When do drivers yield to cyclists at unsignalized roundabouts? Empirical evidence and behavioral analysis

Ary P. Silvano[*]
Department of Transport Science,
KTH - Royal Institute of Technology,
Teknikringen 72, Stockholm 100 44, Sweden.
Telephone: 46(0) 8790 8427
Fax: 46(0)8 21 2899
Email: aryps@kth.se

Xiaoliang Ma
Department of Transport Science,
KTH - Royal Institute of Technology,
Teknikringen 72, Stockholm 100 44, Sweden.
Telephone: 46(0)8 790 8426
Email: xiaoliang.ma@abe.kth.se

Haris N. Koutsopoulos
Department of Civil and Environmental Engineering
Northeastern University
360 Huntington Avenue
Boston, MA 02115
Telephone: 617 373 2444
Email: haris@mit.edu

* Corresponding author: aryps@kth.se

Word count: 5430 words (Abstract + Text +References) +6 figures & tables (6 X 250) = 6930 words

Submission Date: March 15, 2015

Ary P. Silvano, Xiaoliang Ma and Haris N. Koutsopoulos

Abstract

Cycling popularity has shown an increasing trend during the last decades in many cities of Europe and USA because of its environmental and health benefits. However, cyclists are frequently involved in traffic accidents, especially, when they interact with vehicles at unsignalized intersections. There is still lack of evidence and analysis on how such interaction is performed. This paper explores empirical evidence of the vehicle-bicycle interaction on a typical Swedish roundabout, and provides insights into factors influencing car drivers' yielding decisions when they interact with cyclists. The vehicle-bicycle interaction was divided into category groups (*Non-Conflict*, *Conflict*, *Yield,* and *Non-Yield*) and their speed differences were analyzed by group. Furthermore, a discrete choice model was developed to estimate behavioral aspects of such interactions. The observed data showed a higher and significant speed variation among vehicles, whereas bicycles exhibited lower variation across the groups. The modelling results revealed that the yielding probability decreased when the speed of the vehicle was higher. On the other hand, the bicycle speed had little impact on drivers' decision to yield. More importantly, the yielding probability increased significantly by the proximity of the cyclist to the conflicting zone. The yielding rate of drivers can be improved by keeping vehicles' speed under 20 km/h, as drivers have the capacity to detect and yield to cyclists.

Keywords: Vehicle-bicycle interaction, roundabout, yielding behavior, logistic regression models.

1. INTRODUCTION

Bicycling, as a non-motorized mode, is becoming increasingly relevant in transport planning because of its potential benefits for energy, environment, and health. Researchers and public authorities consider bicycling as a mode of transport and cyclists as travelers. Thus bicycling is no longer considered only a recreational activity. In Stockholm, the number of cyclists has shown an increasing trend in the last decade, especially for trips towards the inner City *(1)*. In addition, a number of bicycling sharing systems (*BSS*) have been introduced (and become popular) in many cities around the world, overcoming some of the problems related to bicycling and providing means for one-way trips supporting public transport systems *(2, 3)*. However, bicycling safety is still the focus of attention and requires a better understanding of bicycling needs and relationships with other modes of transport. Especially, the interaction with motorized vehicles is a crucial aspect for the public, practitioners, and researchers. According to the literature, vehicle-bicycle interactions can be divided into three main types, depending on the interaction as follows:

- ✓ Longitudinal interaction (Vehicle-bicycle interaction next to links). This situation happens when cyclists travel on bicycle lanes or paths next to the traffic stream. Safety considerations are mainly the width of the bicycle lane/path, vehicles' speed, and vehicle and bicycle volumes *(4, 5, 6, 7)*;
- ✓ Mixed interaction (Vehicle-bicycle longitudinal interaction within links). This interaction occurs when drivers and cyclists share the road without any physical barrier to divide the travel modes. Safety considerations are the road width, overtaking opportunities, lateral lane position, vehicle and bicycle speeds and volumes *(8, 9)*.
- ✓ Crossing interaction (Vehicle-bicycle interaction at crosswalks). Two types of crossings can be considered: signalized and unsignalized intersections. At signalized intersections, traffic lights allow for separation of primary conflicts. The remaining secondary conflicts e.g., vehicle turning right or left and cyclist heading through, may lead to serious conflicts/accidents. On the other hand, at unsignalized crossings (including roundabouts) priority rules govern vehicle-bicycle interactions.

Normally, at these unsignalized crosswalks, cyclists have priority above vehicle traffic according to the traffic regulations in Sweden. However in reality, such *"priority"* is also based on expectations and assumptions *(10)* i.e., the expectation that the driver has detected the approaching conflicting cyclist and the driver being able or willing to give way. According to Svensson and Pauna *(11),* the yielding rate increases as the bicycle flow gets higher and give-way signs increase the yielding rate when the signs are located before the crossing. Furthermore, the authors report that drivers' yielding rate to cyclists in Sweden is on average 58% in Sweden. Consequently, there is still a large proportion of drivers who do not comply with the *"expectation"* to yield to cyclists. Other studies have shown that the yielding rate decreases as the speed of the vehicle increases due to the fact that the driver has less time to detect and react to the presence of cyclists *(12)*.

