} ranged between 25.5 m/s for countermeasure 2 and 26 m/s for baseline condition). Such values were similar to the recorded values on field on two-lane rural roads with posted speed limit of 90 km/h or 55mph and with cross-sections that had similar driving lane and shoulder widths of those analyzed in the present study (Kay et al., 2014; Garcia et al., 2015).

4.2 Effects of the presence/absence of the cyclist

The effect of the presence/absence of cyclist was statistically significant on the lateral position (*d*) and the average lateral position (d_{av}) ($F_{(1,38)}$ = 148.546; P = 0.000 and $F_{(1,38)}$ = 156.264; P = 0.000, respectively) (tab. 3). Test between subjects indicated that for absence of cyclist *d* (*d* = 1.96 m) was statistically significantly higher than that for the cyclist presence condition (mean difference = 0.52 m; P = 0.000; *d* = 1.44 m), highlighting as the cyclist presence induces an average displacement of 0.52 m to the center of the road. It should be noted that the value of lateral position when the cyclist was present (*d*=1.44 m) corresponds to a lateral clearance between vehicle and bicycle equal to 1.31 m (assuming the vehicle width equal to 1.60 m and the leftbicycle handlebar width equal to 0.20 m). Such value is consistent with the values of lateral clearance obtained on cross-sections similar to those of the present study (Walker et al., 2014, Llorca et al., 2014, Garcia et al., 2015**).**

Also d_{av} had similar results; for the absence of cyclist condition the average lateral position (d_{av} =1.96 m) was statistically significantly higher than that for the presence of cyclist condition (mean difference = 0.22 m; P = 0.000; $d_{av=}$ 1.74 m).

The effect of the presence/absence of cyclist was not statistically significant on the overtaking speed (*V* was equal to 25.6 m/s in cyclist presence and 25.7 m/s in cyclist absence) and the average overtaking speed (V_{av} was 25.8 m/s in cyclist presence and absence).

4.3 Effects of the geometric element

The effect of the geometric element was statistically significant on *d* ($F_{(2.374,90.198)}$ = 28.248; P = 0.000), on d_{av} ($F_{(2.619,99.506)}$ = 18.130; P = 0.000), on *V* ($F_{(1.719,65.322)}$ = 47.412; P = 0.000) and on V_{av} ($F_{(1.697,64.498)}$ = 46.724; P = 0.000) (tab. 3).

Test between subjects indicated that the lateral position on the left curve (1.35 m) was statistically significantly lower than that on the right curve (mean difference = -0.41 m; P = 0.000; d = 1.76 m), on the tangent 450 m long (mean difference = -0.50 m; P = 0.000; d = 1.85 m) and on the tangent 650 m long (mean difference = -0.50 m; P = 0.000; d = 1.85 m). No other mean difference was statistically significant.

Similar results were obtained for d_{av}; the average lateral position for the left curve (1.74 m) was statistically significantly lower than that for the right curve (mean difference = -0.15 m; P = 0.000; d_{av} = 1.89 m), for the tangent 450 m long (mean difference = -0.13 m; P = 0.000; d_{av} = 1.87 m) and for the tangent 650 m long (mean difference = -0.17 m; P = 0.000; d_{av} = 1.91 m). No other mean difference was statistically significant.

Test between subjects on V showed that the value of this variable for the tangent 450 m long (26.83 m/s) was statistically significantly higher than that for the left curve (mean difference = 2.09 m/s; P = 0.000; V=24.74 m/s) and for the right curve (mean difference = 2.74 m/s; P = 0.000; V=24.12 m/s). Also V for the tangent 650 m long (27.17 m/s) was statistically significantly higher than that for the left curve (mean difference = 2.43 m/s; P = 0.000) and for the right curve (mean difference = 3.05 m/s; P = 0.000). The differences between the two tangents and between the right and left curve were not statistically significant.

Similar results were obtained for V_{av}. The average overtaking speed for the tangent 450 m long (26.83 m/s) was statistically significantly higher than that for the left curve (mean difference = 1.77 m/s; P = 0.000; V_{av} = 25.06 m/s) and for the right curve (mean difference =2.39 m/s; P = 0.000 V_{av} = 24.44 m/s). Also for the tangent 650 m long, the average overtaking speed (27.19 m/s) was statistically significantly higher than that for the left curve (mean difference = 2.14 m/s; P = 0.000) and for the right curve (mean difference = 2.76 m/s; P = 0.000). The values of V_{av} between the tangents were not statistically significantly different, while for the right curve V_{av} was statistically significantly lower (24.44 m/s) than that for the left curve (mean difference = -0.62 m/s; P = 0.019).

4.4 Interaction effects

The interaction cross-section by presence/absence of cyclist affected in a statistically significant way the lateral position ($F_{(1.309,49.734)} = 6.466$; $P = 0.009$) and the average lateral position ($F_{(1.894,71.954)} = 19.533$; $P = 0.000$) (tab. 3).

The figure 3.a shows that the cyclist presence induced the driver to move towards the centerline (compared to the recorded position for cyclist absence) with a decreasing trend while the shoulder width or the bicycle lane width increased (the driver moved 0.68 m for the baseline condition; 0.52 m for the countermeasure 1 and 0.36 m for the countermeasure 2). That highlights a different level of interference, due to the presence of the cyclist, on the driver trajectory for the several cross – sections.

Figure 3 - Interaction effect of the cross-section by presence/absence of cyclist on a) lateral position; b) average lateral position

Results in terms of average lateral position (fig. 3.b) were similar to those obtained for d. It should be noted that as the shoulder (or bicycle lane) width increased, the driver travelled closer to the centerline (d_{av} was 1.85 m for baseline condition, 1.71 m per countermeasure 1 and 1.66 m per countermeasure 2) and, thus further from the cyclist.

The interaction geometric element by presence/absence of cyclist affected in a statistically significant way d_{av} ($F_{(2.178,82.754)} = 9.437$; $P = 0.000$), V ($F_{(2.564,97.439)} = 7.315$; $P = 0.000$) and V_{av} ($F_{(2.519,95.731)} = 4.314$; $P = 0.010$) (tab. 3). No interaction effect geometric element by presence/absence of cyclist was found on d ($F_{(1.692,64.305)} = 0.771$; $P = 0.447$). However, it should be noted that for absence of cyclist condition, the driver assumed on the left curve a less lateral position than that on the other geometric elements (for left curve d was 1.64 m while for the others element the values of d were between 2.02 m and 2.13 m) (fig. 4a), highlighting in this way a clear propensity to cut the left curve.

