This is a preprint of an article published by Elsevier in Accident Analysis & Prevention, available online: https://doi.org/10.1016/j.aap.2018.03.010

Drivers Overtaking Bicyclists - An Examination Using Naturalistic Driving Data

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Abstract

This paper demonstrates a unique and promising approach to study driver-bicyclist interaction by using in-vehicle sensory data from naturalistic driving studies, which provide rich and quantitative information from a driver's perspective. A total of 4,789 events of drivers overtaking bicyclists were extracted from an existing naturalistic driving study in the U.S. The vehicle encroachment to the left-side lane and distance to the bike lane (or paved shoulder) marking at the time of overtaking were used as two overtaking metrics. A number of factors were examined, including the left-side lane marking type, presence of a bike lane or paved shoulder, left-side traffic, lane width, and driver distractions. Notable findings include that (1) when a bike lane or paved shoulder was present, a dashed non-center line (i.e., same direction traffic on the left side) was associated with significantly less encroachment and closer distance to the bike lane/shoulder marking compared to a solid centerline; (2) an alarming 7.8% of the events occurred when the drivers were distracted within five seconds prior to the overtaking. That translates to one distracted driver for every 13 times a bicyclist is overtaken. In addition, drivers manipulating a cell phone was associated with significantly less encroachment compared to non-distracted driving. The quantitative results of this work could be potentially used by traffic engineers, policy makers and legislators to support the designs of better road infrastructures, programs, policies, and traffic laws that aim to improve the safety of all road users. The quantitative results could also be used as a baseline to develop, test, and benchmark automated vehicles to interact with bicyclists.

Keywords: Bicycle; Vulnerable road users; Overtaking; Driver distraction; Naturalistic driving

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1. Introduction

Bicycling has long been an important mode of transportation for its economic, environmental, and health benefits. In recent years there has been a growing trend of bicycling in Europe and the United States (McKenzie, 2014; Pucher & Buehler, 2017). The growth of bicycling is likely to increase even more in the future with innovations such as bike sharing and electric bikes (Pucher & Buehler, 2017). However, bicyclists are vulnerable road users who get little protection in an event of a crash that involves motor vehicles. The safety issues of riding a bicycle on roadways with mixed traffic have been a growing concern. And the perceived danger of cycling in motorized traffic has been a major deterrent to more bicycling (Jacobsen et al., 2009). In the European Union countries 2,112 cyclists were killed in road accidents in 2014, accounting for 8.1% of all road fatalities (CARE, 2016). In the United States there were 840 pedalcyclists killed in motor vehicle crashes in 2016 (National Highway Traffic Safety Administration (NHTSA), 2017a). An estimated 45,000 pedalcyclists were injured in motor vehicle crashes in 2015 (NHTSA, 2017b). A study by Pucher and Dijkstra (2003) found that bicyclists in the United States were 12 times more likely than car occupants to get killed (72 vs 6 fatalities per billion kilometers), and bicyclists in the United States are twice as likely to get killed as bicyclists in Germany and over 3 times as likely as bicyclists in Netherland.

Among all types of crashes involving bicyclists, a motorist approaching a bicyclist from behind is particularly dangerous and much more likely to result in serious injuries and fatalities. An early study by Cross and Fisher (1977) conducted interviews and on-site investigations of 753 non-fatal crashes and 166 fatal crashes, and found that motorist overtaking bicyclists (Problem Type 13) accounts for 24.6% of fatal crashes and 4.0% non-fatal crashes. More recently, NHTSA Fatality Analysis Reporting System (FARS) started to use a more detailed coding manual (NHTSA, 2016) for pedestrian and bicyclist fatal crashes, which now includes coding for the bicycle crash types (PB30B: Crash type - bicycle). The crash types include four categories that involve "Motorist Overtaking Bicyclist": (1) "Undetected bicyclist" (Code 231), (2) "Misjudged Space" (Code 232), (3) "Bicyclist swerved" (Code 235), and (4) "Other/unknown" (Code 239). Table 1 shows the top ten fatal bicyclist crash types in the United States in 2016. As can be seen crashes related to "motorist overtaking" take three spots out of the top four most common bicyclist fatal crash types. The top spot "Motorist Overtaking - Other/Unknown" also seems to suggest the difficulties of determining and understanding the causes of this type of crashes from post-crash investigations.

An independent study by The League of American Bicyclists also shows that rear-end collisions accounted for 40% of the 481 bicyclist fatalities that they investigated (League of American Bicyclists, 2014). In any case, it is evident that motorist overtaking bicyclists is one of the most problematic crash types.

Table 1. Top ten bicyclist fatal crash types in the U.S. in 2016, data extracted from NHTSA (n.d.)

Rank	Crash Type	Fatalities	Percent
1	Motorist Overtaking - Other/ Unknown	108	13%
2	Motorist Overtaking - Undetected Bicyclist	73	9%
3	Parallel Paths - Other / Unknown	62	7%
4	Motorist Overtaking - Misjudged Space	58	7%
5	Unknown Approach Paths	49	6%
6	Bicyclist Ride Through - Signalized Intersection	47	6%
7	Bicyclist Left Turn - Same Direction	43	5%
8	Bicyclist Ride Through - Sign-Controlled Intersection	42	5%
9	Bicyclist Ride Out - Other Midblock	31	4%
10	Wrong-Way / Wrong-Side - Bicyclist	30	4%
	All other types	298	35%
	Total fatalities	841	100%

Driver distraction has been a significant contributing factor of road accidents. According to the NHTSA in 2015 distracted driving accounted for 3,477 fatalities and an estimated 391,000 injuries in the U.S. (National Center for Statistics, 2017). In addition, these numbers are likely under-reported due to the difficulties in identifying driver distraction during accident investigation. A naturalistic driving study shows distraction of secondary tasks (i.e., those tasks not necessary to driving) account for 23% of all crashes and near-crashes (Klauer et al., 2006). The National Occupant Protection Use Survey (NOPUS) on driver electronic device use observed 1,600 sites and 48,177 vehicles in the U.S. in 2016, and reported that 3.3% of passenger vehicle drivers were holding cell phones to their ears while driving and 2.1% of the drivers were visibly manipulating handheld devices while driving (Pickrell et al., 2017). Reed and Ebert (2016) manually coded driver activities in in 9,856 video frames from a naturalistic driving study (Safety Pilot Model Deployment (SPMD), the same study that would be used in this paper). It was found that the drivers had a phone in their right hands in 6.5% cases, in their left hands in 2.6% cases, and on their laps in 2% cases. A distracted driver may pose great danger to the surrounding vulnerable road users who share the same roads. However, to our knowledge there are few studies on the real-world prevalence of driver distractions specifically related to approaching bicyclists.

Promising solutions to reduce or mitigate bicycle-related crashes and conflicts includes developing safer infrastructures, evidence-based guidelines and regulations, effective education and training programs to drivers and bicyclists, and advanced driver/bicyclist support technologies. However, the development of the solutions depends on a good understanding of how drivers and bicyclists interact with each other on real-world roadways in dynamic driving/riding scenarios. Given the importance of the issue, efforts have been made by researchers to investigate the motorists' overtaking behaviors using objective data. One common method involves using instrumented bicycles with cameras and sensors to measure objective information such as the overtaking proximity, GPS location, and bicycle speed, and collecting data by riding the instrumented bicycle on public roads (e.g., Walker, 2007; Shackel & Parkin, 2014). Some other studies used covert cameras or tape strips with pneumatic tubes on roadside to record overtaking behaviors at fixed locations (e.g., Jilla, 1974; Kroll & Ramey, 1977; Duthie et al., 2010; Kay et al, 2014) or a driving simulator with virtual bicyclists (Hamann et al., 2016; Bella & Silvestri, 2017). From these studies it is generally believed that found that drivers' overtaking behavior is affected by a wide range of factors as listed below. (1) Bicyclist characteristics: riding position on the road (Walker, 2007; Savolainen et al., 2012), apparent gender (Walker, 2007; Chuang et al., 2013), riding alone or in a group (Savolainen et al., 2012), helmet use (Walker, 2007, Note this was argued by Olivier & Walter (2013) as not significant), and handling of wheel angle, speed and speed variation (Chuang et al., 2013); (2) Road and environmental characteristics: lane width (Shackel & Parkin, 2014), presence of bike lane (Parkin & Meyers, 2010; Chapman & Noyce, 2012; Mehta et al., 2015), presence of centerline (Shackel & Parkin, 2014) and centerline rumble strips (Savolainen et al., 2012), road markings (Shackel & Parkin, 2014; Mehta et al., 2015), posted speed limits (Parkin & Meyers, 2010), road vertical grade (Chapman & Noyce, 2012), road surface conditions (Chuang et al., 2013), oncoming traffic (Savolainen et al., 2012; Shackel & Parkin, 2014), far lane traffic (Mehta et al., 2015), presence of a "Share the Road" sign (Kay et al., 2014); (3) Vehicle characteristics: vehicle size and type (Walker, 2007; Chapman & Noyce, 2012; Parkin & Meyers, 2010; Shackel & Parkin, 2014; Chuang et al., 2013; Mehta et al., 2015);