In Sweden, vehicles exiting roundabouts have the responsibility to yield to pedestrians and cyclists on the crosswalks. According to the literature, there is a large percentage (>40%) of car drivers who fail to fulfill the yielding expectation. From a behavioral perspective, it is important to identify factors which might contribute to this large percentage of failures. One of the most important factors is the speed of the vehicle. According to Räsänen and Summala *(13)* vehicles at higher speeds have difficulties to observe cyclists, leading to a failure to yield to the cyclist. At high speeds, car drivers have less time to detect cyclists, and to react accordingly. For instance, Summala et al., *(14)* investigated drivers' visual search when interacting with cyclists at T-intersections governed by priority rules in Finland. They found that drivers turning right focused their attention to traffic coming from the left and scanned the right leg less frequently and also later in the process. The authors explained the behavior as one where drivers focused on the traffic on the left considering it much more frequent and dangerous compared to less frequent traffic on the right during the critical phase. They evaluated the impact of speed humps on drivers' visual search as well and concluded that speed reduction measures can result in lower vehicle speeds and more time to focus on cyclists approaching from the right. In another study *(15)* an in-depth analysis of vehicle-bicycle collisions was conducted. The authors investigated and reconstructed more than 180 vehicle-bicycle accidents in Finland. In 37% of the collision cases (related directly to two-way bicycle pathways and intersections governed by priority rules), both the driver and the cyclist did not realize the presence of or yielded to the other party involved. The authors identified two mechanisms underlying the collisions: i) lack of attention resulting in not detecting other road users and ii) unjustified expectations with respect to the behavior of the other road user. The most common collision involved vehicles turning right and cyclists approaching from behind on the right side of the vehicle. An explanation was that drivers pay more attention to the traffic on the left. In these accidents, 11% of the drivers did notice the cyclist just before impact. On the other hand, 68% of the cyclists did notice the driver and 92% of those cyclists believed that the driver would yield as expected.

Wood et al., *(16)* evaluated drivers' perceptions and attitudes towards cyclists. The authors reported that most of the vehicle-bicycle crashes were caused by the driver being *"not-able-to-see"* the cyclist on time to avoid the collision. They also found that cyclists overestimated the distance at which they would be recognized by a driver by almost 100%. Another important aspect of the vehicle-bicycle interaction is the "risk perception" i.e., how dangerous a traffic situation is perceived by either the cyclist or the driver. Chaurand et al. *(17)* evaluated several vehicle-bicycle common crash situations, and found that the perceived risk of an accident decreased with experience for both cyclists and drivers in such situations. They also found that the perceived risk was higher for drivers compared to cyclists in the same traffic situation.

Understanding vehicle-bicycle interactions is still an important topic for investigation. Two main issues are identified through literature review. The driver detecting and reacting to an approaching cyclist during a right turning maneuver needs further investigation. More importantly, the driver yielding decision process and its influential factors, especially at unsignalized crosswalks, should be better understood so that models and tools can be developed to facilitate the evaluation of different policies or engineering treatments for a better bicycling environment. Therefore, this paper aims at collecting and analyzing empirical evidence of the vehicle-bicycle interaction process at an unsignalized roundabout. Such evidence can provide insights into factors which influence drivers' behavior to fulfill other users' expectations. Specifically, the factors directly affecting the yielding decision of drivers are explored using statistical modelling approaches. The rest of the paper is organized as follows: Section 2 describes the data collection and analysis procedures. Section 3 presents a statistical approach to model the yielding decision process by car drivers. Section 4 presents the empirical results and discussion on the essential factors obtained by model estimation, and the paper is finally concluded in Section 5.

2. DATA COLLECTION AND ANALYSIS

2.1 Vehicle-bicycle interaction zones

Generally, in Sweden, teamwork is promoted among drivers within the traffic system to account for a polite and safe interaction. Unsignalized crosswalks are normally governed by priority rules. Drivers exiting a roundabout have the responsibility to give way to any other road user traversing the crosswalk. Normally, before drivers reach the crosswalk, they are expected to examine the situation upstream into the sidewalk or road for the possible presence of cyclists. Similarly, cyclists are expected to look for vehicles as they approach the crosswalk to ensure a safe crossing. Due to the different dynamics, the vehicle-bicycle interaction comprises two important zones:

- ✓ A conflict zone (*CZ*) where the vehicle and bicycle trajectories meet or cross with potential collision if trajectories are sustained.
- ✓ An interaction zone (*IZ*) where the driver and the cyclists begin to interact or negotiate to avoid a potential collision.

The *CZ* zone is often painted at priority intersections (including roundabouts) and can be considered the whole crosswalk. Therefore, the *CZ* is a common and overlapping area for both, vehicle and bicycle. On the other hand, different vehicle and bicycle dynamics, such as speed, acceleration, reaction times, and braking forces, imply that drivers and cyclists begin monitoring each other at different locations from the *CZ*. Therefore, two different interaction zones are defined:

- ✓ Car *IZ* begins at the *CZ* and extends further into the roundabout.
- ✓ Bike *IZ* begins at the *CZ* and extends further upstream into the sidewalk or bicycle path/lane.

