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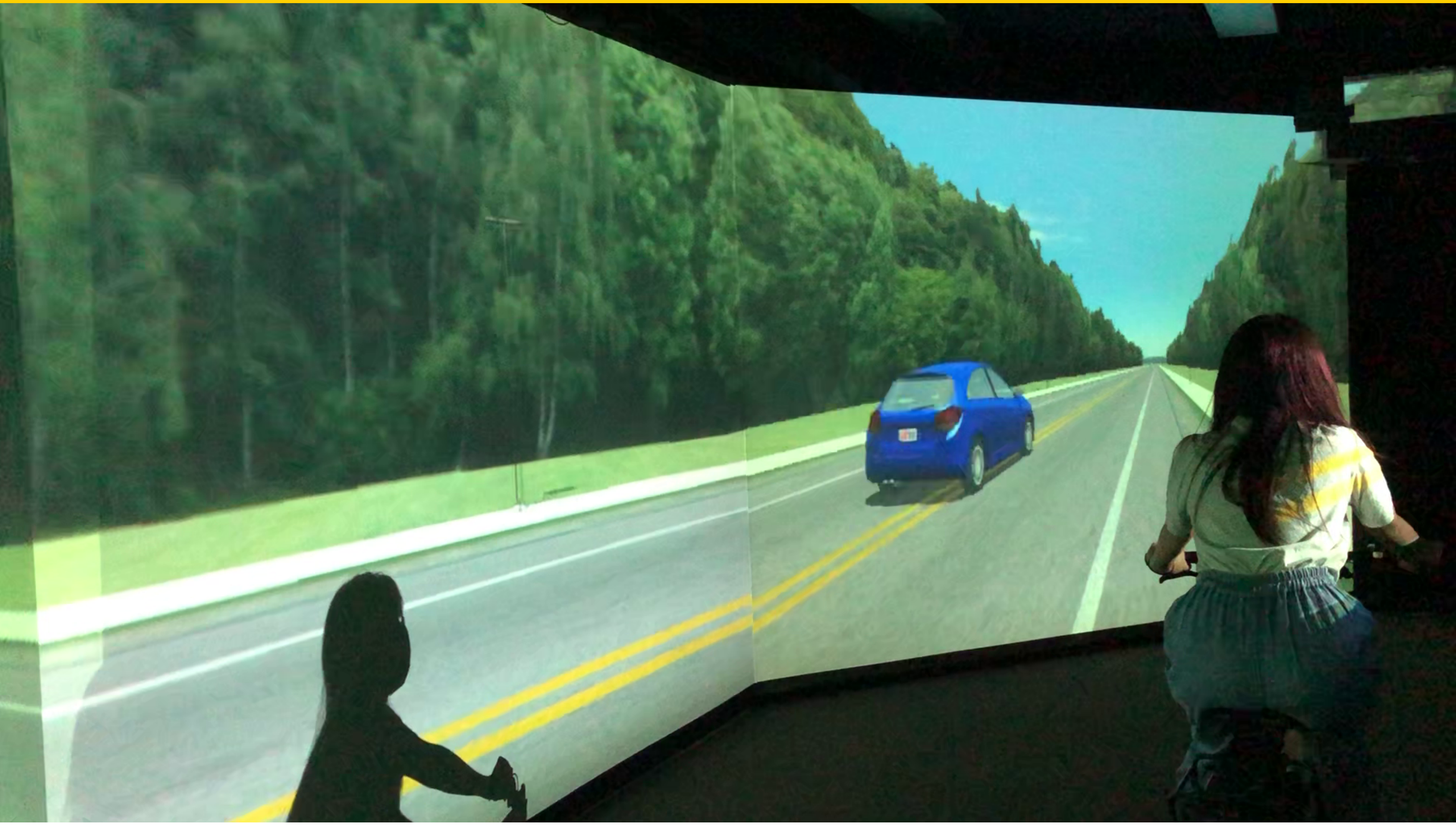

A Data-Driven Autonomous Driving System for Overtaking Bicyclists

Brian T.W. Lin, PhD
Shan Bao, PhD
Huizhong Guo, PhD
Szu-Tung Chen
Tzu-Hsuan Chuang
Hao-Jie Su

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by
Brian T. W. Lin, Ph.D.
Assistant Research
Scientist

Shan Bao, Ph.D.
Research Associate
Professor

Huizhong Guo, Ph.D.
Research Fellow

Szu-Tung Chen
Graduate Researcher

Tzu-Hsuan Chuang
Graduate Researcher

Hao-Jie Su
Graduate Researcher

University of Michigan

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Contacts

For more information:

Brian T. W. Lin, Ph.D.
2901 Baxter Road
Ann Arbor, MI 48109-2150
Phone: (734) 647-5812
Email: btwlin@umich.edu

Shan Bao, Ph.D.
2901 Baxter Road
Ann Arbor, MI 48109-2150
Phone: (734) 936-1127
Email: shanbao@umich.edu

CCAT
University of Michigan Transportation Research Institute
2901 Baxter Road
Ann Arbor, MI 48152
uumtri-ccat@umich.edu
(734) 763-2498

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16. Abstract

This research aims to develop data-driven models for suggesting the initiation of an automated car-to-bicycle overtaking process that will be assessed subjectively by human drivers and bicyclists in a driving simulator environment. A naturalistic driving dataset with 102 vehicles involved served as the data source for model development. The models were implemented to a CarSim software as the driving simulator platform for an experiment. Thirty-two participants were recruited to evaluate the models from driver's and bicyclist's perspectives on the aspects of satisfaction and perceived risk of collision. It was found that both drivers and bicyclists felt less satisfied and perceived higher risk if the overtaking was engaged with a faster speed and the presence of oncoming traffic. However, the effect to bicyclists could be mitigated with the application of a dedicated bicycle lane. Bicyclists also sought more lateral room to the vehicle when being overtaking, although drivers were satisfied with the current settings without perceiving any significant risk. Therefore, the developed models should be adjusted in the future by considering the perceptions by bicyclists and other road users. Stakeholders, such as automated feature developers and policy makers, should refer to the models carefully with paying attention to the inconsistency between driver's and bicyclist's perspectives.

17. Key Words	**18. Distribution Statement**
Car-to-Bicycle overtaking, naturalistic driving data, classification models, safety perception, subjective assessment, human factors	No restrictions.

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1. Introduction

Car-to-bike overtaking is a task with high risk to both drivers and bicyclists. Collision may happen if drivers incorrectly estimate the required time to pass an object (Jones and Heimstra, 1964). Gray and Regan (2005) denoted that overtaking a slower object is one of the more dangerous situations for drivers. In 2020, 97,763 crash incidents occurred due to vehicle passing or overtaking (NHTSA, 2022b). And in the same year, there were 938 bicyclist fatalities in traffic crashes, and 38,886 bicyclists were injured in the United States (NHTSA, 2022a). Whilst 64 percent of bicyclist fatalities happened at non-intersection locations, the first impact from the front of vehicles accounts for 83.2 percent of bicyclist fatalities and 73.7 percent of bicyclist injuries. As bicyclists share the road with motor vehicles, bicyclists become one of the most vulnerable groups (Chong et al., 2010). Currently, Advanced Driver Assistance Systems (ADAS) has become commercially available in recent years and some technologies are able to help overtake the other road users and reduce crashes, including Lane Departure Warning (LDW), Blind Spot Detection (BSD), Forward Collision Warning (FCW), and Autonomous Emergency Braking (AEB) systems. However, these ADAS functions were developed based on the perspective of driver while the vulnerable road users' perception was ignored (Kitazawa and Kaneko, 2016; Kuwata et al., 2008). Furthermore, it is not clear how the risk perception of drivers and bicyclists differs under the support from ADAS for various on-road scenarios. Very limited studies have examined ADAS from bicyclists' point of view. Therefore, this study aimed to (1) build computational car-to-bike overtaking models based on naturalistic driving datasets, (2) implement the computational models as an automated overtaking function in a driving simulator environment, (3) evaluate the models from the perspective of drivers and bicyclists, and (4) investigate the factors with impact on the perception of risk and other subjective measurements for drivers and bicyclists. These findings will provide implications for the design of safe and satisfying car-to-bicycle overtaking.

1.1 Critical Factors for Overtaking Maneuver

Previous studies have revealed factors associated with overtaking maneuvers. Feng et al. (2018) examined correlation between the lane marking and overtaking maneuvers and found that drivers performed less lane-crossing when the bicycle lane or pavement shoulder presented. From the bicyclist's perspective, the dearth of dedicated bicycle infrastructure induced a lower safety perception and thus people were prone to deny cycling for commute (Akar and Clifton, 2009). In terms of roadway characteristics, increased posted speed limits demonstrated a positive correlation with raised lateral overtaking distance (Rubie et al., 2020; von Stulpnagel et al., 2022), while lane boundary was regarded as a safety factor in the automated overtaking research (Kitazawa and Kaneko, 2016; Kuwata et al., 2008). On the other hand, Haworth et al. (2018) found no significant difference in car-to-bike lateral passing distance while the driver conducted the overtake within a wider lane road. Additionally, according to Shackel and Parkin (2014), the overtaking maneuver exhibited no significant variance in lateral passing distance when the posted speed limits were set to 20 mph or 30 mph.