These findings are important in gaining insights into the driver-bicyclist interaction during the overtaking. However, the data collected from the instrumented bicycles or roadside cameras lack the continuous and high time-resolution data about the driver operations and vehicle movements. Given that during the overtaking the driver is the main decision maker in selecting the timing of initiating the overtaking, and setting the vehicle lateral displacement and speed, it may be of great value to investigate the overtaking from the driver' perspective by directly examining the driver behavior and vehicle movement using in-vehicle sensory data from cameras and other sensors.

Another application of studying driver-bicyclist interaction is related to developing automated vehicle technologies. One critical challenge in developing automated vehicles is that they need to share the existing infrastructure with non-motorized road users such as bicyclists and pedestrians (Ziegler et al., 2014). Given the complexity of the real-world road environment and the variability and less predictability of the non-motorized road users, it is a complicated and crucial area to study how the automated vehicles should be programed to interact with these road users both safely and efficiently. One promising way to help answer this question is to observe and measure how human drivers interact with the non-motorized road users on real-world roadways, and use the resulting objective data as potential benchmarks to support the development of automated vehicles when interacting with bicyclists (Delp et al., 2015).

Naturalistic driving studies typically use instrumented vehicles to continuously record a wide variety of objective and high time-resolution data of the vehicle kinematics and road environment. The vehicles were driven by study participants for their everyday trips in an unsupervised and unobtrusive manner. The data collected in these studies have been valuable in helping researchers to understand many aspects of driver behaviors such as drivers' acceptance and adaptation to in-vehicle safety systems (Sayer et al., 2011), driver aggressiveness (Feng et al., 2017b), driver distraction (Bao et al., 2015, Feng et al., 2017a, Li et al., 2017, Wang et al., 2017), and driver parking search behavior (Hampshire et al., 2016). In this paper we aim to examine drivers' behavior of overtaking bicyclists using in-vehicle sensory data from an existing naturalistic driving study - the Safety Pilot Model Deployment (SPMD) (Bezzina & Sayer, 2015). SPMD was a research program funded by U.S. Department of Transportation and conducted by the University of Michigan Transportation Research Institute. In the SPMD study participants drove their instrumented personal vehicle for an extended period of time ranging from one to three years. Specifically, the objective of this paper is to examine whether and how drivers' overtaking maneuvers in terms of (1) encroachment to the left-side lane and (2) distance to the bike lane/shoulder marking are affected by a number of factors, including the left-side lane marking type, presence of a bike lane or paved shoulder, left-side traffic, lane width, and driver distraction.

2. Methods

2.1. Data extraction

Data from the Safety Pilot Model Deployment (SPMD) study were used in this paper. The goal of the SPMD was to support the evaluation of the connected vehicle technologies in a real-world, concentrated environment. About 3,000 personal vehicles, truck fleets, and transit buses were recruited from the Ann Arbor, Michigan area from 2012 to 2015. While all of the participating vehicles were equipped with vehicle awareness devices transmitting a vehicle’s GPS coordinates, speed, and heading, about 140 vehicles were equipped with a variety of sensors including four cameras and a data acquisition system which collected over 100 channels of vehicle data (e.g., speed, steering, braking, lane position) with high sampling rate (typically 10-50 Hz). The collected SPMD data include a total of about 2.5 million miles or 100,000 hours of driving.

In the SPMD study a camera-based Mobileye® system was equipped in a selection of the instrumented vehicles. The system is able to detect several types of objects (e.g., cars, bicyclists) in front of the instrumented vehicle. And the time when such detections were made was automatically marked in the data set. Figure 1 shows a screenshot of the SPMD data that shows two video channels (forward-facing and driver-facing) and four data channels (from top to bottom: vehicle speed, brake pedal actuation, vehicle longitudinal acceleration, and vehicle distance to right-side lane boundary). In the forward-facing video it shows a bicyclist was riding in front of the instrumented vehicle before being overtaken. The driver-facing video could be used to identify driver distraction such as cell phone use during the overtaking.

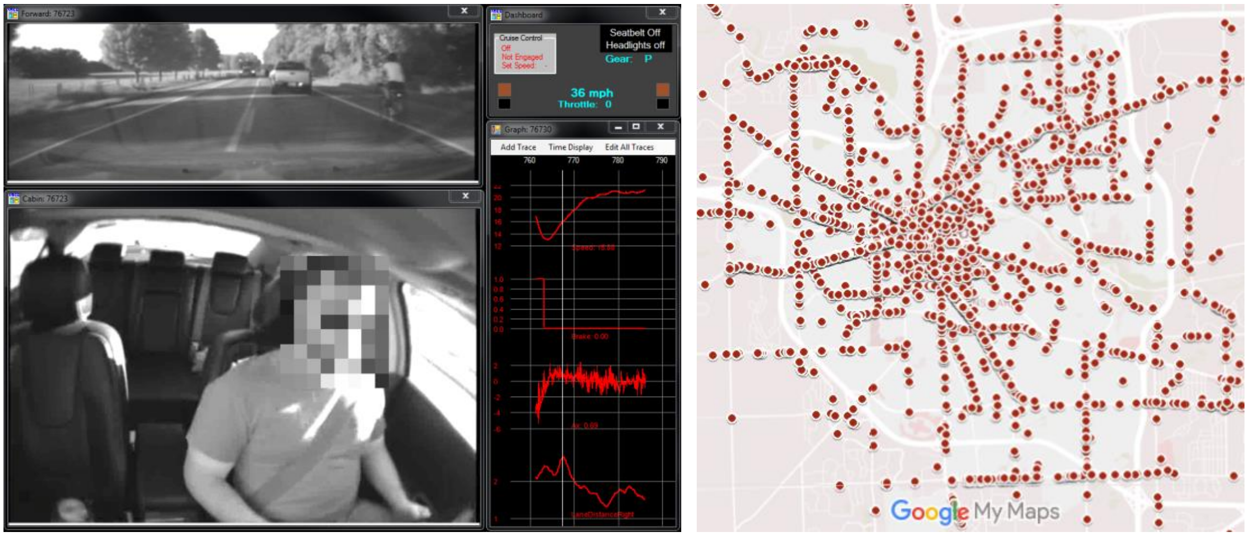

Fig. 1. Overtaking events from the Safety Pilot Model Deployment (SPMD) data set

The Mobileye® data were firstly used to locate in the database the driving events in which bicyclists was detected. The videos of such events were extracted and manually reviewed by trained data reductionists to verify the overtaking and extract additional information. In this paper an overtaking is defined as when (1) the vehicle passed the bicyclists from the left side of the bicyclists, and (2) the vehicle was initially approaching the bicyclists from the outmost lane within ten seconds prior to the overtaking. The second part of the definition is to exclude the cases when, for example, the vehicle was always traveling in the left traffic lane and thus the bicyclist was always separated from the vehicle by the right traffic lane. If more than one bicyclist was overtaken in a video, the time when the first bicyclist were overtaken was used as the overtaking time. Some additional information were also extracted from the event video, including the time of the overtaking, types of left-side lane markings, the presence of bike lane or paved shoulder, the presence of left-side traffic. More detailed description of the factors can be found in the data analysis section below. Note that the SPMD study does not have a camera facing directly to the right side. The time of the overtaking was estimated by the time when the bicyclist firstly disappears in the forward-facing camera view. The forward-facing camera has a horizontal field of view of 92 degrees and sampling rate of 5 Hz. In rear cases when the lane markings or bike lanes were not clear from the video, Google Street Views with the GPS locations of the events were used to obtain the information.