Each *IZ* has different lengths due to different vehicle and bicycle characteristics. The car *IZ* extends up to 10 m from the *CZ*. Due to the specific geometry of the studied roundabout, the driver has full visual coverage over the sidewalk at 10 m distance from the *CZ*. The driver can detect the presence of cyclists, and is able to react and decide whether to fulfill the yielding expectation or not. Therefore, the location is considered as the decision point for drivers and may vary among different facilities and drivers. On the other hand, the bike *IZ* extends up to 30 m from the *CZ*, divided into 3 segments of 10 m each. The segments are defined as *S1*, *S2* and *S3* as shown in Figure 1(a).

2.2 Data collection

To investigate drivers' yielding behavior to cyclists, vehicle and bicycle trajectories are needed. Information on the presence of yielding events is also crucial for the analysis. As a result, data acquisition to analyze drivers' yielding decisions is a labor intensive task. One way to ease and overcome such difficulties is by video recordings and data extraction using image processing. During the data collection, vehicle-bicycle interactions at a typical roundabout in Stockholm were observed. The data was collected on a weekday in the autumn 2013 during the afternoon rush hour

(16:00 – 18:00). Weather conditions were normal, dry, and clear. Video equipment was used to capture vehicle-bicycle interactions. A mast tower of 15 m in height with 2 cameras was installed and configured to visually cover the conflict and interaction zones. The video cameras saved the images for post processing. The study area was a one-lane roundabout located near Stockholm University. A video analysis program, called SAVA *(18)*, was used for data extraction. After image calibration, the program allows for drawing of virtual lines on the film so that moving objects can be traced as they traverse the study area. A log file is created with subject ID and timestamps at each virtual line. Afterwards the speed can be derived from the time and distance recorded. From video observations, the yielding events were also identified, based on drivers' deceleration or speed adaptation to let a cyclist traverse safely the crosswalk. Figure 1(b) shows the film analysis with some virtual lines drawn. Additionally, Figure 1(c) and 1(d) illustrate drivers' and cyclists' vision angle at the beginning of their interaction zones respectively.

2.3 Event Groups

When a vehicle exits a roundabout and passes through the bicycle crossing, the following events may take place:

- ✓ *Non-Conflict*: the driver does not encounter any cyclist, thus crossing freely and leaving the *IZ* and *CZ* zones without any interruption.
- ✓ *Conflict*: the driver interacts with the cyclist due to a potential collision.

It is assumed that there is *Conflict* if vehicle and bicycle are simultaneously in their respective *IZ*. Moreover, the arrival time difference (*ATD*) between the vehicle and the bicycle at the boundary of each interaction zone is the key variable to establish a *Conflict* event. Larger *ATD* values imply that it is less likely that the trajectories of the vehicle and bicycle meet at the *CZ*. On the other hand, shorter *ATD* values indicate that it is likely that a *Conflict* is perceived by the driver. From video observations and based on the *ATD* values at the boundaries of each *IZ*, a threshold of 5.5 seconds was identified to discriminate between *Non-Conflict* and *Conflict* events. Based on this threshold, observations are classified into the following events:

- ✓ $Non-Conflict$ $(ATD > 5.5\ seconds)$
- ✓ $Conflict$ $(ATD \leq 5.5\ seconds)$

Furthermore, in the conflict situation, a driver may have two options:

a. Yields to the interacting cyclist or
b. Passes through the *IZ* and *CZ* zones without yielding to the interacting cyclist.

Therefore, a *Conflict* leads to two subsequent events:

- ✓ $Non-Yield$ $(if\ the\ driver\ does\ not\ yield\ given\ ATD \leq 5.5\ seconds)$
- ✓ $Yield$ $(if\ the\ driver\ yields\ given\ ATD \leq 5.5\ seconds)$

Finally, the vehicle-bicycle interaction events can be classified into 4 groups as follows: *Non-Conflict*, *Conflict*, *Yield* and *Non-Yield* for vehicles and bicycles. In the bicycle case, *Yield* refers to a cyclist interacting with a driver who does yield and, similarly, for the other groups.

2.4 Data analysis

Table 1 summarizes descriptive statistics about various measures of interest. Statistical tests at $\alpha = 5\%$ level of significance were conducted to test the null hypothesis that the means are the same. The tests indicated that the differences were significant in most of the cases. For instance, the mean vehicle speed difference between *Non-Conflict* and *Conflict* groups is 2.90 km/h (*t-statistic = 2.55*). As expected, vehicles interacting with bicycles have lower speed in comparison to *Non-Conflict* (free) vehicles. The mean vehicle speed difference between the *Conflict* and *Yield* groups is 6.16 km/h (*t-statistic = 11.88*). Naturally, yielding vehicles present the lowest mean speed of all vehicle groups since they adapt the speed to let cyclists traverse the crosswalk safely. It was expected that the *Non-Conflict* group would present the highest speed given no disturbance from any cyclist. However, it is interesting to observe that the speed difference between the *Non-Conflict* and *Non-Yield* groups is negligible with 0.04 km/h difference (*t-statistic = 0.03*). In the *Non-Yield* case, it can be argued that either the driver did not detect the cyclist or the cyclist was far enough from the *CZ* thus the driver had the opportunity to go through the *CZ* before the cyclist.