Other factors such as traffic conditions and vehicle characteristics may influence the overtaking maneuver as well. For instance, the shorter time to collision with an oncoming vehicle not only reduces the drivers' safety perception due to potential crash with bicyclists but also shapes the drivers' overtaking strategy (Piccinini et al., 2018). This finding is in line with the notion that the driver decides whether to conduct an overtaking maneuver by assessing the obstacle-free space between their vehicles and the oncoming traffic (Asaithambi and Shravani, 2017). Comparing to factors such as lane width, shoulder width, posted speed limits, and vehicle speed, oncoming traffic shows a more pronounced influence on the overtaking maneuver of drivers (Dozza et al., 2016).

1.2 Safety Perception in Overtaking Events: Driver's Perspective, Bicyclist's Perspective

The safety perception of overtaking tasks presents a unique interplay between the viewpoints of both drivers and bicyclists, offering distinct insights that contribute to the broader understanding of road safety.

Prior research has diligently explored the safety perception held by drivers who engage in overtaking maneuvers. Rasch et al. (2022) discovered a significant decline in drivers' perceived safety in a car-to-bike overtaking event when the time-to-collision (TTC) with oncoming traffic is shortened. This intriguing finding underscores how drivers factor influence in the safety of bicyclists, yet drivers' perceived safety also hinges on the potential risk of colliding with vehicles coming from the opposite direction. In addition, the shorter maneuver duration and larger deviation distance could both increase the safety perception of drivers when they implement overtaking tasks (Sourelli et al., 2021). For bicyclists' perspectives, Llorca et al. (2017) found that higher overtaking speed led to an elevated perceived risk of bicyclists. From the perspective of drivers, Dozza et al. (2016) revealed that the varied lateral distances to bicyclists occurred while drivers adopted distinct overtaking strategies. However, the effect of speed and lateral distance should be further probed as bicyclists' safety perception may vary with different lateral distance and overtaking speed levels. In previous overtaking algorithm studies, the parameters, such as relative speed and distance (Petrov and Nashashibi, 2014; Kitazawa and Kaneko, 2016; Tomar et al., 2021), overtaking initiation distance and speed (Tomar et al., 2021), and prescribed safety distance (Petrov and Nashashibi, 2014; Kuwata et al., 2008), were also included in research to perform an automated collision-free, safe overtaking maneuver.

On the other hand, the bicyclists' safety perception significantly influences their motivation to bike. Landis et al. (1997) brought into focus the influence of bike lane designs on bicyclists' perceived safety. The status of biking infrastructure, encompassing bike lane design, bike parking facilities, and pavement conditions, is a significant safety concern for bicyclists. The dearth of such facilities discourages people from using bikes for commuting (Akar and Clifton, 2009). A field study by Llorca et al. (2017) delved into rural areas, uncovering how bicyclists' safety perception is impacted by both the lateral space available and the speed of overtaking vehicles. In two-lane rural environment, bicyclists did not consistently report a lower risk perception with a larger lateral distance toward the overtaking vehicle. However, bicyclists who were overtaken by heavy vehicles with higher speeds reported the highest perceived risk. In line with this thought, Rasch et al. (2022) revealed that smaller lateral distances and higher overtaking speeds diminish bicyclists' perceived safety. The perceived safety of bicyclists was significantly threatened due to the concern of being hit or destabilized by the overtaking vehicles. Accordingly, when bicyclists were in the closest lateral position against the overtaking vehicle, they perceived the least perceived safety.

Rasch's study shed light on intriguing discrepancies between how drivers and bicyclists interpret their perceived safety. While drivers significantly based the perceived risk of a head-on collision with oncoming vehicles, bicyclists place greater weight on factors like lateral space and the speed of overtaking vehicles to form their safety perception. These differing viewpoints raise vital concerns in the context of shared spaces on road, necessitating comprehensive strategies that accommodate both perspectives for a safer coexistence on the roads.

1.3 Research Goal & Research Questions

An automated car-to-bike overtaking feature designed solely from the perspective of motorists could pose a risk to overtaken cyclists if their perception was not considered. Despite a growing body of research on cycling safety, notably by Nazemi et al. (2021) employing virtual reality bicycle simulation, there remains a dearth of studies focusing on automated overtaking maneuvers within an immersive experimental context grounded in bicyclists' perceived safety. A successful car-to-bike overtaking solution necessitates meeting the satisfactory and safety perception levels for both motorists and bicyclists. Thus, two-step research was conducted in this project. The first study utilized naturalistic driving data to identify critical parameters for an overtaking decision and to build decision-making models to predict the initiation of a car-to-bicycle overtaking maneuver. The models were further employed in the second study to create a series of simulated car-to-bicycle overtaking scenarios under different experimental conditions, where their associations with the safety and risk perception of drivers and bicyclists can be both evaluated. This research aims to facilitate the development of an automated car-to-bike overtaking feature that integrates the perceptual preferences of both motorists and cyclists through two studies. The research questions for this research are presented as follows:

1. What were the critical parameters that form the distinguished types of overtaking decision?
2. How did drivers and bicyclists satisfy and perceive the risk from the automated overtaking concluded by the manual driving models?
3. What were the significant factors that influence the perception of different road users during automated overtaking?

2. Study I: Development of Autonomous Car-to-Bicycle Overtaking Function

This section will cover data preparation and reduction, selected variables, modeling methods, and the modeling results that would serve as the environment to be implemented into the second study.

2.1 Method

2.1.1 Data Preparation

All the car-to-bicycle overtaking events were extracted from the Safety Pilot Model Deployment (SPMD) naturalistic driving data conducted by the University of Michigan Transportation Research Institute between 2013 and 2015 (Bezzina & Sayer, 2015). In SPMD, 102 vehicles were equipped with the data acquisition system (DAS) that collected the vehicle dynamics and a camera-based Mobileye system that detected and recognized several types of objects ahead, such as cars, motorcycles, and bicycles. All the data were synchronized to the sampling rate of 10 Hz. This study referred to the car-to-bicycle overtaking events applied in a previous study (Feng et al., 2018) that extracted 7,375 bicyclist-detection events and further filtered the events that the following conditions must be satisfied in a single event.

1) There was only one bicycle detected by Mobileye and shown in the field of view before overtaking.
2) The bicycle must travel in the same direction as the vehicle.
3) The trafficway had only one lane for each direction.
4) The vehicle must pass the bicycle on its left.
5) The time-series graph for yaw rate signals (rate of change of the heading angle) over the overtaking process must include two consecutive vertices (local peaks) at different signs, which implied that vehicles changed the heading towards the adjacent lane and later changed back, so the yaw rate signals formed a sinusoidal-shaped curve. The sinusoid of yaw rate represented that the vehicle had lateral movements and stayed.

After the filtering, 740 overtaking events were selected and categorized as the scenarios with and without the presence of dedicated bike lanes and traffic in the oncoming lane. The outcome is shown in Table 1.

Table 1. Overtaking Scenario Allocation

740 Overtaking Events	Shared Lane	Dedicated Bike Lane
No Oncoming Traffic	327	202
Oncoming Traffic	81	130

2.1.2 Variables

The variables extracted from SPMD and their definitions were shown as below.

- Time (s): Time elapsed since the beginning of each trip

- Travel distance (m): Distance traveled by the vehicle collected by the odometer
- Velocity (m/s): Longitudinal velocity of the instrumented vehicle
- Heading (degree): Compass direction in which the vehicle was traveling
- Yaw rate (degree/s): Rate of change of the heading angle
- Lane position (m): Lateral distance from the Mobileye device to the center of the lane
- Gap (m): Distance from the Mobileye device to the detected bicycle
- Relative velocity (m/s): Relative velocity between the instrumented vehicle and bicycle ($Velocity_{Vehicle}$ - $Velocity_{Bicycle}$)

The variables of velocity, lane position, gap, and relative velocity were selected as the predictors for modeling. Yaw rate and heading were used to filter overtaking events, as mentioned in Data Preparation. Some other variables were collected for data reduction and processing, such as acceleration and brake pedal applications and longitudinal and lateral accelerations. They provided additional evidence for selecting valid overtaking events.

All the variables were collected at two points: (1) first detection and recognition of the bicycle by Mobileye and (2) initiation of an overtaking. The first detection and recognition by Mobileye usually occurred when the vehicle approached the distance of 30-40 meters behind the bicycle, depending on the complexity of the infrastructure, weather, and the size of the bicycle and bicyclist. The data collected at the first point served as the counterfactual for the classification models that the driver did not initiate an overtaking maneuver. The definition of an overtaking initiation was when the yaw rate just began increasing (vehicle moved towards left) without decreasing until reaching to the vertex of the time-series yaw rate signal graph (local maximum). The data collected at this point served as a "go" for an overtaking, while those at first detection served as a "no-go."