2.2. Data analysis

The vehicle encroachment to the left-side lane was calculated based on the vehicle lane position (relative to the left and right side lane boundary) which was continuously measured by the Mobileye® system at 10 Hz. The vehicle encroachment is defined as the distance from the left edge of the vehicle to the left lane marking at the time of the overtaking. An encroachment of zero means the vehicle left edge is in line with the left lane marking. Figure 2 illustrates the vehicle trajectory during one overtaking event from the SPMD data. Note that Mobileye® may not be able to accurately measure the vehicle lane position at the time of overtaking, for example, due to discontinued or faded lane markings. Mobileye also reports the quality for each of the measurement. The encroachment was calculated only if a high quality to the left-side lane marking was reported.

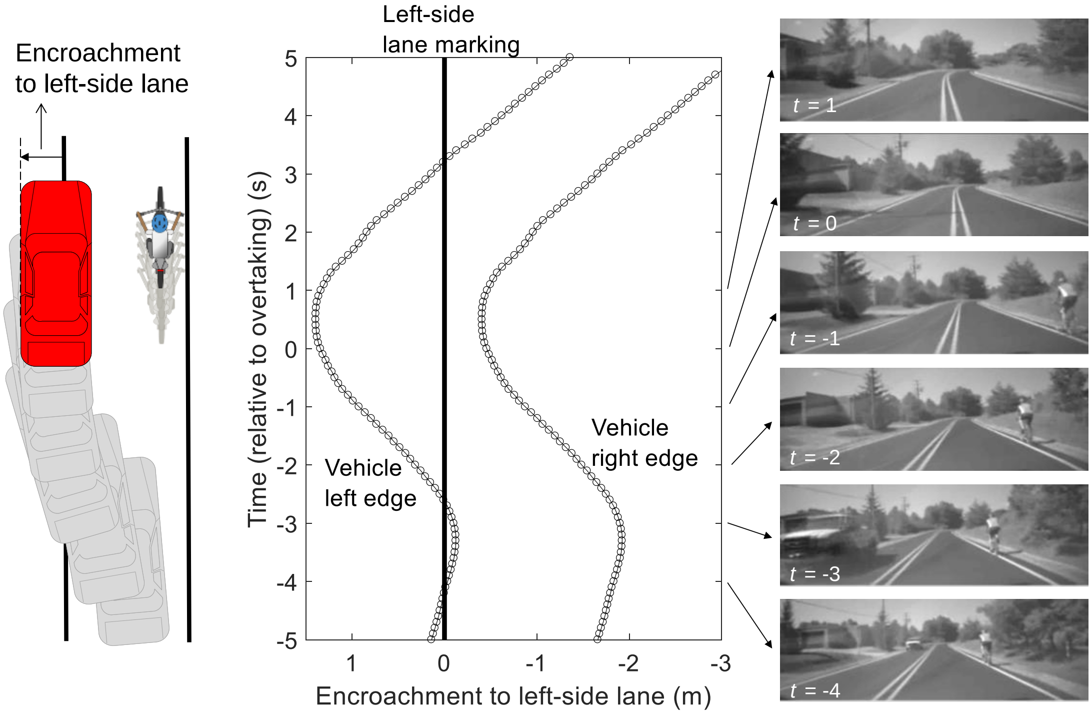

Fig. 2. Illustration of the vehicle lane encroachment when overtaking bicyclists

When there was a bike lane or paved shoulder, the distance from the vehicle right edge to the bike lane/shoulder marking was also calculated (if a high quality to the right-side lane marking was reported). In this paper we did not include this metric for the events with only the road edge, as we found there were many low quality measures to the right-side lane boundary when the right-side boundary did not have a painted lane marking (e.g., road curb).

Five factors were examined in this paper: (1) left-side lane marking types, (2) presence of bike lanes or paved shoulders, (3) presence of left-side traffic, (4) lane width, and (5) driver distraction prior to overtaking.

(a) Solid centerline (double yellow) + road curb (b) Solid centerline (no-passing) + paved shoulder

(c) Dashed line + road curb (d) Center left-turn lane + bike lane

(e) Oncoming traffic (for solid centerline) (f) Adjacent traffic (for dashed line) (rear-left view)

Fig. 3. Examples of left-side lane marking types, bike lane/shoulder, and left-side traffic

Left-side lane marking type: The overtaking events from the SPMD data set include a wide variety of road configurations. In this paper we focus on the three most common types of left-side lane marking: a solid centerline, a dashed non-center line, and a center left-turn lane line. A solid centerline is typically used in a two-lane road to separate the two-way traffic. It includes (1) double yellow lines (Figure 3a) and (2) a solid yellow line with a broken yellow line (indicating a no-passing zone) (Figure 3b). A dashed non-center line (simply referred to as "dashed line" hereinafter) is separating traffic lanes on roads with two or more lanes in the same direction (Figure 3c). They are typically four-lane two-way roads or two-lane one-way streets. A center left-turn lane is located in the middle of a two-way street and is marked on both sides by two painted lines (Figure 3d). The inner line is broken and the outer line is solid. The center left-turn lane is for vehicles to prepare for and make a left turn (or U-turn when permitted). The overtaking events with other types of left-side lane marking were excluded for the analysis. Examples of such events include the overtaking that occurred at intersections, on roads with no centerline, with road median, or with dashed centerline.

Presence of bike lanes or paved shoulders: Two groups were used for this analysis. The first group is with the presence of a bike lane or paved road shoulder (simply referred to as “bike lane/shoulder” hereinafter). In this analysis a bike lane specifically refers to an on-road marked bike lane with a white solid line and with no physical separation from the traffic lane. A paved shoulder specifically refers to a paved road shoulder that is at least 4 feet wide and in ridable condition (determined by the data reductionists based on the video clips). The second group is road edge without a bike lane or paved road shoulder (simply referred to as “road edge” hereinafter). This group includes road curb or unpaved road shoulder. Note in this paper we focus on the “narrow lane” (i.e., *a travel lane less than 14 feet (4.3 m) in width, which therefore does not allow bicyclists and motorists to travel side-by-side within the same traffic lane and maintain a safe separation distance* (Nabors et al., 2012)). Thus we excluded the overtaking that occurred in a wide curb lane (i.e., *a travel lane at least 14 feet wide, adjacent to a curb* (Nabors et al., 2012)) and when the bicyclists were riding in a street parking lane.

Presence of left-side traffic: If the left-side lane marking is a solid centerline, the left-side traffic refers to the oncoming traffic in the left-side lane. If the vehicle passes an oncoming vehicle within one second before and five seconds after overtaking the bicyclists, it is counted as an overtaking with left-side traffic (Figure 3e). If the left-side lane marking is a dashed line, the left-side traffic refers to the same-direction traffic in the left-side lane behind the instrumented vehicle. If a vehicle can be identified from the rear-left facing camera on the instrumented vehicle, it was counted as with left-side traffic (Figure 3f). For the center left-turn lane, there was no left-side traffic in the majority of cases. If there was a vehicle in the center left-turn lane or the vehicle reaches a median refuge island within five seconds after the overtaking, the event was excluded for analysis, as in these cases the driver may not be able to move into the center lane.

Lane width: The Mobileye® system continuously measures the distance from the center of the vehicle to the left- and right-side lane boundaries. The lane width can be calculated by simply sum up the two distances. However, we found the distance measure from the vehicle to the right-side lane boundary may not be as accurate and reliable when the right side is only a road curb without a painted lane marking. Thus the lane width was only calculated for the overtaking events when there was a bike lane/shoulder and when Mobileye® reported high quality in both the left and right side lane marking measures.

Driver distraction: Naturalistic driving data provide continuous and detailed information on the driver activities inside the vehicle. Driver distraction activities prior to overtaking bicyclists was also examined by reviewing the driver-facing camera videos. A similar scheme to Pickrell et al., (2017) was adapted with four types of driver distraction related to electronic device use. It is to note that in our analysis we aim to focus on the driver distraction immediately prior to the overtaking. Thus a driver distraction was flagged only if the behavior was observed within five seconds prior to the overtaking. In other words, if the driver terminated the distraction behaviors more than five seconds prior to the overtaking and remained undistracted up to the overtaking (even the drivers may still have the phone in their hands), it was not counted as distraction in our analysis.