Figure 4 - Interaction effect of the geometric element by presence/absence of cyclist on a) lateral position (statistically not significant); b) average lateral position

The presence of the cyclist induced the driver to displace towards the centerline in variable extent between 0.43 m on the tangent 650 m long and 0.57 m on the left curve. It should be noted that the lateral position values when the cyclist was present are equivalent to lateral clearance between vehicle and bicycle equal to 1.11 m on tangent 650 m long, 1.18 m on tangent 450 m long, 1.26 m on right curve and 1.68 m on left curve (assuming the vehicle width equal to 1.60 m and the leftbicycle handlebar width equal to 0.20 m). It should also be noted that the displacement towards the centerline on the left curve due to the presence of the cyclist determines a distance of the vehicle left side from the opposing lane of only 0.27 m (1.07 m – 0.80 m that is the half width of the vehicle). Therefore, the cyclist presence on the left curve, inducing on the driver trajectory a concordant effect (moving away from the cyclist) with that induced by the geometry (tendency to cut the curve), determines an excessive and risky displacement of the vehicle to the opposing lane.

With respect of the average lateral position it was observed that, for absence of cyclist condition, the values of d_{av} confirms the driver propensity to cut the left curve (the minimum value equal to 1.77 m was recorded for left while for the others element the values of d_{av} were 2.01 m or 2.05 m) (fig. 4b).

The interaction effects geometric element by presence/absence of cyclist for V and V_{av} were similar (fig. 5) Results indicated that speeds on tangents were almost the same in the condition of presence and absence of the cyclist. A similar result was observed for the left curve; in this case, the driver tended to cut his/her trajectory and, thus, he/she did not need to reduce the speed. Conversely, for the right curve, the speeds (V and V_{av}) were lower for the condition of presence of the cyclist.

Figure 5 - Interaction effect of the geometric element by presence/absence of cyclist on: a) overtaking speed; b) average overtaking speed

4.5 Outcomes of the questionnaire

The results of the questionnaire showed that 62% of the drivers did not perceived risk while they overtook the cyclist for the baseline condition. For the countermeasure 1 and 2 about 80% of the drivers did not perceived risk during the interaction with the cyclist.

5. DISCUSSION

Statistical analysis showed that the effect of the cross-section was statistical significant on d and d_{av} but not on speeds (V and V_{av}). In particular, d and d_{av} were higher when the vehicle lane was wider (i.e. the shoulder or bicycle lane width was the narrowest). This finding highlights that the width of the vehicle lane affects the lateral position adopted by the driver inducing him/her to choose a trajectory close to the axis of the vehicle lane. However, the width of the vehicle lane does not affect the driver's speed. Considering that the 3 cross-sections have the same width (equal to 4.50 m, sum of the widths of the vehicle lane and shoulder or bicycle lane), the obtained result shows that the driver, for the speed adoption, perceives the 3 cross-sections in the same way, although they are differently organized in terms of lane and shoulder width. This result is consistent with previous findings that highlighted a different driver speed behavior by varying the overall width of the cross-section (Godley et al., 2004; Bella, 2013).

The effect of the presence/absence of the cyclist was statistically significant on d and d_{av}, while the recorded speeds (both the overtaking speed and the average overtaking speed) were not affected by the presence/absence of the cyclist. This means that the cyclist affected only the trajectory of the driver but not its speed. This result is in line with the outcomes of a study by Garcia et al. (2015), who observed speed reductions (from the condition of free – flow to the condition of cyclist presence) near to zero on some two-lane rural roads.

The lateral position (d) and the average lateral position (d_{av}) were higher when the cyclist was absent. Conversely, when the cyclist was present, the driver perceived him as an obstacle and, thus, he/she moved closer to the centerline of the road. This result was expected and confirms the outcomes of previous studies (e.g. Walker et al., 2014; Llorca et al., 2014; Garcia et al., 2015**).**

Interesting results were highlighted from the interaction effect cross-section by presence/absence of cyclist (statistically significant) on d and d_{av}. Results on the lateral position showed a decreasing level of influence on the driver trajectory due to the presence of the cyclist with the increasing of the shoulder or bicycle lane width (the displacement towards the centerline was 0.68 m for the baseline, 0.52 m for the countermeasure 1 and 0.36 m for the countermeasure 2). The results on average lateral position highlighted that a wider bicycle lane ensures a higher later clearance distance between driver and cyclist, allowing safer overtaking maneuver. These results confirm the crucial role of the bicycle lane width on the lateral clearance (Llorca et al., 2014; Garcia et al., 2015).

Statistical analysis showed that the geometric elements affected all the variables (d, d_{av}, V and V_{av}). The lateral position for the left curve (1.35 m) was statistically lower than that for the tangents (1.85

m) and for the right curve (1.76 m). Moreover, the result on d_{av} was similar. These findings highlight that the driver took a different trajectory on the left curve; in particular, he/she was closer to the centerline, meaning that he/she tended to cut the curve. This outcome is consistent with the findings of several studies (Felipe and Navin, 1998; Bella, 2013; Garcia et al., 2015).

The effects on V and on V_{av} were similar; the overtaking speed and the average overtaking speed were almost the same for the tangents 450 m and 650 m long (about 26.8 m/s and 27.1 m/s respectively), while were lower on the left and the right curve. These results were expected and show that the driver adopts a higher speed on the less demanding geometric elements. Moreover, for the left curve V (24.74 m/s) and V_{av} (25.06 m/s) were higher than those for the right curve (24.12 m/s and 24.44 m/s, respectively). This outcome was determined by the trend of the driver to cut the left curve; this allows him/her to maintain higher speed compared to that for the right curve.