2.1.3 Modeling Method and Model Evaluation

Given the binary outcome for an overtaking decision of a "go" or "no-go", logistic regressions were applied to classify the initiation of an overtaking. Four logistic regression models would be developed, and each was for a type of scenario, as shown in Table 1. Each regression model would include all the four predictors as an initial model and the insignificant predictors would be excluded from the final model. The optimal threshold for classifying overtaking initiation for each scenario was selected as the one that led to the maximum summation of the performance of sensitivity (true positive rate, TPR) and specificity (true negative rate, TNR) for a confusion matrix, which indicated the best prediction for actual events. The thresholds would be implemented in the driving simulator environment elaborated in Study II for an overtaking maneuver to be initiated once the predicted probability exceeded the threshold.

A receiver operating characteristic (ROC) curve that included TPR and false positive rate (FPR) would be created for each overtaking decision model, along with the confusion matrices and area under curve (AUC). With a confusion matrix, the classification performance would be analyzed through the following metrics, including TPR, TNR, positive predictive value (PPV), negative predictive value (NPV).

2.2 Results

The classifications by logistic regressions were shown in Table 2. For all the four scenarios, the factors of gap and relative velocity significantly impact the overtaking decision. Shorter gap and greater relative velocity (vehicle faster than bicycle) will lead to greater probability to initiate an overtaking. Lane position was not a significant factor for overtaking initiation across all the scenarios. Drivers did not have much lateral movement before the start of overtaking.

The factor of vehicle velocity was a significant factor for the scenarios with a dedicated bicycle lane, for which higher velocity led to greater overtaking probability. It implied that when overtaking a bicycle in a dedicated bicycle lane, drivers would speed up before overtaking. However, from the perspective of modeling, the factors of velocity and relative velocity would be highly correlated if a bicycle did not have much variation on its speed, which caused the collinearity and reduced the model performance. Therefore, the factor of velocity would be excluded from the final models, and gap and relative velocity formed the models for all the scenarios.

Table 2. Logistic Regressions for Overtaking Decision Models at Four Types of Scenarios

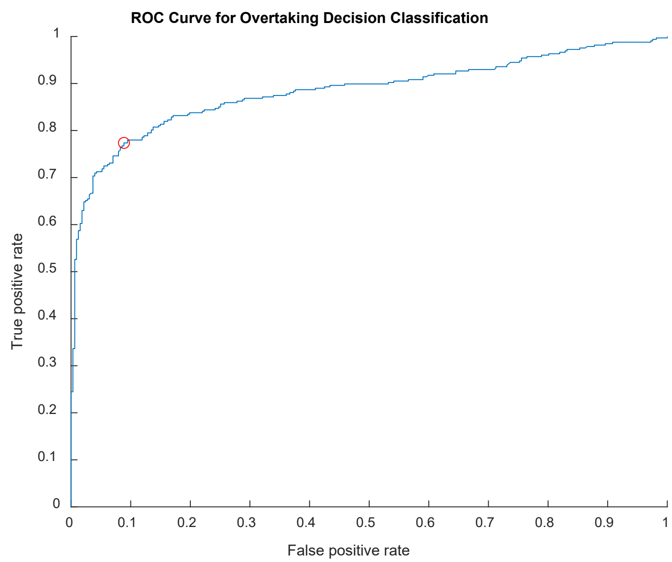
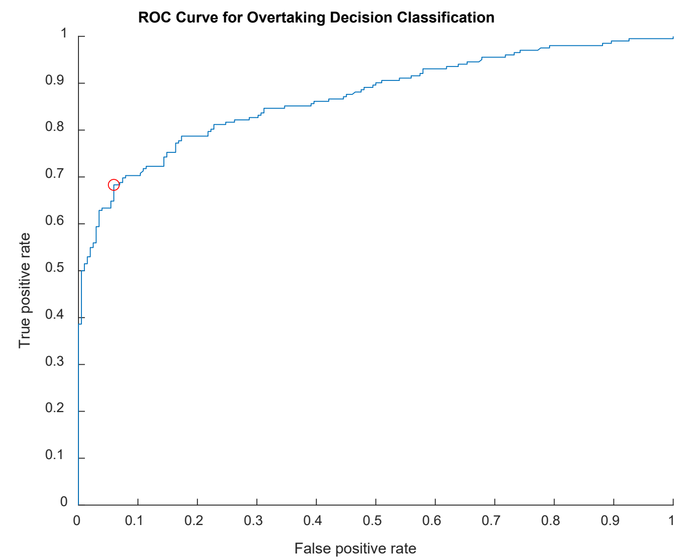
(a) No Oncoming Traffic, Shared Bike Lane						
Source	**Initial Model**			**Final Model**		
	Coefficient	t	p	Coefficient	t	p
Intercept	-1.7641	-5.21	<0.001	-1.6280	-6.37	<0.001
Velocity (*V*)	0.0093	0.38	0.71			
Gap (*R*)	0.1056	9.98	<0.001	0.1067	10.63	<0.001
Relative velocity ($\dot{R}$)	0.3244	9.38	<0.001	-0.3204	9.81	<0.001
Lane position (*P*)	-0.0391	-0.71	0.48			
(b) No Oncoming Traffic, Dedicated Bike Lane						
Source	**Initial Model**			**Final Model**		
	Coefficient	t	p	Coefficient	t	p
Intercept	-0.6755	-1.53	0.13	-1.3607	-4.52	<0.001
Velocity (*V*)	-0.0768	-2.02	0.04			
Gap (*R*)	0.0946	7.92	<0.001	0.0841	7.97	<0.001
Relative velocity ($\dot{R}$)	0.2727	6.29	<0.001	-0.3033	7.19	<0.001
Lane position (*P*)	0.0801	0.98	0.33			
(c) With Oncoming Traffic, Shared Bike Lane						
Source	**Initial Model**			**Final Model**		
	Coefficient	t	p	Coefficient	t	p
Intercept	-0.9287	-1.23	0.22	-1.2584	-2.52	0.01
Velocity (*V*)	-0.0476	-0.74	0.46			
Gap (*R*)	0.1060	4.66	<0.001	0.0992	4.86	<0.001

Relative velocity ($\dot{R}$)	0.3845	4.39	<0.001	-0.4078	4.82	<0.001
Lane position (*P*)	-0.0072	-0.05	0.96			
(d) With Oncoming Traffic, Dedicated Bike Lane						
Source	**Initial Model**			**Final Model**		
	Coefficient	t	p	Coefficient	t	p
Intercept	-0.5515	-0.98	0.33	-1.0969	-2.92	<0.01
Velocity (*V*)	-0.1239	-2.32	0.02			
Gap (*R*)	0.1104	6.36	<0.001	0.0900	6.22	<0.001
Relative velocity ($\dot{R}$)	0.3866	5.67	<0.001	-0.4325	6.63	<0.001
Lane position (*P*)	-0.1451	-1.26	0.21			

With the classification models, ROC curves were generated (as shown in Tables 3 and 4), which showed the combinations of the TPR (sensitivity) and FPR (1-specificity) calculated from the confusion matrices by applying different probability thresholds. Previous studies suggested that AUC between 0.8 and 0.9 was considered excellent for classifications (Mandrekar, 2010). Since AUC for all the four models was greater than 0.8, these models were considered appropriate for classification.

As mentioned in section 3.1.3, thresholds selected as the optima should maximize the summation of sensitivity and specificity from the confusion matrix, with which the other metrics could also be obtained. By utilizing this strategy, the cost of misclassifying an overtaking initiation was assumed to be equal to that of misclassifying a non-overtaking situation. Table 3 and 4 also show the ROC curves with true positive and false positive rates and the classification performance matrix for each of the four scenarios with its optimal threshold. Although the accuracies of all the four models were greater than 80%, the sensitivities were lower than specificities, which meant that the models performed better as suggesting 'not' to initiate an overtaking. On the other hand, high PPV indicated that many of the overtaking initiation predictions were true positives, which met our expectation.