3. Results

3.1. Data overview

After applying the criteria described in the previous section, a total of 7,375 events were initially identified from the SPMD database. Each event were compiled into a 25-second video clip that include four video channels (forward-facing, rear-left, rear-right, and driver-facing). After the video coding by the data reductionists, a total of 4,789 events were verified as overtaking events, in which the vehicle approached an on-road bicyclist from behind and passed the bicyclist from the left side. Typical cases of the excluded events are (1) the bicyclist made a turn before being approached by the vehicle, (2) the vehicle made a turn before approaching the bicyclist, (3) the bicyclist was riding on a physically segregated side path or sidewalk. No crash occurred in the verified overtaking events. The majority of the overtaking events occurred in the Southeast Michigan, with the highest concentration in the City of Ann Arbor (see Figure 1). This is as expected as all the SPMD study participants were recruited from the Ann Arbor area. However, it is to note that the participants were not restricted to where they can drive during the study. There were overtaking events occurred in other areas. In this paper all the events were included regardless of the geographic locations.

3.2. The effects of left lane marking type, bike lane/shoulder, and left-side traffic

In this section we examine whether a driver's lateral maneuver of the vehicle during overtaking bicyclists is affected by the types of left-side lane marking, presence of on-road marked bike lane or paved shoulder (simply referred to as "bike lane/shoulder" hereinafter), and presence of left-side traffic. Two metrics was developed to quantify driver's lateral maneuver of the vehicle during overtaking: (1) encroachment to left-side lane, and (2) distance from vehicle right edge to bike lane/shoulder (if present). A total of 2,560 overtaking events remained for the analysis on the encroachment. Figure 4 shows the encroachment grouped by left-side lane marking type, presence of bike lane/shoulder, and left-side traffic. Given a typical instrumented vehicle width of 1.8 m, an encroachment of greater than this value means the vehicle completely crossed over to the left-side lane. The vertical dotted line separates the cases of complete crossing over and partial lane crossing.

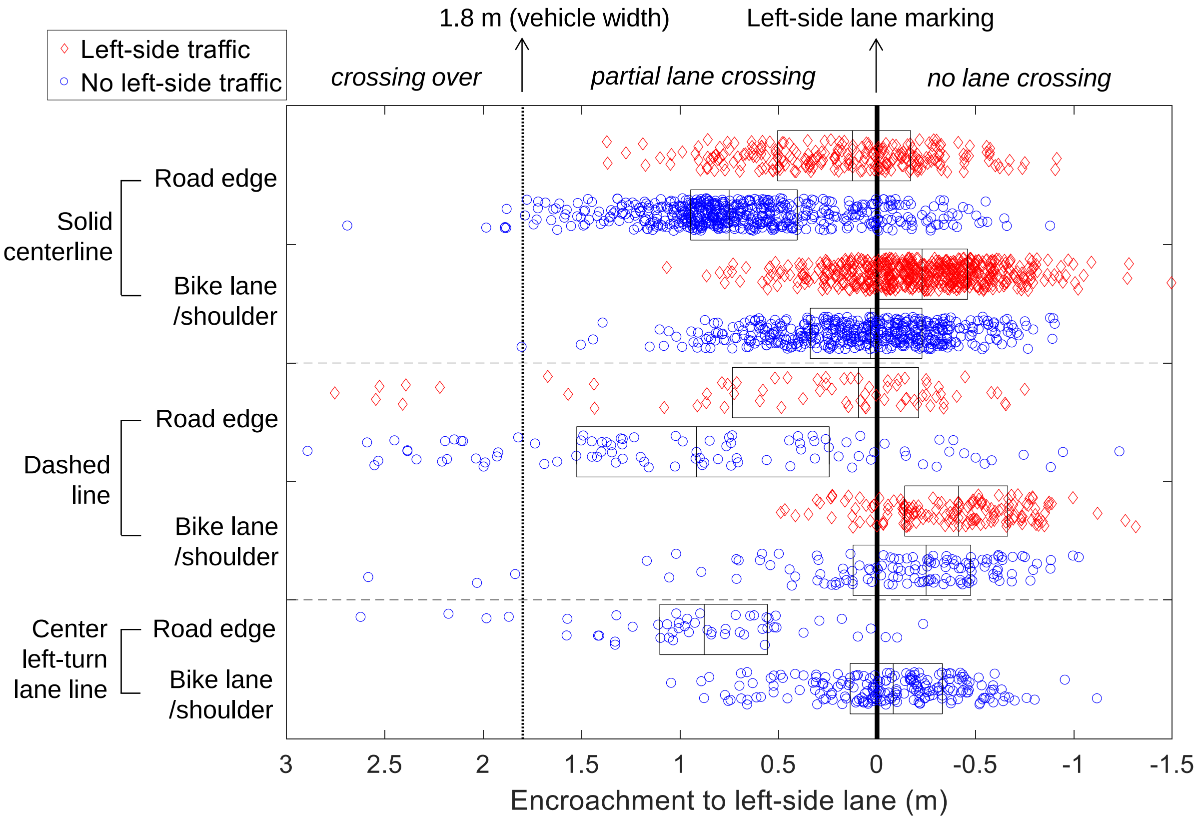

Fig. 4. Vehicle encroachment to left-side lane at the time of overtaking. Note on each box, the central mark indicates the median, and the right and left edges indicate the 25th and 75th percentiles, respectively. The spread of the data on the vertical axis is for data visualization only.

The Shapiro-Wilk normality tests show that the data from the groups in Figure 4 do not always follow a normal distribution (all $p < 0.05$ with four exceptions). Levene's test for homogeneity of variance show that the data from the groups also do not have equal variance ($p < 0.001$). Since both the normality and homogeneity of variance assumptions of ANOVA (analysis of variance) were violated, the Kruskal-Wallis (K-W) test by ranks (nonparametric equivalent of one-way

ANOVA) was used to compare the encroachment between the ten groups in Figure 4. Table 2 shows the K-W test results of the pairwise comparisons with the effect size measured by Cohen's *d* (Cohen, 1977). In a comparison of A vs. B, a negative value of Cohen's *d* indicates the values in group A are smaller than the values in group B. Table 3 summarizes the statistics of the encroachment for each group.

Table 2. Statistical test results of the vehicle encroachment

Comparison	Condition	χ^2	*p*-value	Cohen's *d*
Traffic vs. no traffic	Solid centerline + road edge	155.5	< 0.001	-1.03
	Solid centerline + bike lane	118.4	< 0.001	-0.74
	Dashed line + road edge	16.6	< 0.001	-0.62
	Dashed line + bike lane	16.0	< 0.001	-0.56
Road edge vs. bike lane	Solid centerline + traffic	125.7	< 0.001	1.01
	Solid centerline + no traffic	320.8	< 0.001	1.29
	Dashed line + traffic	58.3	< 0.001	1.37
	Dashed line + no traffic	70.3	< 0.001	1.41
Solid centerline vs. dashed line	Road edge + traffic	0.3	0.61	-0.36
	Road edge + no traffic	8.9	< 0.01	-0.45
	Bike lane + traffic	25.4	< 0.001	0.46
	Bike lane + no traffic	29.4	< 0.001	0.42
Center left-turn vs. solid centerline	Road edge + no traffic	6.4	< 0.05	0.44
	Bike lane + no traffic	14.0	< 0.001	-0.32
Center left-turn vs. dashed line	Road edge + no traffic	0.2	0.63	-0.05
	Bike lane + no traffic	7.1	< 0.01	0.13