The interaction effect geometric element by presence/absence of cyclist highlighted that the presence of the cyclist induced the driver to displace towards the centerline in variable extent for the different geometric elements. On the less demanding geometric elements, the minimum lateral clearances between driver and cyclist (equal to 1.11m on tangent 650 m long and 1.18 m on tangent 450 m long) were recorded. However, such lateral clearances (both higher than three feet, which is the minimum value suggested by several guidelines (Smith, 2009) were sufficient to allow the driver to maintain the same speed adopted in the condition of cyclist absence. On the left curve, the presence of the cyclist, inducing on the driver trajectory a concordant effect (moving away from the cyclist) with that induced by the geometry of the left curve (tendency to cut the curve), determined a high lateral clearance between driver and cyclist (1.68 m), but also an excessive and risky displacement of the vehicle to the opposing lane. This critical condition was also amplified by the high speed adopted by the driver, which was similar to that adopted for the condition of cyclist absence. On the right curve, the presence of the cyclist determined also a displacement towards the center of the road and then a lateral clearance of 1.26 m, higher than the lateral clearance values recorded in tangents. This outcome can be reasonably explained by the driver propensity to move further from the cyclist (compared to the same interaction on tangents) to perform the demanding maneuver of entering in the right curve. The complexity of the interaction with the cyclist on such demanding geometric element also led to a speed reduction compared to the cyclist absence condition.

6. CONCLUSIONS

This study aimed at analyzing the driver's behavior during the overtaking maneuver of a cyclist under three different cross-sections (all with same width, but with and without a bicycle lane and for different widths of bicycle lane) and four geometric elements of the alignment (2 tangents with different lengths, right curve and left curve). The main results were the following.

The width of the vehicle lane affects the lateral position adopted by the driver, inducing him/her to select a trajectory that is close to the axis of the vehicle lane, but it does not affect the driver's speed. The same driver speed behavior recorded on the 3 cross-sections seems to depend on the overall width of the cross-section (the same for the 3 cross-sections) and not on the different widths of the vehicle lane and shoulder or bicycle lane.

The cyclist affected the trajectory of the driver but not his/her speed. The driver perceived the cyclist as an obstacle and, thus, he/she moved closer to the centerline of the road without reducing the speed.

The presence of the cyclist determined different levels of influence on driver's trajectory for the 3 cross-sections: compared to the lateral position adopted when the cyclist was absent, the displacement towards the centerline was decreasing with the increasing of the shoulder or bicycle lane width. In addition, it was clear that a wider bicycle lane ensures a higher later clearance distance between driver and cyclist, allowing safer overtaking maneuver.

The driver had a different behavior in terms of lateral position on the left curve compared to those that were recorded on the other geometric elements. More specifically, the driver travelled nearest to the centerline on the left curve, meaning that he/she tended to cut the trajectory. The results on the speeds were expected and showed that the driver adopts a higher speed on the less demanding geometric elements.

The interferences of the cyclist on driver's behavior depend on the geometric elements. On tangents, the lowest lateral clearances (nevertheless higher than that the suggested minimum values in literature) were recorded and no speed reduction, compared to the condition of cyclist absence, was observed. On the left curve, the highest lateral clearance was recorded. Two concordant causes determined it: the tendency of the driver to move away from the cyclist and to cut the curve. This led to an excessive and risky displacement of the vehicle to the opposing lane, whose criticality was also emphasized by the high speed adopted by the driver. Finally, on the right curve, the lateral clearance was higher than that recorded on tangents, probably due to the necessity of the driver to perform the demanding maneuver of entering in the right curve, which also determined a speed reduction.

These results provide useful suggestions for the most efficient cross-section reorganization of existing two-lane rural roads to improve the road safety. More specifically, it should be recommended to:

These results provide useful suggestions for the most efficient cross-section reorganization of existing two-lane rural roads to improve the road safety. More specifically, it should be recommended to:

- reserve as much as possible wide bicycle lanes to ensure higher later clearance distances between driver and cyclist during the overtaking maneuver;
- reduce the speed limit to reduce the dangerous dynamic effects on the cyclist (in particular on tangents, where the less lateral clearance was recorded) and to make less critical and less difficult the overtaking maneuver of a cyclist on the curves.

The current study investigated only one value of the curve radii (200 m); considered the criticality of the driver-cyclist interactions on the curves, further analysis should be carried out to study the driver behavior on a wide range of radii values. In addition, considering that the oncoming traffic was found by several studies in literature as one as the main variables that affect the driver behavior during the overtaking maneuver of a cyclist, further researches should be focused to evaluate the influence of several levels of oncoming traffic. Further studies could extend also the analysis to the effects of groups of cyclists, which is a frequent condition of cycling on two-lane rural roads.

Finally, it should be highlighted that the present study was conducted using the advanced driving simulator of the Department of Engineering – Roma Tre University. Therefore, the caveats that are usually referred to driving simulator studies must be raised. Among these, the main is referred to the possibility that the driver's behavior observed in driving simulation can be different from that in the real world. Although the driving simulator used in the present study was validated for the analysis of drivers' behaviors on two-lane rural roads (Bella, 2008b), it is not possible to implicitly assume the validity of the simulator for the driver – cyclist interaction study (Bella, 2009). In other words, the actual correspondence between the behavior observed in simulation and that recorded on field in the same condition of driver – cyclist interaction should be verified. A such specific validation study has not yet been developed. However, it should be noted that for the aim of the current study, only the relative validity (which refers to the correspondence between the effects of different variations in the driving situation) is required (Tornos, 1998). It should also be noted that the recorded data showed that the drivers reacted differently at the different road scenarios, giving reasonable results. In addition, the obtained results are consistent with the outcomes of previously studies conducted on field. Therefore, there are reasonable guarantees that the present driving simulator study provides reliable findings in terms of relative effects induced by cross-section configurations and geometric elements on the driver's behavior during the interaction with a cyclist along a two-lane rural road.

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REFERENCES

AASHTO - American Association of State Highway and Transportation Official (2012). Guide for the Development of Bicycle Facilities, fourth ed.

ACI-ISTAT. (2012). Ciclisti – 2012. http://www.aci.it/fileadmin/documenti/studi_e_ricerche/dati_statistiche/incidenti/Utenti_non_motorizzati_e_incidenti.pdf

Ata, M.K., Langlois, R.G. (2011). Factoring Cycling in Transportation Infrastructure: Design Considerations Based on risk Exposure, ITE Journal. 2011. Vol. 81(8) pp. 49–53.

Bella, F. (2005). Validation of a driving simulator for work zone design. Transportation Research Record: Journal of the Transportation Research Board, No 1937. TRB of the National Academies, Washington, DC, pp. 136–144.