Table 3. Results for Overtaking Classification of Overtaking Events without Oncoming Traffic

<table>
<tr><td>Scenario</td><td colspan="4">(a) No Oncoming Traffic, Shared Bike Lane</td><td colspan="4">(b) No Oncoming Traffic, Dedicated Bike Lane</td></tr>
<tr><td>ROC</td><td colspan="4">
</td><td colspan="4">
</td></tr>
<tr><td>AUC</td><td colspan="4">0.8847</td><td colspan="4">0.8701</td></tr>
<tr><td>Optimal threshold</td><td colspan="4">0.6078</td><td colspan="4">0.6464</td></tr>
<tr><td rowspan="4">Confusion matrix</td><td colspan="2" rowspan="2">Number of observations 654</td><td colspan="2">Prediction</td><td colspan="2" rowspan="2">Number of observations 404</td><td colspan="2">Prediction</td></tr>
<tr><td>Overtaking</td><td>No overtaking</td><td>Overtaking</td><td>No overtaking</td></tr>
<tr><td rowspan="2">Actual</td><td>Overtaking</td><td>252</td><td>75</td><td rowspan="2">Actual</td><td>Overtaking</td><td>137</td><td>65</td></tr>
<tr><td>No overtaking</td><td>29</td><td>298</td><td>No overtaking</td><td>12</td><td>190</td></tr>
<tr><td>Sensitivity</td><td colspan="4">0.7706</td><td colspan="4">0.6782</td></tr>
</table>

Specificity	0.9113	0.9406
Accuracy	0.8410	0.8094
PPV	0.8968	0.9448
NPV	0.7989	0.7451

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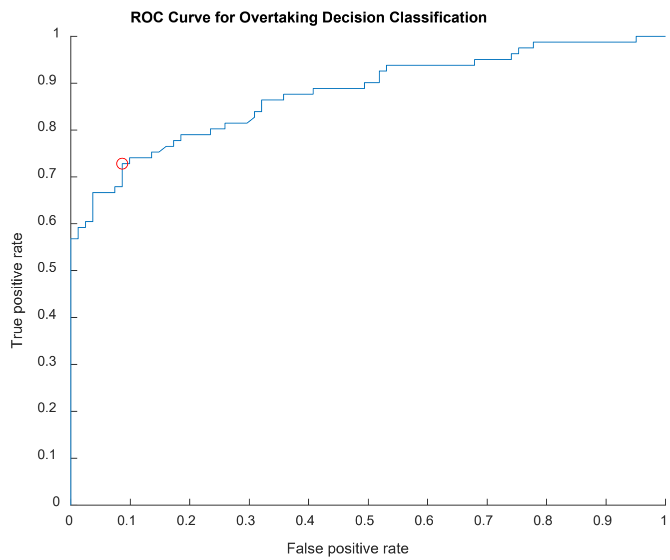
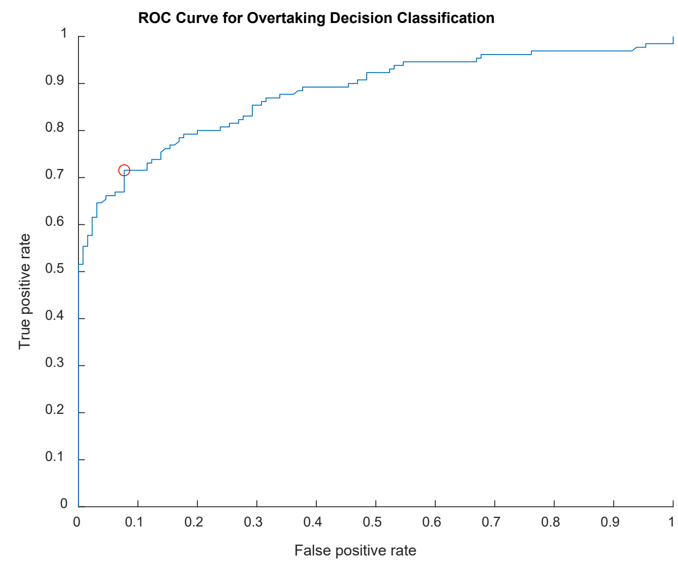
Table 4. Results for Overtaking Classification of Overtaking Events with Oncoming Traffic

<table>
<tr><td>Scenario</td><td colspan="4">(a) With Oncoming Traffic, Shared Bike Lane</td><td colspan="4">(b) With Oncoming Traffic, Dedicated Bike</td></tr>
<tr><td></td><td colspan="4">
</td><td colspan="4">
</td></tr>
<tr><td>AUC</td><td colspan="4">0.8781</td><td colspan="4">0.8794</td></tr>
<tr><td>Optimal threshold</td><td colspan="4">0.6066</td><td colspan="4">0.6233</td></tr>
<tr><td rowspan="4">Confusion matrix</td><td colspan="2" rowspan="2">Number of observations 162</td><td colspan="2">Prediction</td><td colspan="2" rowspan="2">Number of observations 260</td><td colspan="2">Prediction</td></tr>
<tr><td>Overtaking</td><td>No overtaking</td><td>Overtaking</td><td>No overtaking</td></tr>
<tr><td rowspan="2">Actual</td><td>Overtaking</td><td>58</td><td>23</td><td rowspan="2">Actual</td><td>Overtaking</td><td>92</td><td>38</td></tr>
<tr><td>No overtaking</td><td>7</td><td>74</td><td>No overtaking</td><td>10</td><td>120</td></tr>
<tr><td>Sensitivity</td><td colspan="4">0.7160</td><td colspan="4">0.7077</td></tr>
</table>

Specificity	0.9136	0.9231
Accuracy	0.8148	0.8154
PPV	0.8923	0.9020
NPV	0.7629	0.7595

2.3 Conclusions for Study 1

Through the logistic regressions, the decision for initiating an overtaking maneuver was classified. It was found that shorter distance between the vehicle and bicycle (gap) and greater relative velocity led to sooner initiation of an overtaking maneuver. Also, when overtaking at the location with oncoming traffic and a dedicated bike lane, faster vehicle velocity led to higher overtaking probability, which implied that drivers speeded up before initiating an overtaking. Overall, the classifier performance across the four scenarios was promising, especially with low false alarms (type I error), so overtaking would not be suggested at an inappropriate time.

Classification models to be implemented to the second study had optimal thresholds selected. We would specifically manipulate the variables that were not involved in the models or were difficult to quantify and would test them in an experimental environment of Study II.

It was noteworthy that the results of this study were based on manual driving data, and this assumed that what the driver did when driving manually might be preferred if the automation were to do something similar. Thus, the findings of this study could serve as a practical automated overtaking platform for the second study of this project. However, the mechanism for executing overtaking maneuvers differed between human drivers and automated systems. Human drivers primarily behaved based on their overtaking decisions on safety concerns (Dozza et al., 2016), while automated vehicles rely on obstacle identification and collision probability to navigate overtaking dynamics (Dixit et al., 2018). Although the factors with impact on manual overtaking may not be completely applied to automated vehicle scenarios, the goal of this project was to develop driver-behavior-centered models based on collision-free datasets that suggested safe overtaking behavior.

3. Study II: Subjective Assessment and Perception on Overtaking Scenarios

In Study II, an experiment based on Study I was conducted to explore bicyclists' and drivers' satisfaction assessment and risk perception toward multiple factors for a driver-centered car-to-bike overtaking performance.

3.1 Method

Tn experiment was conducted in a driving simulator environment The experimental factors are the overtaking vehicle's speed, the existence of bike lanes, the distance between the overtaking vehicle and the bicyclist, and the existence of oncoming traffic during the overtaking event. We detail the experiment design, questionnaires design, experiment procedure, and data analysis in this section. This study was approved by the Institutional Review Boards of the University of Michigan (HUM00205126).

3.1.1 Participants

Sixteen male and 16 female participants with a valid driver's license were recruited via the UM Health Research portal. The age of male participants was from 24 to 75 years (mean = 46.1, standard deviation = 19.2) and from 20 to 75 years (mean = 46.7, standard deviation = 19.9) for females. All participants were paid $50 for their participation.

3.1.2 Apparatus

This experiment was conducted in a driving simulator where the overtaking scenarios could be emulated and played from bicyclists and drivers' viewing angle based on the decision-making models and descriptive concluded in Study I. CarSim was the driving simulation software applied in this experiment that emulated car-to-bicycle overtaking scenarios shown on the projections. Figure 1 illustrates the environmental configurations for drivers and bicyclists. For drivers, a fixed-based full-size Nissan Versa cabin was utilized, which faced towards three projections that covered 120-degree field of view with the resolution of 1024x768 pixels. The screen projection was located 15 feet and 10 inches in front of the driver's seat. What drivers would experience is shown in Figure 2a. For bicyclists, a 24-inch-wheel bicycle (Genze e102) was located next to the three projection screens, simulating the scenarios bicyclists cycling in a dedicated bicycle lane or a shared lane with motorists who overtook on the left. Three screen projections on the front, side, and back were location at 15 feet and 9 inches, 7 ft and 4 inches, and 13 ft and 6 inches from the bicycle, respectively (as shown in Figure 1). What bicyclists would experience is shown in Figure 2b. Both drivers and bicyclists stayed stationary and watched the scenario videos, either in the cabin or on the bicycle seat.