Cyclists on the other hand, present lower speed variation across the classified groups. The mean speed difference between *Conflict* and *Yield* groups is 0.57 km/h (*t-statistic = 1.39*). The speed difference is not statistically significant. This small difference can be an indication that cyclists try to impose (force) a yielding decision on drivers since cyclists are confident on their *"priority"* and do expect the driver to yield. This reveals a risky behavior from the cyclist i.e., the cyclist is confident that the driver has detected him/her and would react to his/her presence. As mentioned in the previous section, Wood et al., (*16*) report that cyclists overestimate by twice the distance at which they would be recognized by a driver. The fastest bicycle group is the *Non-Conflict* group with mean speed of 16.82 km/h. Of course, it was expected that this group would present the highest speed since they were not disturbed by any vehicle. On the other hand, the lowest bicycle speed group is the *Yield* group with mean speed of 15.77 km/h. The speed difference between *Non-Conflict* and the *Yield* groups is small (1.05 km/h).

Figures 2(a) and 2(b) plot the cumulative speed distributions for all vehicle and bicycle classified groups. Vehicle speed differences are clearly distinguished among the various groups, particularly, the difference of the *Yield* group (solid line) compared to all other vehicle groups (See Figure 2(a)). The results suggest that the *Non-Yield* group has basically the same speed as the *Non-Conflict* group. Figure 2(a) also shows that more than 90% of the drivers who yielded had a speed under 20 km/h. Similarly, bicycle speed profiles for different event groups are presented in Figure 2(b). Again, the *Yield* group demonstrates the lowest speed level (solid line). In addition, Figure 2(c) shows a scatter plot of vehicle versus bicycle speeds considering the cyclist's location by Segment and whether the driver yielded or not from the *Conflict* group. Interestingly, the plot indicates that low speed vehicles provide for a higher yielding rate. This result supports the idea that drivers have more time to better detect and react to the cyclist's presence at low speeds. On the other hand at high speeds, drivers do not yield as expected. The position of the cyclist plays an important role on driver's decision according to the results. Most of the *Non-Yield* observations are with drivers at speeds above 18 km/h and cyclists in Segment 3 (>20 m). Therefore, the results show that the yielding rate decreases for higher vehicle speeds and for larger distances from the bicyclist to the *CZ*.

3. MODELING THE PROBABILITY OF YIELDING

The data analysis in the previous section provides useful insights on the yielding probability. The substantial difference between free vehicles and those interacting with bicyclists for example, indicates that the yielding probability is significantly affected by vehicle speed. Bicycle speed had a relatively small impact according to the lower variation among the groups. Additionally, the proximity of the cyclists to the conflict zone should have some impact on drivers' yielding decisions. The analysis in this section aims at developing a model that identifies the important factors that explain these decisions. The explanatory variables considered are summarized in Table 2.

Logistic regression, a statistical approach appropriate for modeling binary response data was used to estimate the model (similar approaches have been used to investigate the vehicle and pedestrian interactions *(19)*). The probability of yielding, given that vehicle-cyclist conflict takes place, is given by a logit model:

$$P(Y=1|X) = e^{V(X)} \big/ 1+e^{V(X)} \quad (1)$$

$V(X)$ is the systematic utility function of the decision to yield given by:

$$V(X) = X \cdot \beta = \beta_0 + \beta_1 x_1 + \ldots\ldots + \beta_5 x_5 \quad (2)$$

where, $\beta = [\beta_0\ \beta_1 \ldots \beta_5]^T$ is a vector of parameters and $\mathrm{X} = [\mathrm{x}_1\ \mathrm{x}_2 \ldots \mathrm{x}_5]^{\mathrm{T}}$ a vector of explanatory variables that determine the final yielding probability. *Y=1* represents a yielding event. The models, with different specifications, were estimated using IBM SPSS *(20).*

4. RESULTS

Three models are estimated. Model I relates the yielding probability to the speed of the vehicle. Model II relates the yielding probability to the speeds of the vehicle and bicycle. Model III includes the cyclist's proximity in the estimation. The estimated models are presented in Table 3. The *-2LL* and Nagelkerke *R* Square suggest that Model III is the preferred model whose probability estimates are depicted in Figure 3(a). The plot shows how the presence of cyclists in Segments 1 and 2 relates to higher yielding rates compared to cyclists located in Segment 3. Figure 3(b) exhibits the probability estimates based on Model II with the speed of the bicycle fixed at 3 levels (10, 15, and 20 km/h). The a priori expectation was that higher vehicle speeds lead to lower yielding probabilities. It was also expected that cyclists closer to the *CZ* zone would have greater impact on the driver. According to the results, the speed of the vehicle is negatively correlated to the yielding event as expected. A vehicle with high speed has lower chance to fulfill the yielding expectation because at high speeds, drivers have less time to detect and react to the presence of an interacting cyclist. This finding is also in line with previous literature such as (*12, 15*).