Bella, F. (2008a). New model to estimate speed differential in tangent–curvetransition. Adv. Transp. Stud. Int. J. Vol. 15 pp. 27–36, http://dx.doi.org/10.4399/97888548186823

Bella, F. (2008b). Driving simulator for speed research on two-lane rural roads. Accid. Anal. Prev. Vol. 40 pp. 1078–1087, http://dx.doi.org/10.1016/j.aap.2007.10.015

Bella, F. (2009). Can the driving simulators contribute to solving the critical issues ingeometric design? Transp. Res. Rec. J. Transp. Res. Board 2138, pp. 120–126, http://dx.doi.org/10.3141/2138-16

Bella, F. (2011). How traffic conditions affect driver behavior in passing maneuver. Advanced in Transportation Studies International Journal. (Spec. Issue) pp. 113–126. http://dx.doi.org/10.4399/978885484657911

Bella, F. (2013). Driver perception of roadside configurations on two-lane rural roads: Effects on speed and lateral placement. Accident Analysis and Prevention. Vol. 50 pp. 251-262, doi: 10.1016/j.aap.2012.04.015

Bella, F. (2014a). Driver performance approaching and departing curves: drivingsimulator study. Traffic Injury Prev. 15, 310–318, http://dx.doi.org/10.1080/15389588.2013.813022

Bella, F. (2014b). Operating speeds from driving simulator tests for road safetyevaluation. Journal of Transportation Safety and Security. 6 (03), 220-234, http://dx.doi.org/10.1080/19439962.2013.856984

Bella, F., Silvestri, M. (2015). Effects of safety measures on driver's speed behavior at pedestrian crossings. Accident Analysis and Prevention. Vol. 83 pp. 111–124. http://dx.doi.org/10.1016/j.aap.2015.07.016

Bella, F., Silvestri, M. (2016). Driver's braking behavior approaching pedestrian crossings: a parametric duration model of the speed reduction times. Journal of Advaced Transportation. Vol. 50 630–646, doi: 10.1002/atr.1366.

Bella, F., Calvi, A. (2013). Effects of simulated day and night driving on the speed differential in tangent–curve transition: a pilot study using driving simulator. Traffic Injury Prev. Vol. 14 (4), 413–423, http://dx.doi.org/10.1080/15389588.2012.716880

Bella, F., Calvi, A., D'Amico, F. (2014). Analysis of driver speeds under night driving conditions using a driving simulator. J. Safety Res. Vol. 49, 45–52, http://dx.doi.org/10.1016/j.jsr.2014.02.007

Bíl, M., Bílová, M., Müller, I. (2010). Critical factors in fatal collisions of adult cyclists with automobiles. Accident Analysis and Prevention. Vol. 42, 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. Accident Analysis and Prevention. Vol. 49 pp. 404–409, doi:10.1016/j.aap.2012.03.011.

Chapman, R.J., Noyce, D.A. (2012). Observations of driver behaviors during overtaking of bicycles on rural roads. Transportation Research Record. 2321, 38-45.

Chapman, R.J., Noyce, D.A. (2014). Influence of roadway geometric elements on driver behavior when overtaking bicycles on rural roads. Journal of Traffic and Transportation Engineering (English Edition). Vol. 1, 28 – 38.

Chaurand, N., Delhomme, P. (2013). Cyclists and drivers in road interactions: a comparison of perceived crash risk. Accident Analysis and Prevention Vol. 50, 1176-1184.

Chen, P., Shen, Q. (2016). Built environment effects on cyclist injury severity in automobile-involved bicycle crashes. Accident Analysis and Prevention. Vol 86, 239-246.

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. Vol. 56, 32–41.

D.P.R. (2006). Decreto Presidente della Repubblica 16 Dicembre 1992 nr.495 aggiornato al D.P.R. 6 marzo 2006, n.153. Regolamento di esecuzione e di attuazione del Nuovo Codice della Strada (in Italian).

Dozza, M., Schindler, R., Bianchi-Piccinini, G., Karlsson, J. (2016). How do drivers overtake cyclists? Accident Analysis and Prevention. Vol. 88, 29-36.

Duivenvoorden, K., Hogema, J., Hagenzieker, M., Wegman, F. (2015). The effects of cyclists present at rural intersections on speed behavior and workload of car drivers: a driving simulator study. Traffic Injury Prevention. Vol. 16 pp. 254-259, doi: 10.1080/15389588.2014.937484

European Commission. (2015). Traffic Safety Basic Facts on Cyclists. European Commission, Directorate General for Transport, June 2015. http://ec.europa.eu/transport/road_safety/pdf/statistics/dacota/bfs2015_cyclists.pdf)

Felipe, E., Navin, F. (1998). Automobiles on horizontal curves: experiments and observations. Transportation Research Record 1628, TRB. National Research Council, Washington, DC, 50-56.

Frings, D., Parkin, J., Ridley, A.M. (2014). The effects of cycle lanes, vehicle to kerb distance and vehicle type oncyclists' attention allocation during junction negotiation. Accident Analysis and Prevention. Vol. 72, 411-421.

Fruhen, L.S., Flin R. (2015). Car driver attitudes, perceptions of social norms and aggressive driving behaviour towards cyclists. Accident Analysis and Prevention Vol. 83, 162-170.

García, A., Domènech, A.A., Llorca, C., Gómez, F.A., Ferrer, V. (2015). Effects of road geometry on the interaction between cyclist and vehicles on two-lane rural roads. 5th International Symposium on Highway Geometric Design.

Godley, S.T., Triggs, T.J., Fildes, B.N. (2004). Perceptual lane width, wide perceptual road centre marking and driving speeds. Ergonomics 47 (3), 237-256.

Hamann, C., Peek-Asa, C. (2013). On-road bicycle facilities and bicycle crashes in Iowa, 2007–2010. Accident Analysis and Prevention Vol. 56, 103-109.

Health Organization (2014). Development of methods for quantification of health benefits from walking and cycling. http://www.euro.who.int/en/health-topics/disease-prevention/physical-activity/activities/hepa-europe/hepa-europe-projects-and-working-groups/development-of-methods-for-quantification-of-health-benefits-from-walking-and-cycling.

Heinen, E., van Wee, B., Maat, K. (2010). Commuting by bicycle: an overview of the literature. Transp. Rev. Vol. 30, 59–96.