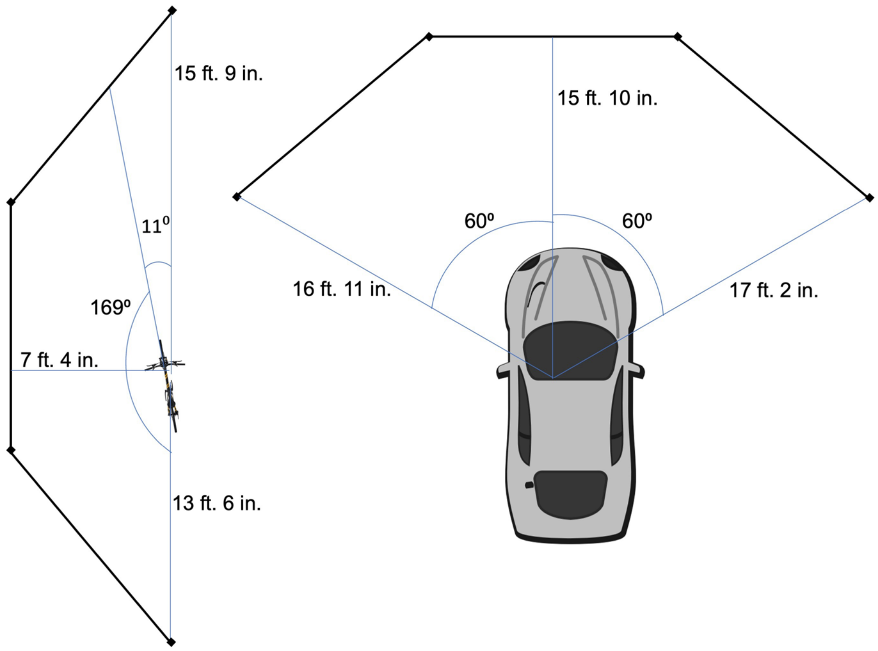
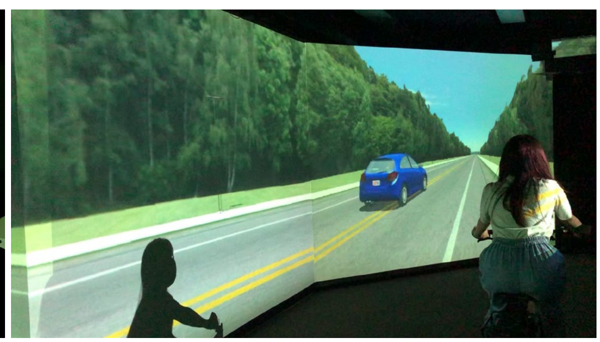


Figure 1. Positions of the Vehicle and the Bicycle to the Screens.

(a) Driver's Perspective



(b) Bicyclist's Perspective

Figure 2. Snapshot of the Simulated Scenarios

3.1.3 Overtaking Scenarios

All the scenarios were implemented in a virtual environment with certain parameters staying constant across all scenarios while others varied among scenarios. Parameters with varied values were manipulated based on either Study I or the literature, as shown below.

- Constant parameters
  - Lane width: 3.5 meters
  - Bicycle lane width: 1 meter
  - Bicycle speed: 5 m/s (~11 mph)
  - Lateral vehicle speed when overtaking: 1 m/s

- Varied parameters
  - Vehicle speed: 25 mph (lower) or 40 mph (higher)
  - Lateral offset: the 50th (smaller) or the 75th (bigger) percentiles of the lateral movement distance while overtaking, extracted from SPMD (see Table 5)
  - Lane type: a dedicated bike lane or a shared lane
  - Presence of oncoming traffic: with or without

Table 5. Lateral Offset at 50th and 75th Percentiles of Drivers from Naturalistic Driving Data

Distance From the Center of the Ego Lane	Shared Lane		Dedicated Bike Lane	
	50th	75th	50th	75th
No Oncoming Traffic	2.14 m	1.83 m	2.07 m	1.84 m
Oncoming Traffic	2.19 m	1.90 m	2.05 m	1.84 m

In the simulated environment, the vehicle began to accelerate from stationary at 200 meters behind the bicycle until reaching the target speed of 25 or 40 mph. The vehicle moved faster than the bicycle and would approach it as the gap in between reduced, the relative speed changed, and the probability of initiating an overtaking was calculated in real time based on the models from Study I. Once the calculated probability became greater than the selected optimal threshold, an overtaking maneuver would be initiated. Here is the example of an overtaking scenario with (1) lower vehicle speed (25 mph), (2) smaller lateral offset (50th percentile), (3) shared lane, and (4) without oncoming traffic.

1) The vehicle and bicycle began to accelerate from stationary until reaching their target speeds of 25 mph (17.9 m/s) and 5 m/s
2) As the vehicle started to drive with 25 mph, the gap between it and the bicycle was 163.9 m and their relative speed was 12.9 m/s
3) The vehicle chased the bicycle and initiated an overtaking at 49.8 m behind the bicycle, while the probability of overtaking initiation exceeded the optimal threshold shown in Table 3a.
4) The vehicle moved laterally with the speed of 1 m/s until reaching the designed offset of 2.14 meters from the center of the ego lane.
5) The vehicle passed the bicycle with the speed of 25 mph and left

3.1.4 Experimental Design

With two levels operated for each factor, this experiment was a 2x2x2x2 factorial design that included the factors of vehicle speed, lateral offset, lane type, presence of oncoming traffic, which were mentioned in section 3.1.3. Each participant would experience all the 16 scenarios (within-subject effect) in a random order with the viewing angles as a driver and a bicyclist, which led to 32 scenarios for a full participation. Participants were counterbalanced to begin with the driver or the bicyclist phase. Once a phase was completed, they moved to the next.

3.1.5 Procedure

Upon arrival, participants were asked to read through and fill out the consent form and the behavior survey questionnaires (Table 3). After completing both forms, the procedure was explained to the participants that there would be two phases of experiments: a driver phase and a bicyclist phase in a pre-determined order. During each phase of the experiment, 16 overtaking scenario videos were displayed to the participants. After watching each video, participants were asked to rate their perceived risk and comfort level for this overtaking scenario (after-scenario questionnaires). At the end of each phase of the experiment, participants were asked to rate their perceived risk based on all 16 overtaking scenarios (the post-test form). The participants were compensated after all forms were collected.

3.1.6 Questionnaires Design

There were three types of questionnaires offered to the participants over the entire experiment: demographic and behavioral survey (Table 6), after-scenario (Table 7), and post-test questionnaires (Table 8). The demographic survey collected participants' age, gender, and their usual driving/biking context, along with nine behavioral survey questions about their driving behavior (selected and modified from Ulleberg and Rundmo (2003)) and ten about their cycling behavior (selected and modified from Hezaveh et al. (2018)) that were on a 5-point Likert scale (1 = never, 5 = nearly all the time).

Table 6. Questions for Driving or Cycling Behavior

Survey Questions for Driving Behavior
1. I drive fast to show others I can handle the car 2. I will overtake the car in front when it is driving at the speed limit 3. I will drive close to the car in front 4. I will disregard a red light on an empty road 5. There are traffic rules which I do not obey in order to keep up the traffic flow 6. Sometimes it is necessary to bend rules to arrive in time 7. If you have good skills, speeding is OK 8. I think it is OK to speed if the traffic conditions allow me to do so 9. Driving is more than transportation, it is also speeding and fun
Survey Questions for Cycling Behavior
1. I will ride close enough to the vehicle in front of me that it is hard to stop in an emergency 2. I yield to pedestrians 3. I bike in the opposite direction of traffic flow 4. I use the bicycle dedicated lane (when they are available) 5. When riding at the same speed as other traffic, I find it difficult to stop in time when a traffic light has turned 6. I've felt angry and aggressive towards another road user

7. I've felt frustrated by other road users 8. I've become angered by another road user and indicated my hostility by whatever means I could 9. I run red lights 10. I speed up to beat the traffic light turning red

After-scenario forms were posed and gathered after each overtaking scenario to obtain participants' satisfaction and risk perception. Six questions were included for the scenarios in the driver phase and seven in the bicyclist phase, on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree). The questions for accessing participants' satisfaction were inspired and modified from the Usefulness, Satisfaction, and Ease of Use Questionnaire (Lund, 2001). The questions for accessing perceptions towards the oncoming vehicle and speed were self-developed items modified from Moore et al. (2005), Bragg and Finn (1982), and Dozza et al. (2016).

Table 7. Questions Posed After Each Scenario

After-Scenario Questions for Driver Phase
1. I am satisfied with the overtaking. 2. The overtaking works the way I want it to work. 3. The overtaking is wonderful. 4. Bicyclist creates a chance of collision when I overtake. 5. The bike is close to me when I overtake. 6. If there is an oncoming vehicle, I care more about the oncoming vehicle than the bike.
After-Scenario Questions for Bicyclist Phase
1. I am satisfied with the overtaking. 2. The overtaking works the way I want it to work. 3. The overtaking is wonderful. 4. Driver creates a chance of collision by overtaking me. 5. Driver drives too fast. 6. The car is close to me when it overtakes. 7. If there is an oncoming vehicle, I care more about the oncoming vehicle than the overtaking car.