Table 3. Summary statistics of the encroachment during overtaking

Lane marking	Bike lane /shoulder	Traffic	# of events	Median (m)	Mean (m)	SD (m)	Crossing over	Partial crossing	No crossing
Solid centerline	No	Yes	247	0.13	0.17	0.45	0%	59%	41%
		No	556	0.75	0.67	0.50	1%	87%	12%
	Yes	Yes	579	-0.23	-0.22	0.36	0%	25%	75%
		No	473	0.03	0.07	0.43	0%	53%	47%
Dashed line	No	Yes	69	0.09	0.37	0.85	9%	51%	41%
		No	94	0.92	0.94	0.95	21%	62%	17%
	Yes	Yes	159	-0.41	-0.38	0.35	0%	14%	86%
		No	128	-0.25	-0.13	0.56	2%	27%	70%
Center left-turn lane line	No	No	52	0.88	0.89	0.56	8%	87%	6%
	Yes	No	203	-0.08	-0.06	0.38	0%	40%	60%

In addition, we also aim to examine the vehicle's distance to the right-side lane boundary. Given that the Mobileye® often reports low quality of lane measurements when the right side is the road edge, we only calculated the distance when a bike lane/shoulder was present. A total of 1,568 overtaking events remained for the analysis on this distance measure. Figure 5 shows the distance grouped by left-side lane marking type and traffic. Note that in the SPMD data set the bicyclist's position on the road at the time of the overtaking as well as the width of the bike lane/shoulder were not measured. Nonetheless, we used a hypothetical bicyclist who has a physical width of 2.5 feet (0.75 m) (95th percentile of typical upright adult bicyclist, AASHTO, 2012) and is riding in the middle of a bike lane/shoulder which is 5 feet (1.5 m) wide (from minimum width of 4-5 feet for bike lane and paved shoulder, AASHTO, 2012). Under these assumptions, the two vertical dotted lines in Figure 5 separate the events with estimated overtaking distance less than the typical minimum passing distance of 3-feet (0.9 m) and 5-feet (1.5 m).

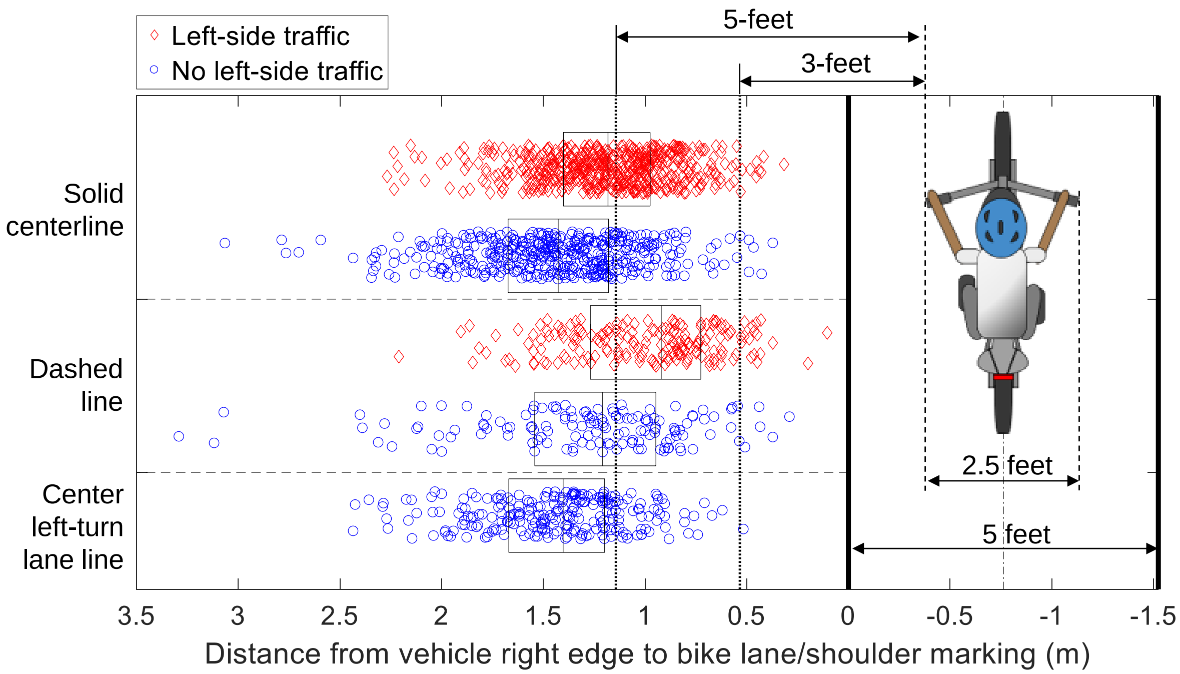

Fig. 5. Distance from vehicle right edge to bike lane/shoulder marking at the time of overtaking

The Shapiro-Wilk normality tests show that the data from the groups in Figure 5 do not always follow a normal distribution (all $p < 0.05$ with one exception). The same ART procedure was used to examine the interaction effects between the lane marking type and left-side traffic. The results show that there was no significant two-way interaction between the left-side lane marking type (solid centerline or dashed line) and left-side traffic ($F(1, 1390) = 0.259$, $p = 0.61$, $\eta^2 = 0.000$). Table 4 shows the K-W test results of the pairwise comparisons. Table 5 summarizes the statistics of the distance for each group.

Table 4. Statistical test results of the vehicle distance to bike lane/shoulder marking

Comparison	Condition	χ^2	*p*-value	Cohen's *d*
Traffic vs. no traffic	Solid centerline	104.4	< 0.001	-0.77
	Dashed line	28.0	< 0.001	-0.60
Solid centerline vs. dashed line	Traffic	41.7	< 0.001	0.48
	No traffic	20.5	< 0.001	0.38
Center left-turn vs. solid centerline	No traffic	0.02	0.90	-0.34
Center left-turn vs. dashed line	No traffic	19.4	< 0.001	0.08

Table 5. Summary statistics of the distance from vehicle right edge to bike lane/shoulder marking

Left-side lane marking	Left-side traffic	# of events	Median (m)	Mean (m)	SD (m)	% under 3-feet passing	% under 5-feet passing
Solid centerline	Yes	550	1.18	1.19	0.33	2%	47%
	No	442	1.43	1.44	0.40	1%	22%
Dashed line	Yes	185	0.92	1.00	0.37	9%	68%
	No	143	1.21	1.30	0.56	3%	44%
Center left-turn	No	248	1.40	1.44	0.36	0%	19%

3.3. The effect of lane width

The width of the traffic lane was calculated for the overtaking events if Mobileye® reports high quality for both the left and right side lane markings. For the scope of the paper only the events with solid centerline and with bike lane/shoulder were analyzed. Figure 6 shows the effects of the lane width on the vehicle encroachment and the distance to bike lane/shoulder marking.

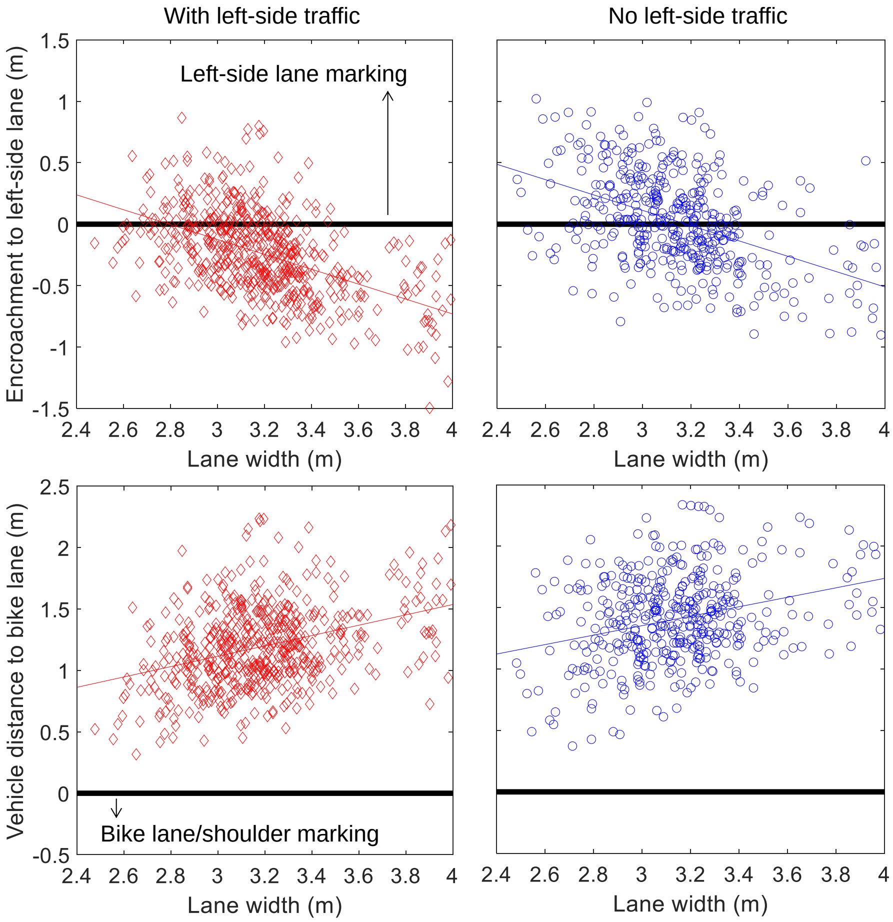

Fig. 6. Scatter plot of lane width vs. vehicle encroachment (top figures) and distance to bike lane/shoulder marking (bottom figures)