Insurance Institute for Highway Safety. (2015) http://www.iihs.org/iihs/topics/t/pedestrians-and-bicyclists/fatalityfacts/bicycles).

ISTAT. (2015). Rapporto ISTAT sugli incidenti stradali. Anno 2014 (in Italian).

Jensen, S.U. (2007). Pedestrian and bicyclist level of service on roadway segments. Transport. Res. Rec. 2031, 43-51.

Kay, J.J., Savolainen, P.T., Gates, T.J., Datta, T.K. (2014). Driver behavior during passing maneuvers in response to a share the road sign treatment. Accident Analysis and Prevention. Vol. 70, 92-99.

Kim, J.K., Kim, S., Ulfarsson, G.F., Porrello, L.A. (2007). Bicyclist injury severities in bicycle – motor vehicle accidents. Accident Analysis and Prevention. Vol 39, 238-251.

Llorca, C., Domenech, A.A., Gomez, F.A., Ferre, V., Garcia, A. (2014). Motor vehicles overtaking cyclists on two – lane rural roads: analysis on speed and lateral clearance. International Cycling Safety Conference 18 – 19 November 2014, Göteborg, Sweden.

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. Vol. 48, 451-456.

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

Ministro dei Lavori pubblici. (1999). Regolamento per la definizione delle caratteristiche tecniche delle piste ciclabili. D.M. 30 novembre 1999 (G.U. n. 225 del 26.9.2000) (in Italian).

Ministry of Infrastructures and Transports, 2001. Decreto Ministeriale del 5/11/2001. Norme funzionali e geometriche per la costruzione delle strade. Istituto Poligrafico dello Stato, Roma (in Italian).

Parkin, J., Meyers, C. (2010). The effect of cycle lanes on the proximity between motor traffic and cycle traffic. Accident Analysis and Prevention. Vol. 42, 159-165.

Provincia di Milano. (2006). Linee guida per la progettazione delle reti ciclabili (in Italian).

Savolainen, P.T., Gates, T.J., Todd, R.G., Datta, T.K., Morena, J.G. (2012). Lateral placement of motor vehicles when passing bicyclists - Assessing influence of centerline rumble strips. Transportation Research Record: Journal of the Transportation Research Board, No. 2314, Transportation Research Board of the National Academies, Washington, D.C., 14-21. doi: 10.3141/2314-03.

Schepers, P., Hagenzieker, M., Methorst, R., van Wee, B., Wegman, F. (2014). A conceptual framework for road safety and mobility applied tocycling safety. Accident Analysis and Prevention Vol. 62, 331-340.

Shackel, S.C., Parkin J. (2014). Influence of road markings, lane widths and driver behaviour on proximity and speed of vehicles overtaking cyclists. Accident Analysis and Prevention Vol.73, 100-108.

Smith, G. (2009). 50 State survey of 3 ft passing laws. Retrieved from http://www.safe-route.org/laws/passing.php

Stone, M., Broughton, J. (2003). Getting off your bike: cycling accidents in Great Britain in 1990–1999. Accident Analysis and Prevention. Vol. 35, 549-556.

Tornos, J. (1998). Driving behaviour in a real and a simulated road-tunnel: a validation study. Accid. Anal. Prev. Vol. 30 (4), 497-503.

Vanparijs, J., Panis, L.I., Meeusen, R., de Geus, B. (2015). Exposure measurement in bicycle safety analysis: a review of the literature. Accident Analysis and Prevention. Vol. 84, 9-19.

Walker, I. (2007). Drivers overtaking bicyclists: objective data on the effects of riding position, helmet use, vehicle type and apparent gender. Accident Analysis and Prevention. Vol. 39, 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. Accident Analysis and Prevention. Vol. 64, 69-77.

Wegman, F., Zhang, F., Dijkstra, A. (2012). How to make more cycling good for road safety? Accident Analysis and Prevention Vol. 44, 19-29.

Zeuwts, L.H.R.H., Vansteenkiste, P., Deconinck, F.J.A., Cardon, G., Lenoir, M. (2016). Hazard perception in young cyclists and adult cyclists. Accid. Anal. Prev. In press. http://dx.doi.org/10.1016/j.aap.2016.04.034

TABLE CAPTIONS

Table 1 - Descriptive statistics.

Table 2 – Statistically significant main and interaction effects

Table 3 –Main and interaction effects on dependent variables

Table 1 - Descriptive statistics.

Cross-section	Cyclist condition	Geometric element	Lateral clearance [m]	d [m]		d_{av} [m]		V [m/s]		V_{av} [m/s]	
			Average	Average	SD	Average	SD	Average	SD	Average	SD
Baseline	Present	Right curve	1.28	1.47	0.44	1.84	0.26	23.58	3.02	24.11	2.71
		Left curve	1.66	1.09	0.59	1.83	0.28	25.52	3.06	25.58	2.66
		Tangent L = 450 m	1.15	1.60	0.36	1.85	0.27	27.01	1.77	26.99	1.71
		Tangent L = 650 m	1.10	1.65	0.44	1.87	0.32	27.23	3.14	27.22	3.05
	Absent	Right curve	0.42	2.33	0.49	2.29	0.37	24.74	3.09	24.79	3.03
		Left curve	0.96	1.79	0.55	1.91	0.29	24.93	2.75	25.20	2.60
		Tangent L = 450 m	0.58	2.17	0.34	2.17	0.33	26.91	2.04	26.89	1.99
		Tangent L = 650 m	0.51	2.24	0.29	2.22	0.26	27.22	1.80	27.22	1.74
Countermeasure 1 (bicycle lane = 1.5 m)	Present	Right curve	1.26	1.49	0.38	1.74	0.21	23.63	3.05	24.29	2.59
		Left curve	1.65	1.10	0.27	1.70	0.24	24.96	3.16	25.36	2.83
		Tangent L = 450 m	1.17	1.58	0.25	1.65	0.25	26.97	2.20	26.97	2.21
		Tangent L = 650 m	1.11	1.64	0.29	1.76	0.21	26.93	1.90	27.01	1.80
	Absent	Right curve	0.83	1.92	0.40	1.96	0.30	24.82	3.23	24.81	3.04
		Left curve	1.19	1.56	0.32	1.71	0.19	24.03	4.83	24.93	2.56
		Tangent L = 450 m	0.39	2.36	0.22	1.99	0.21	26.93	2.44	26.89	2.44
		Tangent L = 650 m	0.70	2.05	0.19	2.01	0.20	27.09	1.98	27.09	1.97
Countermeasure 2 (bicycle lane = 1.75 m)	Present	Right curve	1.24	1.51	0.36	1.66	0.20	23.49	2.87	24.12	2.63
		Left curve	1.74	1.01	0.42	1.58	0.35	24.35	3.58	24.30	5.10
		Tangent L = 450 m	1.21	1.54	0.22	1.66	0.20	26.82	2.24	26.72	2.09
		Tangent L = 650 m	1.11	1.64	0.25	1.71	0.22	26.95	2.13	27.06	2.08
	Absent	Right curve	0.93	1.82	0.36	1.86	0.25	24.46	3.30	24.49	3.16
		Left curve	1.20	1.55	0.41	1.70	0.22	24.09	2.86	24.31	2.76
		Tangent L = 450 m	0.89	1.86	0.30	1.87	0.28	25.88	2.82	25.88	2.79
		Tangent L = 650 m	0.84	1.91	0.23	1.90	0.23	27.60	2.51	27.57	2.48