Post-test questionnaires were posed after the driver or bicyclist phase to collect participants' subjective ratings toward collision risk in different configurations from driver's or bicyclist's perspective to validate the result from after-scenario forms. It included seven questions on 5-point Likert scale (1 = no possibility, 5 = a certain collision). These questions were inspired and modified from Ulleberg and Rundmo (2003) and Bragg and Finn (1982).

Table 8. Questions Posed After Each Phase

Post-Test Questions for Driver Phase
1. With an oncoming vehicle approaching, driving beside or near a bike leads to a chance of collision 2. Without an oncoming vehicle approaching, driving beside or near a bike leads to a chance of collision 3. Driving beside or near a bike in the shared lane leads to a chance of collision 4. Driving beside or near a bike in the bike lane leads to a chance of collision 5. Overtaking with higher speeds leads to a greater chance of collision 6. Overtaking with a shorter distance next to the bicyclist (distance from the vehicle's right side doors to the bicyclist) leads to a greater chance of collision 7. Overtaking with a shorter distance behind the bicyclist (the gap between the vehicle's front bumper and the bicyclist) increases the likelihood of collision.
Post-Test Questions for Bicyclist Phase
1. With an oncoming vehicle approaching, the overtaking vehicle creates a chance of collision 2. Without an oncoming vehicle approaching, the overtaking vehicle creates a chance of collision 3. While biking in the shared lane, the overtaking vehicle beside or near the bike creates a chance of collision 4. While biking in the bike lane, the overtaking vehicle beside or near the bike creates a chance of collision 5. Being overtaken by a vehicle with a higher speed leads to a chance of collision 6. Being overtaken by a vehicle with a shorter distance next to the vehicle (distance from bicyclist to the vehicle's right side doors) leads to a chance of collision 7. Being overtaken by a vehicle with a shorter distance ahead the vehicle (the bicyclist gap to front bumper) leads to a greater chance of collision

3.1.7 Data Analysis

To examine the potential impact of experimental factors on risk perception and comfort ratings during overtaking events, we first performed Factor Analysis on the after-scenario questionnaire answers to obtain a reduced set of latent variables. The factor number was considered from scree plot and the factors were rotated using Promax. The factor scores were then used as dependent variables in the forthcoming models.

A mixed linear regression was used to analyze the main effect and interactions of each experimental factor on the risk perception and comfort ratings. Random effects were included at the subject level to account for the data variation due to repeated measures in this within-subject experiment. The main independent variables of interest were the four experimental factors, i.e., the presence of oncoming traffic (with or without), the lane type (shared lane or bike lane), overtaking vehicle's speed (lower or higher), distances between the overtaking vehicle and the bicyclist i.e., the offset (smaller or bigger). In addition, the model controlled for individual characteristics (gender, age group, driving context, biking context) and their driving and biking behavior scores.

A separate set of models were applied to the Post-Test questionnaire, where the response to each question was treated as dependent variables. In these models, bicyclist-phase and driver-phase data were combined and a new variable was introduced to identify whether this data point was gathered in the driver phase or bicyclist phase. Responses to questions 1 and 2 and to questions 3 and 4 (see Table 8) were also combined. New variables were introduced to identify whether the questions were asked for an overtaking scenario with or without oncoming traffic, or with or without bike lane correspondingly. Thus, a total of five mixed linear regression models were created. Similarly, all models included random effects on the subject level and controlled for gender, age group, driving behavior scores, and biking behavior scores.

All two-way interaction terms were tested and were retained in the final model with p-values smaller than 0.05. The factor analysis was conducted using a factor-analyzer (version 0.4.1) in Python; the linear mixed model was applied via lme4 in R.

3.2 Results

3.2.1 Factor Analysis

Three factors were found from the after-scenario questions for both driver phase and bicyclist phase, as shown in Table 9 and Table 10. Factors D1 and B1, satisfaction with overtaking performance, were mainly composed of questions 1, 2, and 3 for both driver-phase and bicyclist phase. The larger the value of factors D1 and B1, the higher the satisfaction was. Factor D2 and B2, perceived collision risk with bicyclist/vehicle, is mainly composed of questions 4 and 5 for driver-phase, and questions 4, 5, and 6 for bicyclist-phase. The larger the value of factor D2 and B2, the higher the perceived risk. Factor D3 and B3, perceived collision risk with oncoming vehicle, mainly represents question 6 for driver-phase, and questions 4 and 7 for bicyclist-phase. The larger the value of factor D3 and B3, the higher the perceived risk.

Table 9. Driver-Phase Factors

Factor Description	Main Composition Items	
Factor - D1 Satisfaction with overtaking performance	Driver-1 Driver-2 Driver-3	I am satisfied with the overtaking. The overtaking works the way I want it to work. The overtaking is wonderful.
Factor - D2 Perceived Collision Risk with Bicyclist	Driver-4 Driver-5	Bicyclist creates a chance of collision when I overtake. The bike is close to me when I overtake.
Factor - D3 Perceived Collision Risk with Oncoming Vehicle	Driver-6	If there is an oncoming vehicle, I care more about the oncoming vehicle than the bike.

Table 10. Bicyclist-Phase Factors

Factor Description		Main Composition Items
Factor - B1 Satisfaction with overtaking performance	Bicyclist -1 Bicyclist -2 Bicyclist -3	I am satisfied with the overtaking. The overtaking works the way I want it to work. The overtaking is wonderful.
Factor - B2 Perceived Collision Risk with Vehicle	Bicyclist -4 Bicyclist -5 Bicyclist -6	Driver creates a chance of collision by overtaking me. Driver drives too fast. The car is close to me when it overtakes.
Factor - B3 Perceived Collision Risk with Oncoming Vehicle	Bicyclist -4 Bicyclist -7	Driver creates a chance of collision by overtaking me. If there is an oncoming vehicle, I care more about the oncoming vehicle than the overtaking car.

3.2.2 Mixed Linear Model Regression

Table 11 shows the results from the mixed linear models for the subjective data collected from driver's and bicyclist's perspectives. In the driver phase after-scenario models, the main effects of the experimental factor "traffic" and "bike lane" were found in models of factor D1 - satisfaction with overtaking performance, and factor D2 - perceived collision risk with bicyclists. It was found that without oncoming traffic, the drivers had higher satisfaction and perceived lower risk. If the shared lane was presented, drivers would have lower satisfaction and perceived higher risk. The main effect of speed was only found in models of perceived collision risk of the factors D2 and D3. Slower speed led to lower perceived collision risk for drivers. In contrast to speed, the main effect of lateral offset (movement) was only found in the satisfaction model, factor D1. Shorter offset led to lower satisfaction of drivers. Interestingly, the effect of speed was found to be interacted with other factors in the satisfaction model (D1, see Figure 3) and in the perceived collision risk model (D2, see Figure 4). With lower speed, drivers were slightly more satisfied when overtaking at a smaller offset; however, with higher speed, participants were more satisfied when overtaking at a larger lateral offset. In addition, higher speed led to higher perceived risk with the presence of oncoming traffic and no difference on perceived risk when there was no oncoming traffic presented.

In the bicyclist phase after-scenario models, main effects of the factor were found in all the three models. Bicyclists were more satisfied and perceived lower risk when lower speed (Figure 5), larger offset, dedicated bicycle lane, and no oncoming traffic were presented. Interestingly, the interaction effects for factor B2 showed that bicyclists' perceived collision risk with vehicle was more sensitive to speed. When cycling in a shared lane, bicyclists' perceived collision risk with vehicle was more sensitive to offset (Figure 6 and Figure 7). In addition, interaction term for factor B3, implied that when cycling in a shared lane, bicyclist's perceived risk with oncoming traffic were more sensitive to speed (Figure 8).

The post-test models aligned with the finding for the after-scenario models. Participants reported higher collision risk if oncoming traffic and a shared bicycle lane was presented. It was also found that driver was less agreed with question 6 that overtaking with a shorter distance next to the bicyclist did not lead to a significant increase in the chance of collision. This aligned with the after-scenario models' result that offset did not have significant effect on driver's perceived collision risk but significantly affected bicyclist's perceived collision risk.