A multiple linear regression was used to examine the relationship between the encroachment and the lane width and left-side traffic. No significant interaction effect was found between lane width and left-side traffic ($p = 0.81$). A significant regression model was found ($F(2, 960) = 216.0$, $p < 0.001$, $R^2 = 0.311$). Both lane width and left-side traffic were significant predictors of the encroachment (both $p < 0.001$). With left-side traffic, the encroachment can be predicted by the following formula ($encroachment = 1.72 - 0.6135 * lane\ width$, units in meters, same hereinafter). With no left-side traffic, the encroachment can be predicted by the following formula ($encroachment = 1.95 - 0.6135 * lane\ width$). The encroachment decreases by about 0.06 m for each 0.1 m of increase of lane width. When the lane width is available, the vehicle distance to the bike lane/shoulder marking can be calculated using Eq. (1).

$$distance\_to\_bike\_lane = encroachment + lane\_width - vehicle\_width \tag{1}$$

Note the vehicle width is a constant for a given vehicle. Thus the distance to bike lane/shoulder marking can be predicted by plugging the multiple regression functions of the encroachment into Eq. (1). The slope parameter for the lane width when predicting the distance would become 0.3865 (=1-0.6135), which means the distance increases by about 0.04 m for each 0.1 m of increase of lane width.

3.4. Driver distraction

Drivers' distraction activities prior to overtaking bicyclists were identified by reviewing the driver-facing camera videos. Out of the 4,789 verified overtaking events, 154 events (3%) were excluded because we were unable to determine the driver distraction activities due to malfunction or view obstruction of the driver-facing camera. For the remaining 4,635 events, we found that in 388 events the driver was holding a cell phone in either the left or right hand prior to the overtaking. This accounts for 8.4% of the examined events. It was observed that sometimes the driver was holding a cell phone in the hand but was not actively engaged in using the cell phone prior to the overtaking. We further identified that during 363 (7.8%) overtaking events the drivers were actively using the cell phone or engaged in other types of distractions within five seconds prior to the overtaking. Table 6 summarizes the categories and prevalence of each types of driver distraction activities.

Table 6. Categories and prevalence of driver distraction while overtaking bicyclists

	Count	Percentage
Holding cell phones to their ears (termed "*phone calling*")	167	3.6%
Visibly manipulating cell phones (termed "*texting*")	142	3.1%
Holding cell phones to converse in speaker mode	20	0.4%
Other visible distractions (e.g., manipulating center console)	34	0.7%
Total events with driver distraction	363	7.8%
Total events in which driver distraction can be determined	4,635	100%

We further examined how driver distraction prior to the overtaking may affect the vehicle encroachment and distance to bike lane/shoulder marking. Although 167 phone calling and 142 texting events were identified from the overtaking events, they occurred at a wide variety of road configurations and the Mobileye® distance measures may not have high quality measures in these cases. To remove the potential confounders of lane marking type and presence of bike lane, we only focused on the most common combination of solid centerline and bike lane/shoulder for the analysis. Figure 7 shows the encroachment grouped by left-side traffic and driver distraction state.

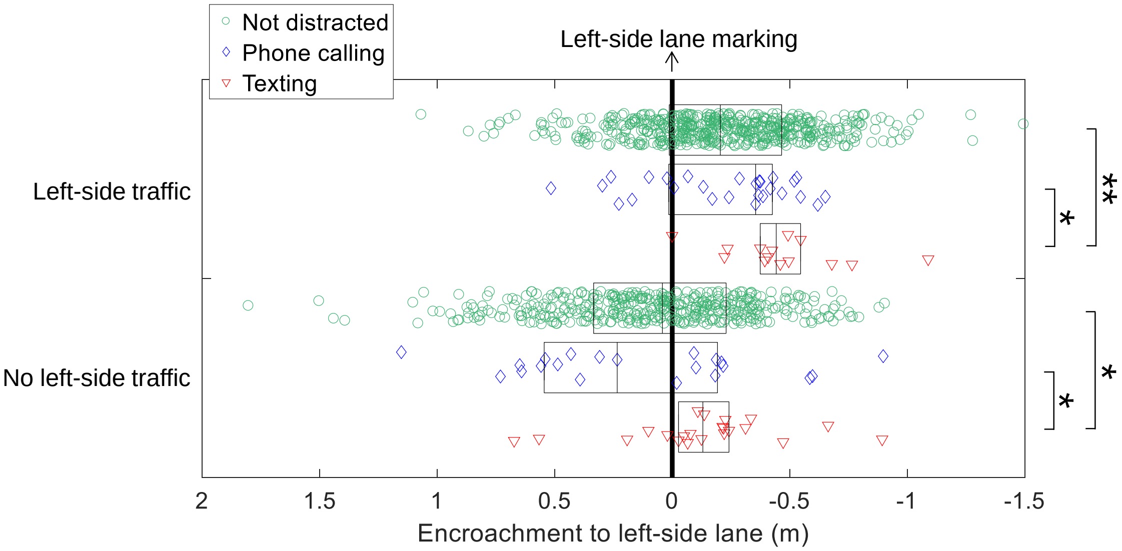

Fig. 7. Vehicle encroachment to left-side lane grouped by driver distraction. *: $p < 0.05$, **: $p < 0.01$

K-W tests show that when there was left-side traffic, *texting* was associated with significantly less encroachment compared to both *not distracted* (χ^2 (1) = 7.6, $p < 0.01$, $d = -0.71$) and *phone calling* (χ^2 (1) = 5.6, $p < 0.05$, $d = -0.86$). There was no significant difference between the *phone calling* and *not distracted* (χ^2 (1) = 0.02, $p = 0.90$). When there was no left-side traffic, *texting* was associated with significantly less encroachment compared to both *not distracted* (χ^2 (1) = 5.0, $p <$ 0.05, d = -0.48) and *phone calling* (χ^2 (1) = 3.9, $p <$ 0.05, d = -0.62). There was no significant difference between the *phone calling* and *not distracted* (χ^2 (1) = 0.77, p = 0.38).

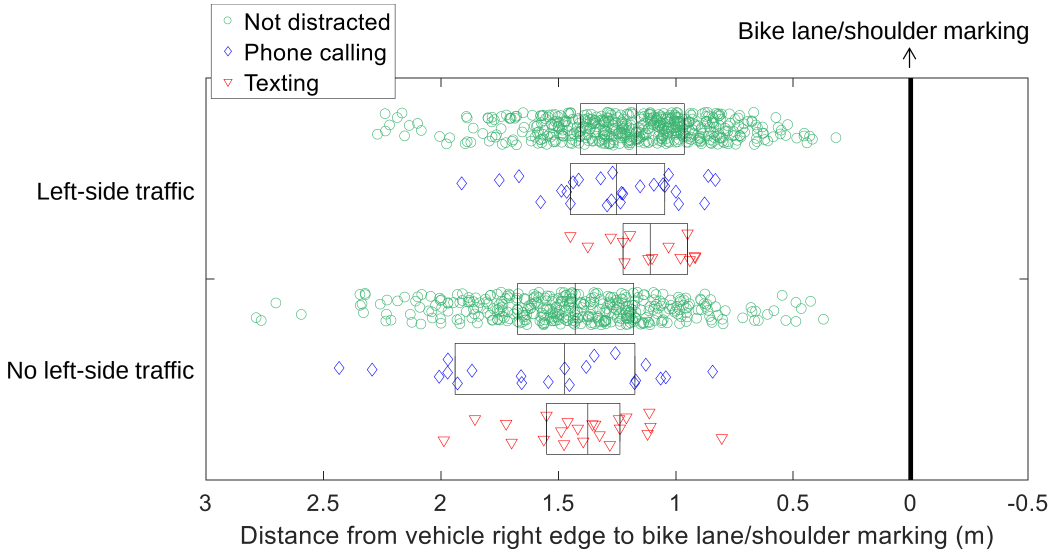

Fig. 8. Distance from vehicle right edge to bike lane/shoulder marking grouped by driver distraction