The impact of the proximity of the cyclist approaching the *CZ* agrees with the expectations as well. A cyclist in Segment 1 relates to higher yielding probabilities compared to the case where there is no cyclist. According to the results, if a driver encounters a cyclist in Segment 1, the probability of yielding increases from 40% to 90% when the vehicle speed decreases from 22 to 15 km/h. There is still a small chance (10 %) to yield if the vehicle speed is 26 km/h. In Segment 2, if a driver interacts with a cyclist, the yielding probability almost doubles when the vehicle speed decreases from 21 to 14 km/h. Of course, if the driver fails to yield, the cyclist is expected to do so and wait for the driver in order to avoid a collision. Consequently, Segments 1 and 2 show a sustained influence on drivers' yielding decisions. Hence, the presence of the cyclist up to 20 m away from the *CZ* has a strong impact on driver behavior. On the other hand, the presence of the cyclist in Segment 3 (>20 m) shows a lower impact on the yielding probability which decreases significantly. For instance, Figure 3(a) shows that a driver, whose speed is 20 km/h and detects a cyclist in Segment 3, has only a 10% probability to yield. If the cyclist is detected in Segment 2, the yielding probability increases to 40% and if the cyclist is in Segment 1 the probability to yield increases to 55%. Therefore, the closer the cyclist is to the *CZ,* the higher the impact is on the driver despite of the vehicle speed. The impact of the distance of the bicyclist from the *CZ* needs further investigation. For example, bicyclists far away may impact drivers in the opposite direction by encouraging them to accelerate instead of yielding, as it was observed in the video recordings. The bicycle speed is positively correlated to the yielding probability according to the results. Figure 3(b) shows that a driver whose speed is 20 km/h has 10%, 30%, and 50% probability to yield for bicycles with speed 10, 15, and 20 km/h respectively.

Model I and Model II have an overall accuracy of 89.9 % and 92.5 % respectively in predicting yielding decisions. On the other hand, Model III has an overall accuracy of 94.1 %. Out of 37 observed yielding events, Model III was able to accurately predict 30 yielding events. In the same way it successfully predicted 145 non-yielding events out of 150 non-yielding observed events. However, it predicted erroneously 5 yielding events which in reality were non-yielding events and predicted 6 non-yielding events which were actually yielding events.

5. CONCLUSION

Understanding driver yielding behavior and its influential factors is important for guiding informed design, planning and even policy decisions. Apart from geometric factors and driver characteristics, which also play an important role on such decisions, other aspects such as the vehicle and bicycle speeds and their relative positions provide insights to better understand the decision process behind *Yield* or *Non-Yield* events. The results indicate that low speed vehicles have a high yielding rate. The *Non-Conflict* and *Non-Yield* groups presented the highest mean speed of all groups (21.9 km/h). The *Non-Yield* group can be considered as "*risky*" drivers. Another interesting result from the data analysis is that the mean speed difference between *Non-Yield* and *Yield* groups is 9 km/h. This result undoubtedly shows the impact of vehicle speed on the yielding decision. On the other hand, cyclists are very confident on their "*priority*" and try to force a yielding decision on drivers as implied by the small speed difference (1.0 km/h) between the *Non-Conflict* and *Yield* bicycle groups.

The results also show that the relative position of the cyclist is an important factor in the yielding decision. A positive impact (increased yielding rate) is reported as cyclists get closer to the *CZ.* The results also indicate that the impact is rather constant or sustained for distances up to 20 m away from the *CZ.* At a distance larger than 20 m the cyclists' impact reduces substantially. Besides, it is possible that cyclists far away from the *CZ* (> 30 m) still have an impact on drivers' yielding decisions yet in the opposite direction i.e., the driver detects that the cyclist is too far away and the large distance induces the driver to speed up instead. The distance threshold where the cyclist' influence ceases or changes suddenly (e.g., decreased yielding rate) is still subject of investigation.

The data analysis indicates that there is not much variability on bicycle's speed across the groups. Model II also confirms that the cyclist speed has a small impact on the driver yielding decision. The estimation results in Model III suggest that the position of the cyclist has a strong influence on driver behavior. This also implies that detecting the cyclist is crucial for drivers' yielding decisions. In addition, the results show that for vehicle speeds below a certain threshold (20 km/h for the studied roundabout) the yielding probability increases rapidly as the cyclist gets closer to the *CZ*. In general, the results provide a better understanding of drivers' yielding decision process to cyclists at one-lane roundabouts.