Table 11. Results of Mixed Linear Models

Source	Satisfaction with Overtaking Performance		Collision Risk with Vehicle/Bicyclist		Collision Risk with Oncoming Traffic	
	Driver (D1)	Bicyclist (B1)	Driver (D2)	Bicyclist (B2)	Driver (D3)	Bicyclist (B3)
(Intercept)	**-1.64*** (-2.599)	**-2.14*** (-2.496)	0.74 (0.965)	1.20 (1.514)	0.86 (1.481)	0.97 (1.307)
Driving/Biking Behavior	0.03 (1.606)	0.03 (1.187)	-0.04 (-1.582)	-0.04 (-1.342)	0.02 (1.055)	0.00 (-0.131)
Age	0.00 (0.316)	0.00 (-0.154)	0.01 (1.969)	**0.02*** (2.562)	0.00 (-0.754)	0.01 (1.835)
Male	-0.06 (-0.306)	0.06 (0.207)	0.07 (0.273)	0.10 (0.388)	0.22 (1.176)	-0.07 (-0.296)
Driving Context (base: Rural) Rural and Urban	**0.83*** (2.323)	0.39 (0.876)	-0.80 (-1.82)	**-0.88*** (-2.105)	-0.30 (-0.896)	**-0.81*** (-2.082)
Urban	**0.78*** (2.263)	-0.04 (-0.086)	-0.78 (-1.844)	0.02 (0.04)	-0.13 (-0.397)	-0.18 (-0.46)
Biking Context (base: None) Rural	-0.02 (-0.041)	0.87 (1.65)	0.11 (0.25)	-0.57 (-1.174)	-0.04 (-0.132)	-0.30 (-0.652)
Rural and Urban	0.35 (0.749)	1.39 (1.963)	-0.76 (-1.31)	**-1.91**** (-2.907)	-0.40 (-0.93)	-0.52 (-0.845)
Urban	-0.13 (-0.449)	**1.32*** (2.648)	0.12 (0.344)	**-1.25*** (-2.701)	0.12 (0.441)	-0.76 (-1.77)
Without Oncoming Traffic	**1.15***** (13.155)	**0.82***** (8.277)	**-0.62***** (-9.642)	**-0.60***** (-6.697)		
Shared Lane	**-0.20**** (-3.187)	**-0.38***** (-4.707)	**0.37***** (8.149)	**0.36***** (3.963)	-0.04 (-0.708)	**0.28*** (2.519)
Lower Speed	0.18 (1.64)	**0.60***** (7.332)	**-0.17**** (-2.601)	**-0.45***** (-6.055)	**-0.13*** (-2.478)	**-0.31**** (-2.816)

Smaller Offset	**-0.18*** (-2.036)	**-0.19***** (-3.344)	0.01 (0.183)	**0.16*** (2.129)	-0.03 (-0.528)	**0.19*** (2.514)
Interaction terms W/o Oncoming Traffic : Shared Lane		**-0.30**** (-2.65)		**0.39***** (3.728)		
W/o Oncoming Traffic : Lower Speed	**-0.29*** (-2.333)	**-0.31**** (-2.656)	**0.20*** (2.141)	**0.30**** (2.893)		
Shared Lane : Lower Speed						-**0.50**** (-3.215)
Shared Lane : Smaller Offset				**0.27*** (2.545)		
Lower Speed : Smaller Offset	**0.31*** (2.46)					

Estimated coefficients significant at α = 0.05 are in bold: ∗∗∗p<0.001, ∗∗p< 0.01, ∗p<0.05

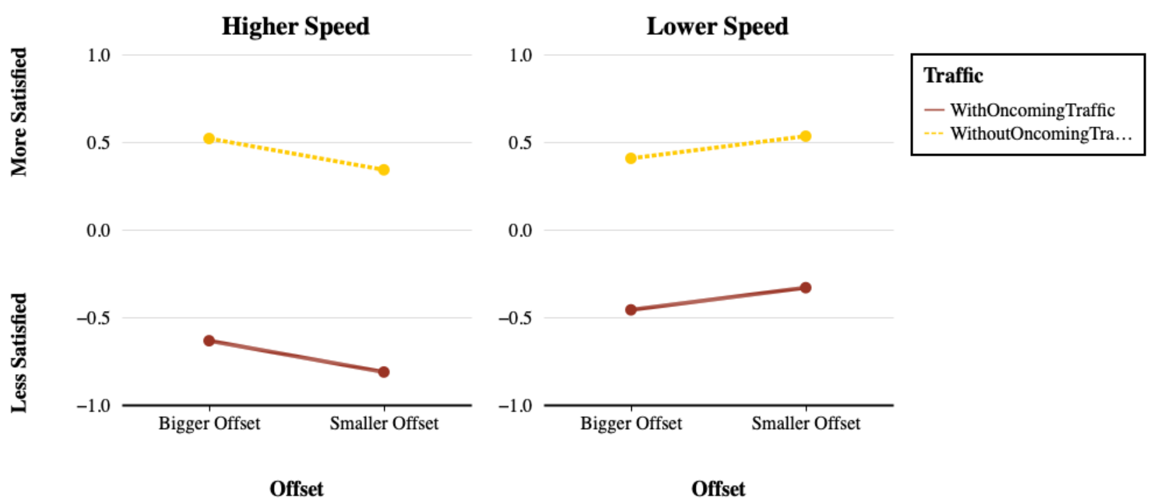


Figure 3. Interaction between Speed and Offset on D1 – Satisfaction

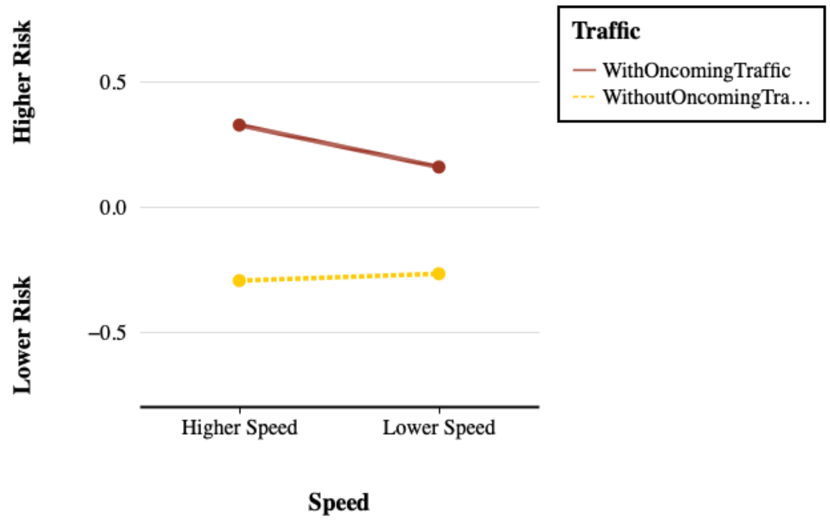


Figure 4. Interaction between Speed and Presence of Oncoming Traffic on D2 – Perceived Risk

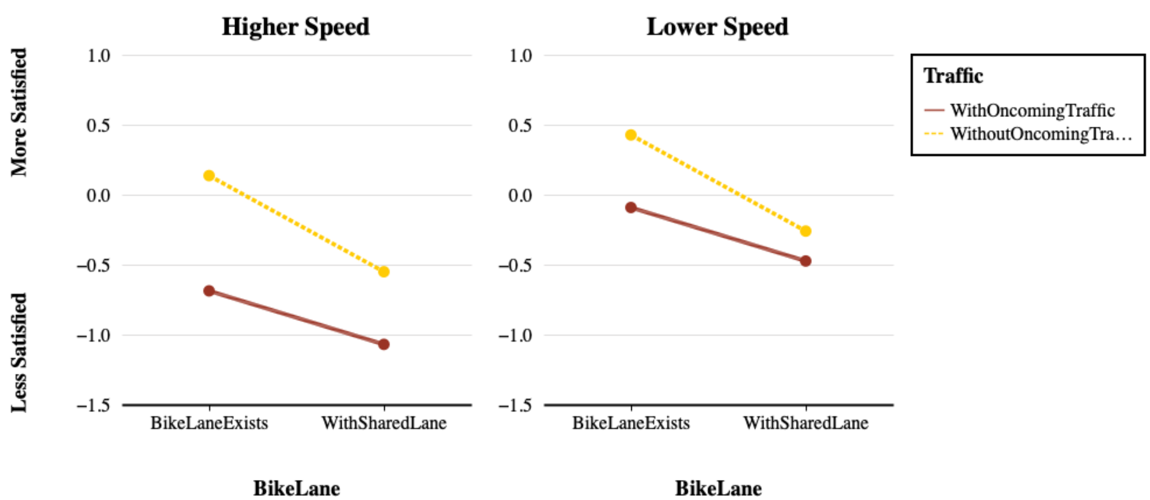


Figure 5. Interaction between Speed, Presence of Oncoming Traffic, and Presence of Bicycle Lane on B1 – Satisfaction