Similarly, Figure 8 shows the distance from the vehicle right edge to bike lane/shoulder marking, grouped by left-side traffic and driver distraction state. K-W tests show that there was no significant difference between any distracted and non-distracted groups either with or without left-side traffic. Specifically, when there is left-side traffic, there was no significant difference between the *texting* and *not distracted* (χ^2 (1) = 0.63, p = 0.43), between the *texting* and *phone calling* (χ^2 (1) = 3.1, p = 0.08), and between the *phone calling* and *not distracted* (χ^2 (1) = 1.7, p = 0.19). When there is no left-side traffic, there was no significant difference between the *texting* and *not distracted* (χ^2 (1) = 0.15, p = 0.70), between the *texting* and *phone calling* (χ^2 (1) = 1.0, p = 0.32), and between the *phone calling* and *not distracted* (χ^2 (1) = 1.1, p = 0.29).

4. Discussion

This paper investigated the effects of a number of road infrastructure, traffic, and driver factors on drivers' lateral maneuver of the vehicle when overtaking bicyclists. Two measures of drivers' overtaking maneuvers were examined: (1) vehicle encroachment to the left-side lane, and (2) the distance from vehicle right edge to a bike lane or paved shoulder at the time of overtaking.

Legal status: During the SPMD data collection phase (2013-2015), there was no specific laws in either the State of Michigan or City of Ann Arbor regarding the minimum distance when passing bicyclists, such as the 3-feet (0.91 m) law in some States in the U.S. (National Conference of State Legislatures, n.d.). The State of Michigan does have a general requirement that "*when passing a pedestrian or a slow-moving vehicle, such as a bicycle, farm equipment or a horse and buggy, allow adequate room so that the person or vehicle is not endangered.*" (Michigan Secretary of State, 2016). In Michigan it was prohibited to pass another vehicle by crossing a solid yellow line or when there is a "no passing" sign (Michigan Secretary of State, 2016). It is to note that in some other States in the U.S. such as the State of Ohio, there are no-passing-zone exceptions that allow drivers to cross the centerline if "*(1) The slower vehicle is proceeding at less than half the speed of the speed limit applicable to that location. (2) The faster vehicle is capable of overtaking and passing the slower vehicle without exceeding the speed limit. (3) There is sufficient clear sight distance to the left of the center or center line of the roadway…*" (Ohio Revised Code, n.d.). However, there are no such exceptions in the State of Michigan. During the data collection phase Michigan already has laws banning text messaging while driving (Michigan Vehicle Code, Section 257.602b), while there was no specific laws banning handheld cell phone use or use of cell phone other than text messaging.

Left-side lane marking - solid centerline: Solid centerline was the most common left-side lane marking type in our data. Even though in the State of Michigan it was legally prohibited for drivers to cross a solid centerline to pass another vehicle (Michigan Secretary of State, 2016), our data show that a substantial amount of the overtaking occurred when the drivers crossed the solid centerline. The percentages range from 28% for the combination of bike lane/shoulder and left-side traffic to 83% for the combination of road edge and no left-side traffic. As argued by Damon and Goodridge (2014), two options for the driver would be either following the bicyclist until the road configuration changes (e.g., end of the solid center line) or crossing the centerline to overtake the bicyclist. Our data confirm their assertion that when there was no bike lane/shoulder, in the majorities of these cases (62% and 85% for with and without oncoming traffic) the drivers already crossed the centerline despite the fact that it was legally prohibited. On the other hand, in 17% of the overtaking the drivers did not cross the solid centerline even there was no oncoming traffic and only road edge. And the drivers almost never (0-1%) completely cross over to the left-side lane even when there was no oncoming traffic. These results may have implications for legislators to consider adding the exceptions of crossing solid centerline when overtaking low-speed vehicles including bicyclists if the road is clear.

Left-side lane marking – dashed line: Our results show that when there was no bike lane/shoulder and no left-side traffic, the dashed line was associated with significantly more encroachment compared to solid centerline. This is not surprising as with no left-side traffic and the bicyclist in the same traffic lane, the drivers may simply make a complete lane change to the left lane to overtake the bicyclist. However, when there was left-side traffic, the encroachment for both solid centerline and dashed line became significantly less, and no significant difference of the encroachment was found between the solid centerline and dashed line. More interestingly, when a bike lane/shoulder was present, the dashed line was associated with significantly less encroachment and significantly closer distance to the bike lane/shoulder marking compared to the solid centerline (either with or without left-side traffic). This result is in a sense contrary to two previous studies by Shackel and Parkin (2014) and Mehta et al. (2015), which found that roads with two lanes in one direction (termed "dual lane" in the former study and "four-lane road" in the latter) were associated with significantly larger overtaking distance compared to the roads with one lane in one direction (termed "single lane" in the former study and "two-lane road" in the latter). The difference in the findings may be from the difference in the definition of overtaking. Both of the mentioned studies used instrumented bicycles to collect the overtaking distance data at the moment when the bicycle was overtaken by a vehicle. On a four-lane two-way road it is likely that all the vehicles traveling in the left lane were recorded. This would include the vehicles that were always traveling in the left lane regardless of the bicyclists. We consider these cases as less relevant to the safety of the bicyclists as the vehicle and bicyclists were always separated by the right traffic lane. In our analysis we only included the overtaking when the vehicle was initially (within ten seconds of the overtaking) at the outmost lane. The approach in the two previous studies is understandable as it would be difficult for instrumented bicycles to identify and exclude the vehicles that were always traveling in the left lane. In this paper we were able to do that by using the continuous data from the instrumented vehicles. It is interesting to see the opposite effect that when a bike lane/shoulder was present, a dashed line was associated with significantly less encroachment and closer distance to bike lane/shoulder marking compared to a solid centerline. This result may seem counter-intuitive as solid centerline generally sends a stronger message of no-crossing compared to a dashed line. One possible explanation is that in the case of a dashed line it may take drivers more mental and physical effort to cross the lane marking compared to a solid centerline. Crossing a dashed line requires the drivers to check the left-side mirror and blind spot to perceive and assess the left-side traffic coming from behind and likely at higher speed, while crossing a solid centerline only requires the drivers to focus on the oncoming traffic down the road. The fact that the bicyclists were riding in a separated bike lane/shoulder may make the drivers feel it is less necessary to make the effort to move over and encroach into the left-side lane. This finding may have implications for traffic engineers to gain insights into drivers' overtaking maneuvers (and the real and perceived risk to bicyclists) that are associated with different types of road configurations (e.g., two-lane rural roads vs. four-lane arterial roads). As our results seem to suggest that when a bike lane/shoulder is present, a driver traveling in the outmost lane of an arterial road (i.e., with a dashed line) may move over less compared to a two-lane two-way road (i.e., with a solid centerline) when overtaking bicyclists.

Left-side lane marking – center left-turn lane line: The results also show that compared to solid centerline and dashed line, center left-turn lane line in general was associated with the most encroachment to left-side lane and the largest distance to bike lane/shoulder marking. This is as expected as the center left-turn lane is dedicated for vehicles to make left-turns only and is generally empty. It is evident that in most events drivers were using the space in this empty lane to give more room to bicyclists when overtaking. However, it is noticeable that with a combination of center left-turn lane line and road edge, the majority of the vehicles crossed the lane marking (i.e., encroachment greater than zero), while with the presence of a bike lane/shoulder, more than half of the vehicles did not cross the lane marking, even when the left-side lane was empty.