Table 2 – Statistically significant main and interaction effects

Independent variable	**F**	**P**	**Wilk's Λ**	**Partial Eta Squared**	**Observed Power**
Cross- section	$F_{(8,31)} = 36.290$	0.000	0.096	0.904	1
Presence/Absence of cyclist	$F_{(4,35)} = 49.774$	0.000	0.150	0.850	1
Geometric element	$F_{(12,27)} = 19.483$	0.000	0.104	0.896	1
Cross- section by Presence/Absence of cyclist	$F_{(8,31)} = 9.222$	0.000	0.296	0.704	1
Geometric element by Presence/Absence of cyclist	$F_{(12,27)} = 11.318$	0.000	0.166	0.834	1

Table 3 –Main and interaction effects on dependent variables

Independent variable	**Dependent variable**	**F**	**P**
Cross- section	Lateral position *(d)*	$F_{(1.359,51.627)} = 9.004$	0.002
	Average Lateral position *(d_{av})*	$F_{(1.708, 64.918)} =112.055$	0.000
Presence/Absence of cyclist	Lateral position *(d)*	$F_{(1,38)} = 148.546$	0.000
	Average Lateral position *(d_{av})*	$F_{(1,38)} = 156.264$	0.000
Geometric element	Lateral position *(d)*	$F_{(2.374,90.198)} = 28.248$	0.000
	Average Lateral position *(d_{av})*	$F_{(2.619,99.506)} = 18.130$	0.000
	Overtaking speed *(V)*	$F_{(1.719,65.322)} = 47.412$	0.000
	Average Overtaking speed *(V_{av})*	$F_{(1.697,64,498)} = 46.724$	0.000
Cross- section by Presence/Absence of cyclist	Lateral position *(d)*	$F_{(1.309,49.734)} = 6.466$	0.009
	Average Lateral position *(d_{av})*	$F_{(1.894,71.954)} = 19.533$	0.000
Geometric element by Presence/Absence of cyclist	Average Lateral position *(d_{av})*	$F_{(2.178,82.754)} = 9.437$	0.000
	Overtaking speed *(V)*	$F_{(2.564,97.439)} = 7.315$	0.000
	Average Overtaking speed *(V_{av})*	$F_{(2.519,95.731)} = 4.314$	0.010

FIGURE CAPTIONS

Figure 1 - Cyclist on cross-section configurations a) baseline condition, b) countermeasure 1, c) countermeasure 2

Figure 2 - Variables of the driver-cyclist interaction

Figure 3 - Interaction effect of the cross-section by presence/absence of cyclist on a) lateral position; b) average lateral position

Figure 4 - Interaction effect of the geometric element by presence/absence of cyclist on a) lateral position (statistically not significant); b) average lateral position

Figure 5 - Interaction effect of the geometric element by presence/absence of cyclist on: a) overtaking speed; b) average overtaking speed

Figure 1

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Figure 2

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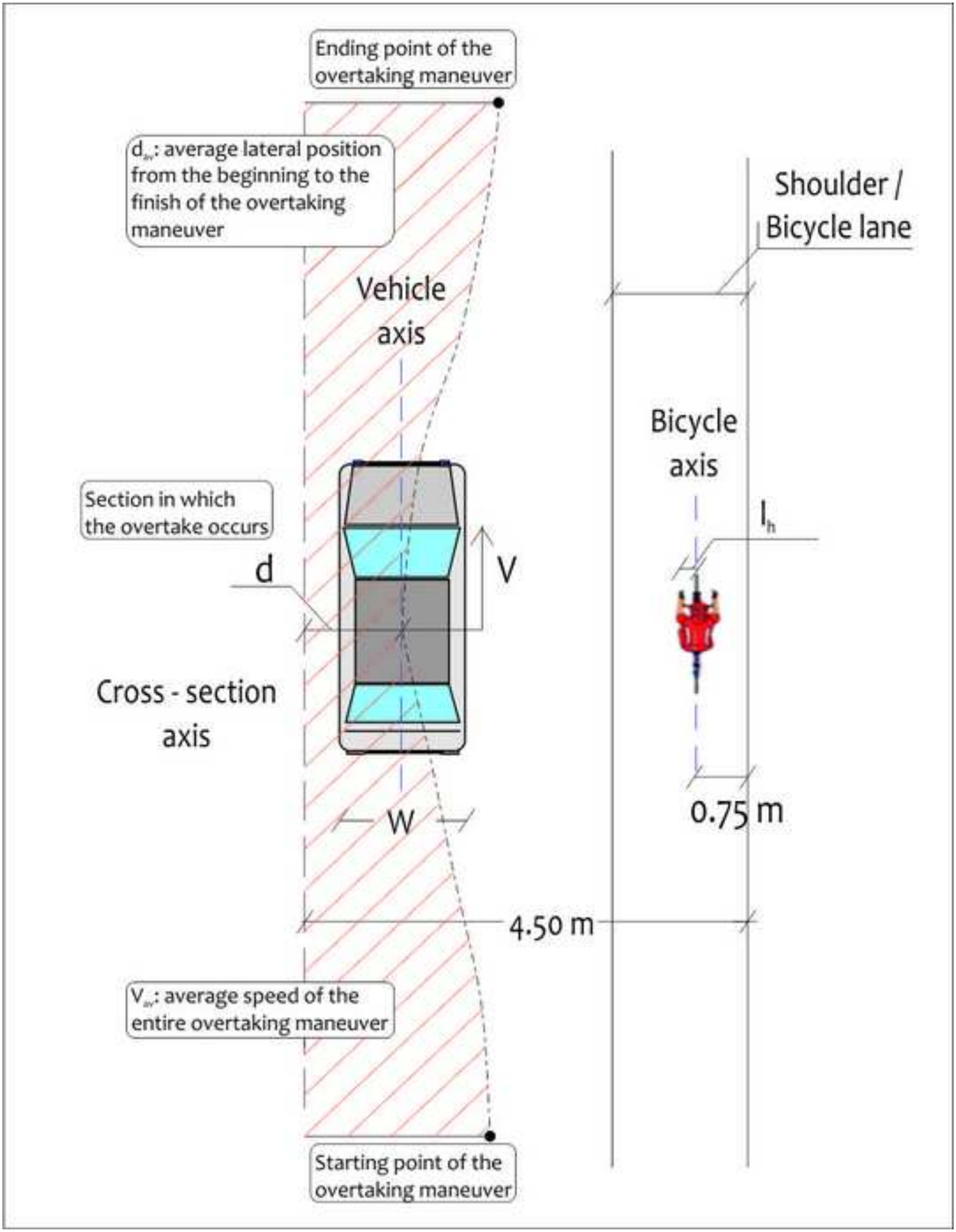