The results presented in the study reflect behavioral aspects and geometric configuration of a typical Swedish roundabout governed by the local traffic regulations. Car drivers have the responsibility to give way to cyclists who may simply traverse the crosswalk. Therefore, the applicability of the results in other contexts, especially outside the Nordic Countries or Europe, needs further investigation and evidence.

ACKNOWLEDGMENTS

The authors would like to acknowledge the steering board of Länsförsäkring (County Insurance Company) for providing the financial support for the study.

REFERENCES

1. Börjesson, M. and Eliasson, J. Chapter 10: The benefits of cycling: viewing cyclists as travellers rather than non-motorists, in John Parkin (ed.) Cycling and Sustainability (Transport and Sustainability, Vol. 1), Emerald Group Publishing Limited, 2012, pp. 247-268.

2. Faghih-Imani, A., Eluru, N., El-Geneidy, A.M., Rabbat, M., Haq, U. How land-use and urban form impact bicycle flows: evidence from the bicycle-sharing system (BIXI) in Montreal. Journal of Transport Geography. In Press, 2014.

3. Frade, I. and Ribeiro, A. Bicycle Sharing System Demand. Procedia – Social and Behavioral Sciences, Vol. 111, 2014, pp. 518-527.

4. El-Geneidy, A. M., Krizek, K. J., & Iacono, M. J. Predicting bicycle travel speeds along different facilities using GPS data: a proof of concept model. In Proceedings of the 86th Annual Meeting of the Transportation Research Board, 2007.

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

6. Minikel, E. Cyclist safety on bicycle boulevards and parallel arterial routes in Berkeley. Accident Analysis and Prevention, Vol. 45, 2012, pp. 241-247.

7. Parkin, J., Rotheram, J. Design speeds and acceleration characteristics of bicycle traffic for use in planning, design and appraisal. Transport Policy, Vol. 17(5), 2010, pp. 335-341.
DOI: 10.1016/j.tranpol.2010.03.001

8. Virkler, M.R. and Balasubramanian, R. Flow Characteristics on shared hiking/biking/jogging trails. In Transportation Research Record: *Journal of the Transportation Research Board, No. 1636*, Transportation Research Board of the National Academies, Washington, D.C., 1998.

9. Taylor, D. and Davis, J. Review of basic research in bicycle traffic science, traffic operations, and facility design. In Transportation Research Record: *Journal of the Transportation Research Board, No. 1674*, Transportation Research Board of the National Academies, Washington, D.C., 1999.

10. Björklund, G. Driver Interaction. Informal rules, irritation and aggressive behaviour. Doctoral Dissertation. Uppsala University, 2005.

11. Svensson, A. and Pauna, J. Trafiksäkerhet och väjningsbeteende I cykel-motorfordon interaktioner. Bulletin 257, Trafik och Väg, Lunds University, 2010.

12. Silvano, A.P., Ma, X. and Koutsopoulos, H.N. A Hierarchical modelling framework for vehicle-bicycle interactions at roundabouts. In Proceedings, The 3rd International Cycling Safety Conference, Gothenburg, Sweden, 2014

13. Räsänen, M. & Summala, H. (2000) Car drivers' adjustments to cyclists at roundabouts. Transportation Human Factors, Vol. 2, No. 1, pp. 1-17. DOI 10.1207/STHF0201_1

14. Summala, H., Pasanen, E., Räsänen, M. and Sievänen, J. (1996) Bicycle accidents and drivers' visual search at left and right turns. Accident Analysis & Prevention, 28(2), 147-153

15. Räsänen, M. & Summala, H. (1998). Attention and expectation problems in bicycle-car collisions: an in-depth study. Accident Analysis and Prevention, Vol. 30, No. 5, pp. 657-666.

16. Wood, J.M., Lacherez, P.F., Marszalek, R.L., King, M.L. (2009). Drivers' and cyclists' experiences of sharing the road: Incidents, attitudes and perceptions of visibility. Accident Analysis and Prevention, Vol. 41, pp. 772-776.

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

18. SAVA, Semi-Automatic Video Analysis (2003). Division of Traffic and Logistics, Royal Institute of Technology – KTH.

19. Schroeder, B. and Rhouphail, N.P. (2011) Empirical behavioral models to support alternative tools for the analysis of mixed-priority pedestrian-vehicle interaction in a highway capacity context. 6th International Symposium on Highway Capacity and Quality of Service. Stockholm, Sweden. June 28 – July 1, 2011.