Presence of bike lane or paved shoulder: The results show that regardless of the left-side lane marking type and traffic, bike lane/shoulder was associated with significantly less encroachment compared to road edge without a bike lane/shoulder. In addition, the variability of the encroachment (see the standard deviation (SD) column in Table 3) was smaller when there was a bike lane/shoulder. These results are constant with previous findings such as by Shackel and Parkin (2014) and Mehta et al. (2015). It may be explained as when there is a marked bike lane/shoulder, drivers may perceive the bicyclists who were on the other side of the bike lane/shoulder marking, as traveling in a separate lane, thus less lateral maneuver of the vehicle was needed. On the other hand, when there was only road edge, drivers may perceive the bicyclists as sharing the same traffic lane as the vehicle, and more lateral maneuver was made. This effect may also be related to the bicyclists' position on the road when there is not a bike lane/shoulder. Based on the video reviews most of the bicyclists were riding near the road edge at the time of being overtaken.

However this factor was not quantified in the analysis due to the difficulty in accurately estimating the bicyclist's position from the data. This effect may also be related to the lane width of the roads associated with and without a bike lane/shoulder. Possibly the traffic lane with only the road edge or curb was also narrower compared to the roads with a bike lane/shoulder, and thus more encroachment would be needed to overtake bicyclists. However, due to the difficulty in accurately measuring the lane width when the right-side is the road edge or curb in our data, the lane width of the roads associated with only the road edge were not analyzed.

Left-side traffic: The results show that regardless of the left-side lane marking type and presence of bike lane/shoulder, the presence of left-side traffic was associated with significantly less encroachment and shorter distance to the bike lane/shoulder marking. And the variability of the encroachment was smaller when there was left-side traffic. These results were consistent with previous findings such as by Shackel and Parkin (2014) and Dozza et al. (2016). If the left-side is a solid centerline and there is oncoming traffic, crossing the centerline means the risk of a head-on crash with the oncoming vehicle. If the left-side is a dashed line and there was adjacent traffic in the left-side lane, encroaching to the left-side lane means the potential conflict with the vehicles in the left lane. Indeed our data show that both the encroachment to left-side lane and the distance to bike lane/shoulder marking was significantly less with the presence of left-side traffic.

Lane width: The results show that wider lanes were associated with significantly less encroachment and larger distance to the bike lane/shoulder marking. Regression models show that for each 0.1 m increase of the lane width, the encroachment decreases by about 0.06 m and the distance to bike lane marking increases by about 0.04 m. However, wider lanes do not necessarily mean it is safer for overtaking bicyclists, as studies have shown that wider lanes are also associated with increased driving speed (e.g., Yagar & Van Aerde, 1983; Shackel & Parkin, 2014).

Driver distraction: By reviewing the driver activities prior to overtaking bicyclists, we found that 8.4% of the overtaking occurred when the drivers were holding a cell phone in their hand. This number is close to the 9.1% (= 6.5% right hand + 2.6% left hand) reported by Reed and Ebert (2016) using the same SPMD data set but with sampling images that were not specific to encountering bicyclists. It was observed that in some cases drivers were holding cell phones in their hand but were not engaged in using the device prior to overtaking bicyclists. We further identified that 7.8% of the overtaking occurred when the driver was visibly engaged in using a cell phone or other types of distraction activities within five seconds prior to overtaking bicyclists.

From the perspective of a bicyclist, that translates to one distracted driver for every 13 times he/she is overtaken. In terms of the types of distractions, holding cell phones to their ears and manipulating cell phones are the two most common types. 3.1% of the overtaking occurred when the drivers were manipulating cell phones (e.g., text-messaging, browsing) within five seconds prior to overtaking. This translates to one such driver for every 30 times a bicyclist is overtaken. This percentage (3.1%) is also higher than the percentage (2.2% in 2015) reported from a recent study by NHTSA based on road-side observations (Pickrell, 2017). Driver distractions in a road crash are usually difficult to identify during post-crash police investigations. The top two bicyclist fatal crash types in the U.S. in 2016 are “Motorist Overtaking - Other/Unknown” and “Motorist Overtaking - Undetected Bicyclist” (see Table 1). The results provide some indirect evidence that possibly a fair amount of the fatal crashes may have involved distracted drivers. Our results further show that when the driver was manipulating a cell phone prior to the overtaking, the encroachment to the left-side lane was significantly less compared to non-distracted driving. One possible explanation is that when a driver is manipulating a cell phone prior to the overtaking, his/her eyes were not always on the road and they may detect the bicyclists at a later time compared to normal driving. In an event of a late detection the driver may be less prepared and more inclined to not encroach to the left-side lane when approaching the bicyclists. It is to note our data do not show evidence of less encroachment for the phone calling group nor closer distance to the bike lane/shoulder marking for the texting or phone calling group. It is potentially due to the fairly small amount of distracted events in terms of statistical test. In order to exclude the potential confounders of left-side lane marking type and presence of bike lane/shoulder, we only used the data from the most common combination of solid centerline and with bike lane/shoulder. In the future we may look for larger naturalistic driving data sets which contain more distracted overtaking events for further investigations.

There are several limitations in this study. First, the data used in this paper were from the SPMD study which was primarily designed for testing and demonstrating connected vehicle technologies. The instrumented vehicles did not have side-facing cameras or proximity sensors that could be used to measure the overtaking proximity, which is a direct measure of the bicyclist safety. There are also other overtaking metrics that were not measured or included in the scope of this paper, such as vehicle speed, time duration and head-on crash risk of lane-crossing, bicyclists’ subjective risk perception (Llorca et al, 2017), and the timing selection of overtaking (an example of bad timing is starting overtaking with a limited sight line and having to cut back in early to avoid an oncoming vehicle). In addition, the participants of the SPMD study were recruited in the Ann Arbor, Michigan area. The City of Ann Arbor is a midsized city with a population of 120,782 in 2016. The road infrastructure, traffic patterns, and bicyclist volume in this area may not representative to other areas (e.g., large urban cities). Secondly, there are a wide range of factors that may potentially influence drivers' overtaking maneuver that were not included in this paper. Examples include bicyclist factors such as bicyclists' position on the road, single or a group of bicyclists, bicyclist visibility, bicycle speed and lateral steadiness, infrastructure factors such as width of the bike lane and paved shoulder, road curvature or grade that may affect driver's sight line, and driver factors such as their experience and ability in detecting bicyclists (Beanland & Hansen, 2017), judging the space to the bicyclists, and their attitude towards bicyclists. In the future we may further investigate some of these factors as well. Thirdly, as with all observational studies, there could be potential confounding factors compared to a randomized experiment. Cautions should be given when interpreting the results and making any causal inference. In our analysis pairwise tests of one factor within subgroups of the other factors (e.g., comparing solid centerline and dashed line under the condition of with bike lane/shoulder and with traffic) were used for controlling confounding from the measured factors. However, there are still possible unknown confounders that were not measured and controlled. In the future we may continue to investigate and identify possible confounders in the analysis of driver-bicyclist interactions using naturalistic driving data.

5. Conclusions

This paper demonstrates a unique approach to study driver-bicyclist interaction by using in-vehicle sensory data from naturalistic driving studies, which provide rich quantitative data on the interactions from a driver's perspective. The results show that alarming percentages (3.6% and 3.1%) of the overtaking involved drivers actively engaging in making callings or manipulating a cell phone with eyes off the road. We found that with a bike lane or paved shoulder, a dashed line on the vehicle's left side was associated with significantly less encroachment and shorter distance to the bike lane/shoulder marking compared to a solid centerline. When a driver was manipulating a cell phone prior to the overtaking, the encroachment was significantly less compared to non-distracted driving. This work is a first step of demonstrating the feasibility and unique value of using naturalistic driving data to study the interactions between drivers and non-motorized road users. The quantitative results could be potentially used by traffic engineers, policy makers and legislators to support the designs of better road infrastructures, programs, policies, and traffic laws that aim to improve the safety of all road users. The results may also be used as a baseline to develop, test, and benchmark the automated vehicles when interacting with bicyclists.

Acknowledgements

Toyota Research Institute ("TRI") provided funds to assist the authors with their research but this article solely reflects the opinions and conclusions of its authors and not TRI or any other Toyota entity. The authors would also like to thank Scott Bogard for his technical support of the SPMD database, Dillon Funkhouser for his support of the video coding, and Matthew Reed for his valuable comments.

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