Figure 3

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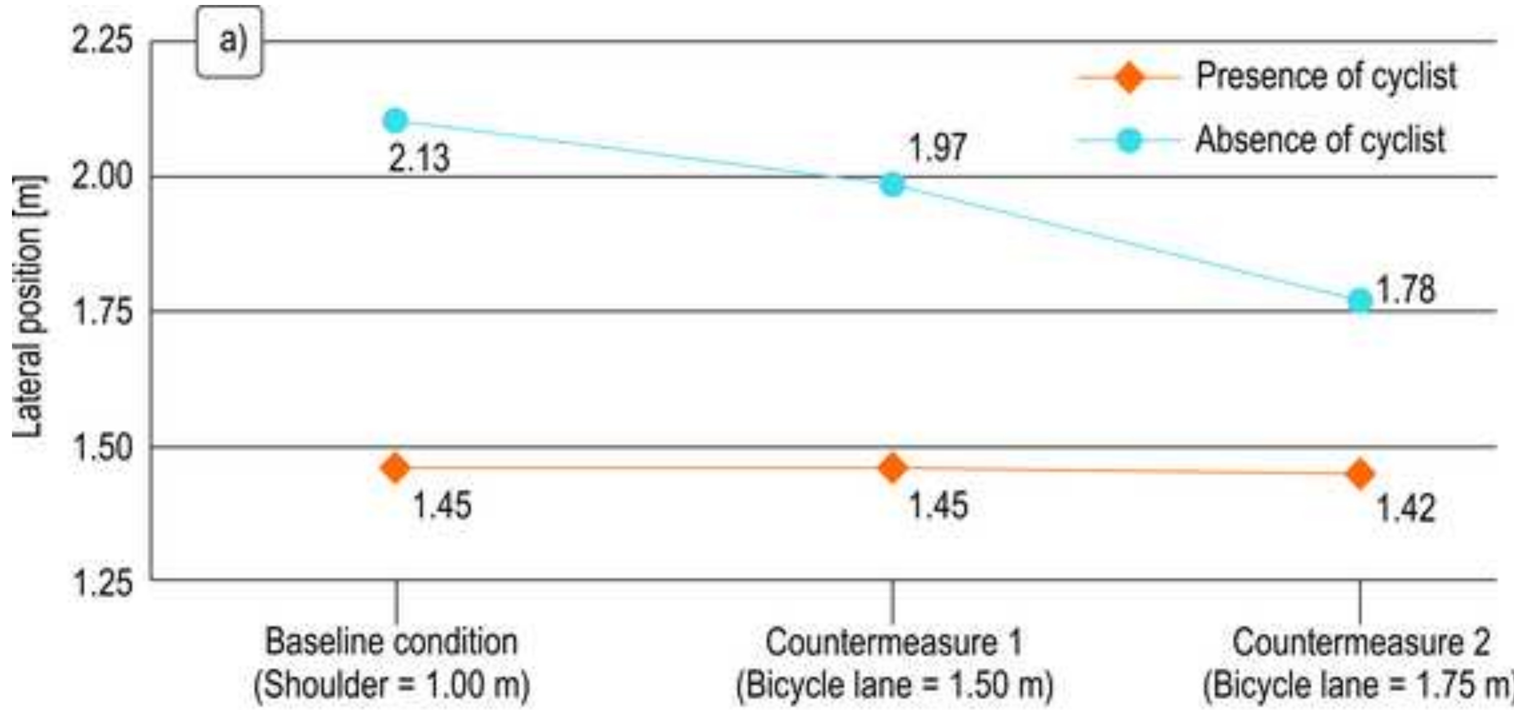