20. IBM SPSS Statistics version 21 (2014).

LIST OF TABLES AND FIGURE CAPTIONS

TABLES:

FIGURES:

TABLE 1 Vehicle and bicycle speeds by group

Event Groups	**Vehicle Speed**		**Bicycle Speed**		**Event Sample**	**Yielding rate (%)**
	Mean	Standard deviation	Mean	Standard deviation		
All Data	20.12	5.80	16.55	1.55	187	
Non-Conflict	21.93	4.78	16.89	1.43	70	
Conflict	19.03	6.09	16.34	1.59	117	32
Yield	12.87	3.88	15.77	1.59	37	
Non-Yield	21.89	4.65	16.61	1.53	80	

TABLE 2 Variable descriptions

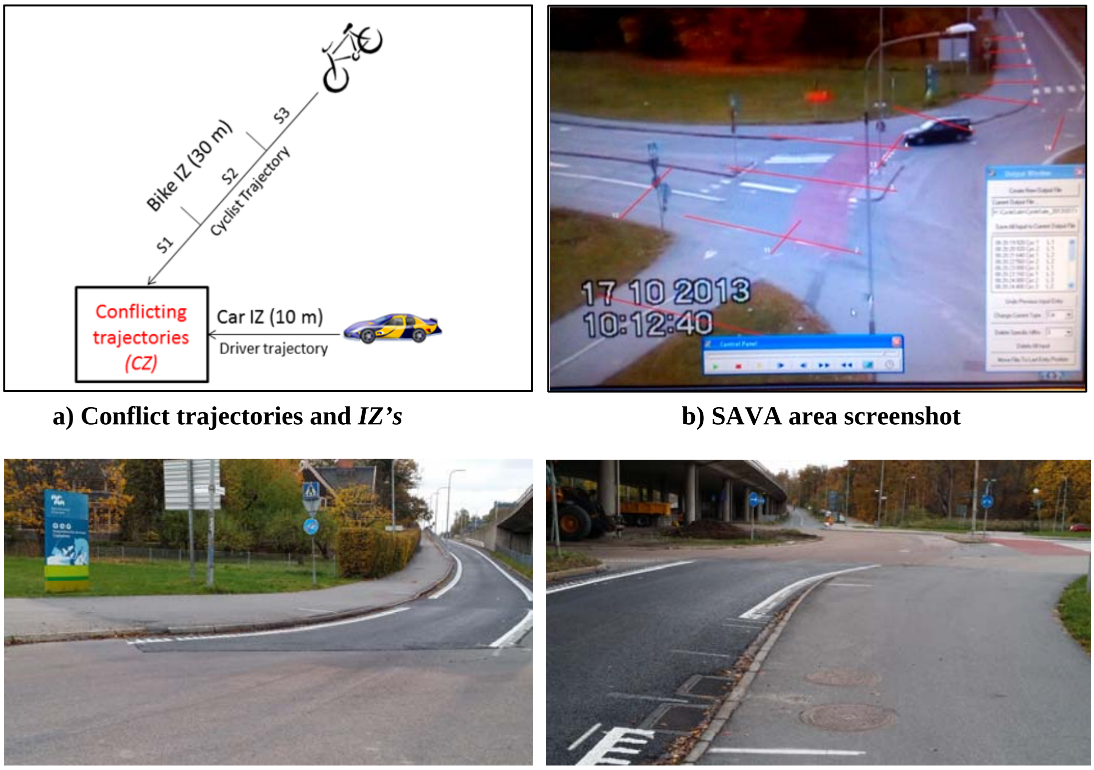
Parameter	Variable	Unit	Description
β_0	na	na	Constant
β_1	V_{car}	Km/h	Instantaneous speed of a vehicle at the start of the Car *IZ* zone (decision point 10 m)
β_2	$Segment$ 1	dummy	1 if the bike is in *Segment 1* (0-10 m) when the car arrives at decision point, else 0
β_3	$Segment$ 2	dummy	1 if the bike is in *Segment 2* (11-20 m) when the car arrives at decision point, else 0
β_4	$Segment$ 3	dummy	1 if the bike is in *Segment 3* (21-30 m) when the car arrives at decision point, else 0
β_5	V_{bike}	Km/h	Bicycle velocity measured with reference to the car at 10 m away from conflict zone

na = not applicable

TABLE 3 Estimation results (*Wald statistic in parenthesis*)

Variable	Parameter	Model I	Model II	Model III
$Constant$	β_0	5.762 *(29.12)*	3.591 *(7.73)*	3.547 *(7.00)*
V_{car}	β_1	-0.411 *(41.09)*	-0.404 *(23.80)*	-0.408 *(22.37)*
$Segment\ 1$	β_2	-	-	4.890 *(23.77)*
$Segment\ 2$	β_3	-	-	4.289 *(13.56)*
$Segment\ 3$	β_4	-	-	2.680 *(7.58)*
V_{bike}	β_5	-	0.236 *(24.63)*	-
$-2LL$		101.210	62.396	55.323
$Nagelkerke\ R\ square$		0.579	0.768	0.798
$Yielding\ events$		37		
$Observations$		187		