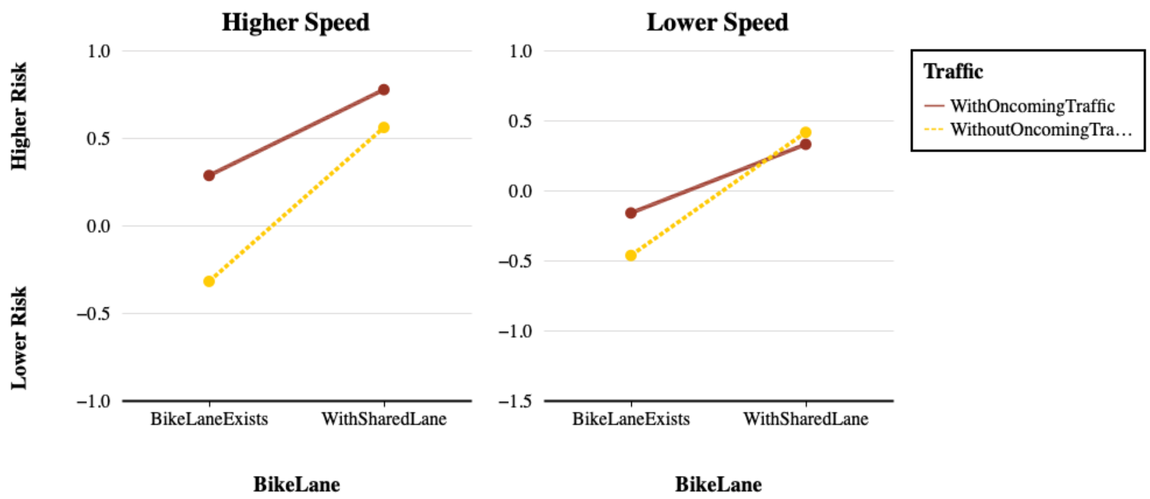


Figure 6. Interaction between Speed, Presence of Oncoming Traffic, and Presence of Bicycle Lane on B2 – Perceived Risk

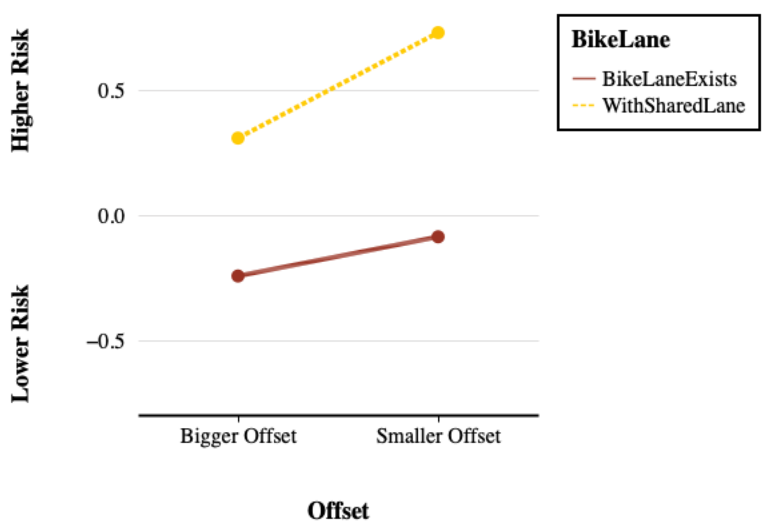


Figure 7. Interaction between Presence of Bicycle Lane and Lateral Offset on B2 – Perceived Risk

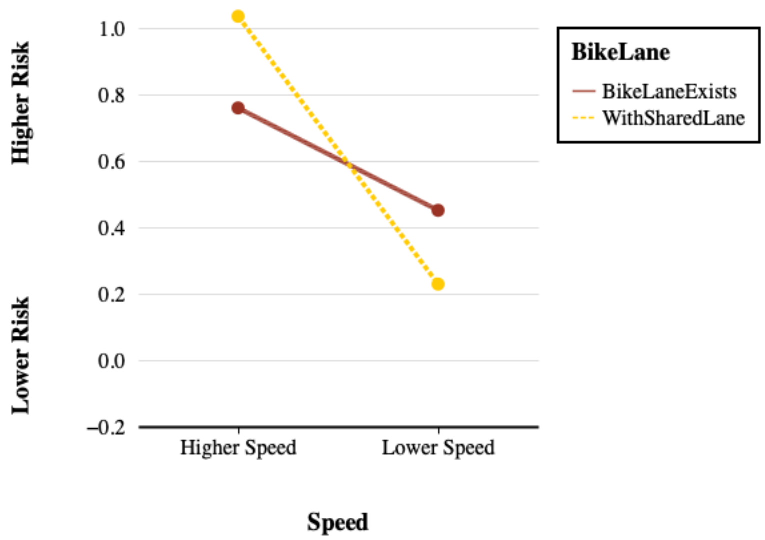


Figure 8. Interaction between Speed and Presence of Bicycle Lane on B3 – Perceived Risk with Oncoming Traffic

3.3 Conclusions for Study II

The goal of Study II was to compare the satisfaction and perceived collision risk on different factors between driver's and bicyclist's perspectives. For satisfaction, there was an interaction between speed and offset for drivers, where drivers prefer different offset while overtaking at different speed. However, different results were found for bicyclists who were more satisfied with lower overtaking speed and larger offset. For perceived risk of collision, unlike bicyclists, no significant effect of lateral offset was found for drivers. Moreover, the interaction analyses implied that bicyclists' perception on the risk of collision were very sensitive to speed and offset when cycling in a shared lane. Bicyclists perceived higher risk of collision towards the overtaking performance: as a dedicated bike lane was presented, a car-to-bicycle overtaking with a lower speed reduce bicyclists' perception of risk. This finding was not observed for drivers.

4. General Discussion and Conclusions

In this research, we explored a naturalistic driving dataset to develop different overtaking prediction models operated by gap and relative velocity between the vehicle and bicycle and conducted a simulator experiment considering the presence of oncoming traffic, bike lane, speed, and offset based on the developed models. The prediction models performed with the accuracy of 80% or higher for different overtaking environments and provided low false alarms (false discovery rate of 10%) that overtaking initiation would not be suggested at an inappropriate time. This research also provided insights that bicyclists and drivers had different satisfaction and perceived collision risks toward the factors that were often considered in the overtaking trajectory models.

It was found that for drivers and bicyclists, overtaking satisfaction reduced and higher collision risk was perceived with the presence of oncoming traffic. This effect became more significant when the vehicle overtook with a higher speed, as the main effect of speed significantly affected their subjective assessment. However, bicyclists' satisfaction could be increased and perceived collision risk could be reduced if a dedicated bicycle lane was applied, which was not found for drivers. Therefore, it is important to deploy dedicated bicycles lanes, so bicyclists will perceive safely when being overtaken; otherwise, the vehicle should overtake with a slower speed.

For the lateral offset about the room between the vehicle and the bicycle during the overtaking, bicyclists perceived more risk of collision when the smaller lateral offset was applied, for which sharing lanes with the motorists increased the perceived risk. However, the risk of collision under those conditions was not perceived by drivers. A major reason was that the lateral offset parameters were solely concluded from the naturalistic driving data and bicyclists' perception was ignored. Also, drivers may overestimate the lateral distance to the bicycle from the driver's seat. It also emphasized the importance of investigating the perspectives from all the road users.

Due to the inconsistent findings for the subjective assessment from the perspectives of drivers and bicyclists, stakeholders who are interested automated driving features should apply the car-to-bicycle overtaking models carefully because the developed models were based on manual driving data. Further adjustment is needed by considering the expectations from the other road users, especially those who shared the roadway with vehicles. From this research, the subjective assessment by bicyclists has not been ready yet to feed quantitative suggestions for improving the automated overtaking models, which will serve as the future direction.

5. Recommendations

This research serves as an initial foundation for the development and evaluation of an automated car-to-bicycle overtaking function. The naturalistic driving data-driven models implemented in a driving simulator were tested from the perspectives of drivers and bicyclists.

Future studies include the implementation with vehicle-to-vehicle (V2V) and vehicle-to-bicycle (V2B) connected environment and conducting the experiment at test facilities. With the connected technology, such as DSRC or 5G network, the limitation for Mobileye can be improved and the positions of the vehicle and bicycle can be accurately shared in real time over the entire overtaking process, even after the vehicle returns to the ego lane.

Also, in the environment of driving simulator, the perception on the true distance and relative velocity is challenging, for which the relative validity (comparisons among different conditions) can be verified but the absolute validity (e.g., estimate for time-to-collision) verification becomes difficult. It would be essential to examine the models by implementing this experiment on a real autonomous platform.

6. Outputs

The outputs shown as below were created during the performance of this research.

- Poster presention at CCAT Global Symposium on April 5th, 2023
- Presentation at CCAT Research Review on July 27th, 2023
- Presentation at SAE Vulnerable Road Users Safety Consortium (VRUSC) Meeting on August 3rd, 2023
- A manuscript submitted to the journal of Transportation Research Part: F

7. Outcomes

Based on the outputs, our research team has established ties with members of SAE VRUSC and State Farm Technology Research and Innovation Laboratory. We will conduct new proposals through their support to improve driver-cyclist interactions on the roads, particularly in instances where their respective expectations conflict. SmartCohort (https://smartcohort.org/), a non-profit organization dedicated to facilitating equitable and resilient urban transportation, has also expressed interest in collaborating for future government funding.

8. Impacts

The overtaking initiation models we proposed have considerable implications for the automotive industry as they develop safe and reliable technology to foster interaction with cyclists on the roads. This is also crucial for government transportation agencies as they establish traffic policies aimed at cyclist protection. Furthermore, this research underscored differing perspectives drivers and bicyclists hold on risk perception, an aspect which merits further exploration in future research questions.

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