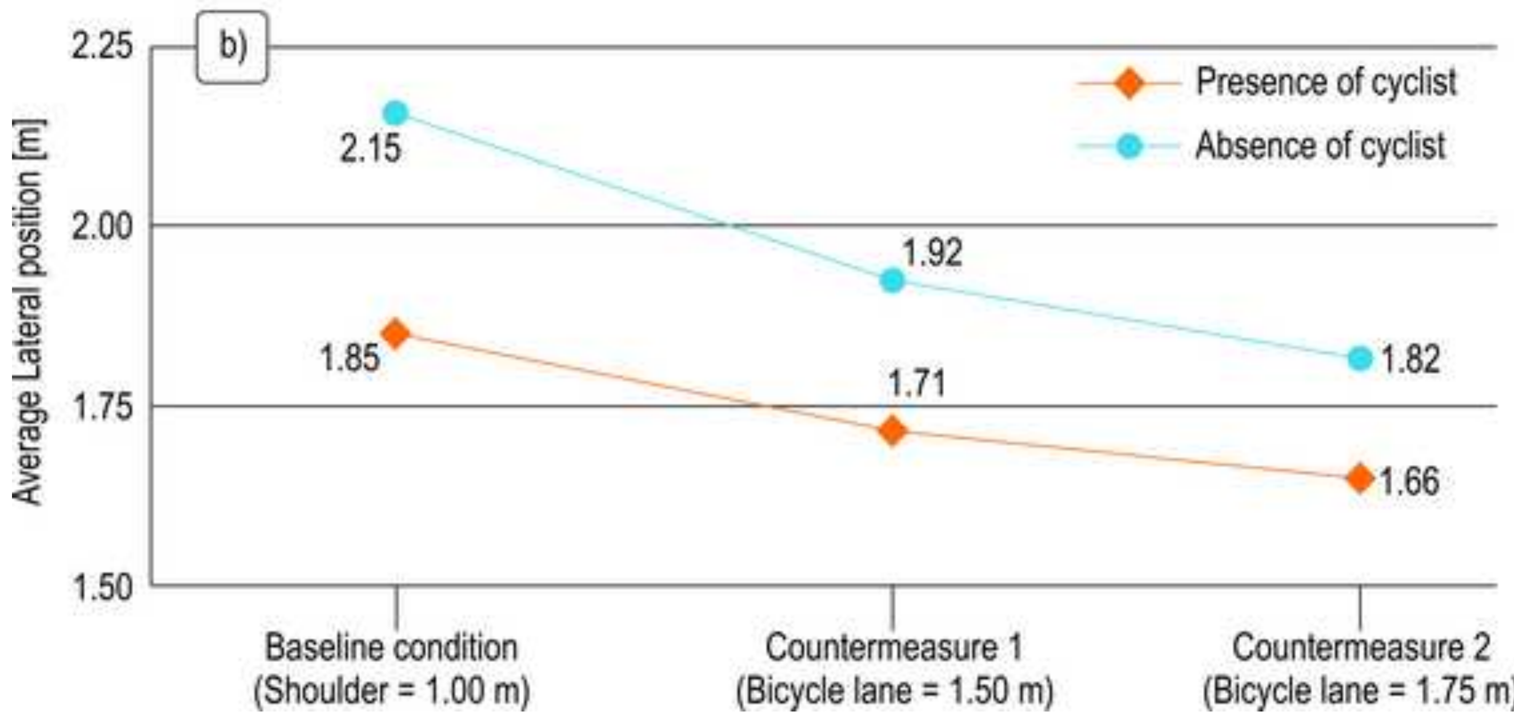

Figure 4
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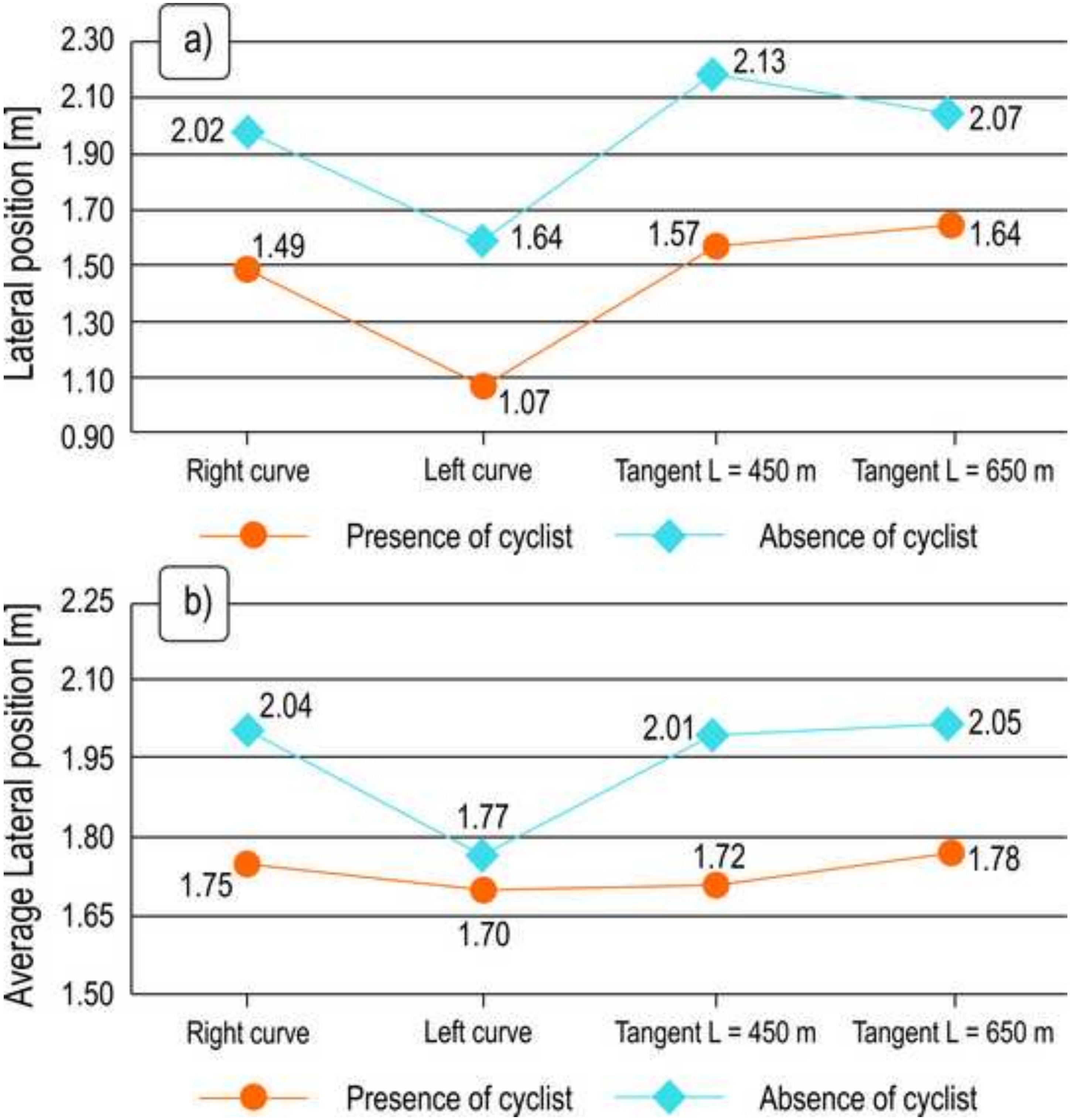

Figure 5

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