(-) = data not applicable



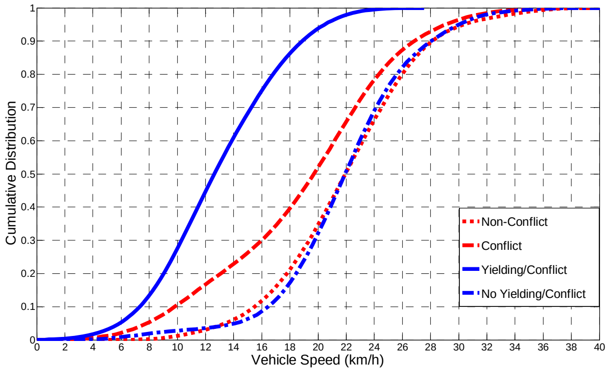
a) Conflict trajectories and *IZ's*

b) SAVA area screenshot

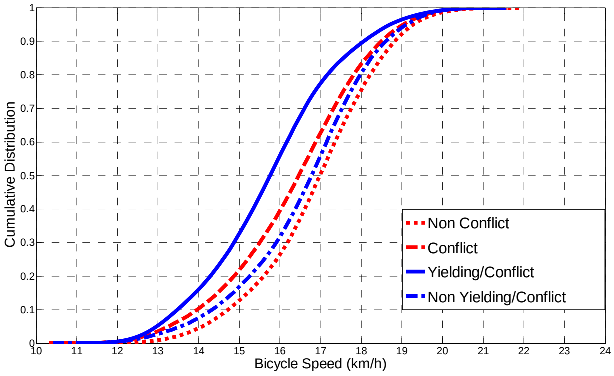
c) Drivers' sight vision at 10 m

d) Cyclists' sight vision at 30 m

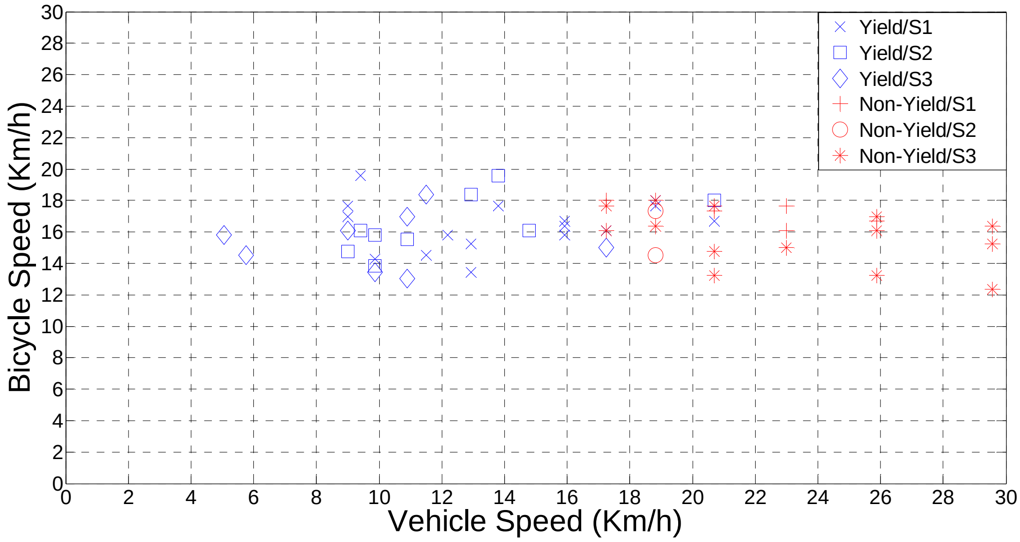
FIGURE 1 Vehicle-bicycle interactions and data collection approach.



a) Vehicle speeds by groups.

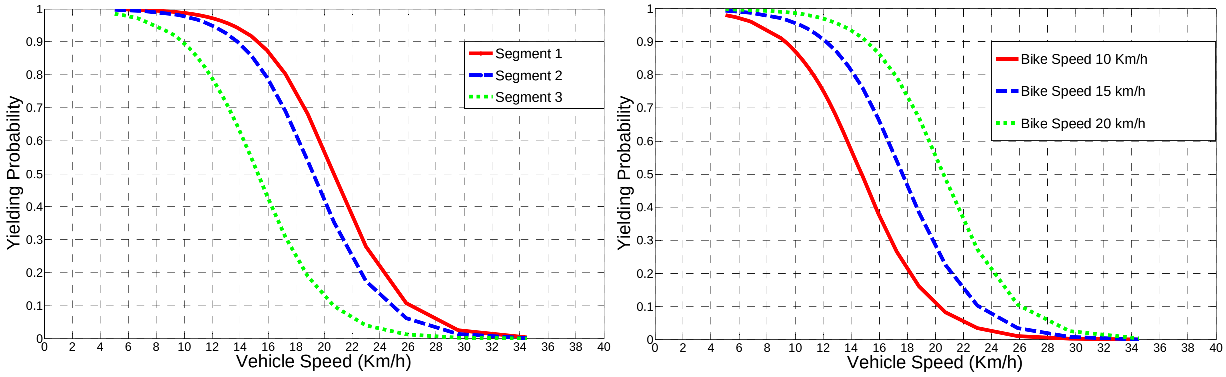


b) Bicycle speeds by groups.



c) Vehicle vs. bicycle speeds by group and segment.

FIGURE 2 Vehicle and bicycle cumulative speeds by groups and scatter plot.



a) Cyclist Proximity **b) Bicycle Speed**

FIGURE 3 Yielding probabilities.