Develop an instrumented vehicle to measure using conditions on the roads

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Abstract :

The present study aimed to demonstrate how an instrumented vehicle, a bicycle, can objectively measure the motorized vehicle-related factors, road-related factors, and bicyclist-related factors to explore the concerned traffic safety issues, such as how the factors influenced motorists' decisions about initial passing distances for a bicyclist. An urban-style bicycle was fitted with one global positioning system, one multi-function logger (including a 3-axis accelerometer, a gyroscope, and a compass), two ultrasonic distance sensors, eight proximity switches, one variable resistor, and five car camera DVR black boxes. There were thirty-four participants using the instrumented vehicle in real traffic. The study clearly demonstrated how the factors influenced the motorists' initial left-side passing distance, including the motorized vehicles, road-related factors, and bicyclist-related factors. The present study demonstrated that an instrumented vehicle is capable of collecting rich data concerning users' behaviors, which could potentially be utilized in various types of studies. However, this method requires a large sample and considerable time and effort for data processing.

Keywords: *Instrumented bicycle, Behavior index, Naturalistic riding*

I. Introduction

The behaviors observed under natural conditions are close to drivers' behaviors in daily life, and these observations have shown the potential to provide new evidence in studies of drivers [1]. However, bicyclists and drivers perceive the same bike-car interaction in different ways [2]. However, many details about the interactions among bicyclists, motorists, roads, and traffic environments that were addressed by ATKINS [3] and [4], such as pothole avoidance, were not extensively explored.

For example, when motorists pass bicyclists, an event that happens frequently, motorists may be unaware of their small lateral distance from the bicyclists and encroach on their riding space; accordingly, this reduces the usable space available to bicyclists. A survey in Australia found that nearly 70% of 1,830 male and female bicyclists reported that the most common form of drivers' harassment was driving too close [5]. A previous bicyclist survey also revealed that some bicyclists were injured in falls when they attempted to avoid a collision with a motorized vehicle [6]. Recently, some studies have adopted a first-person perspective to objectively investigate bicyclists' behaviors while motorists are passing. For example, one study employed a surveyor-cyclist [7] riding an instrumented bicycle fitted with ultrasonic distance sensors and video cameras in various conditions, including with different genders (simulated via the surveyor-cyclist's clothing), with/without a helmet, and at varying distances from the road edge. Another surveyor-cyclist [8] riding an instrumented bicycle (fitted with video cameras) on roads that were 950 cm wide recorded motorist passing events on various roads, with or without a bicycle lane, and with different road speed limits, and the researchers determined passing distances according to the videos. This method was also used in another study [9] to investigate various combinations of road widths and types of bicycle infrastructure. These three studies have successfully accumulated objective lateral distance data for motorists as they pass bicyclists. Nevertheless, as noted in these studies, close passes are physically destabilizing for bicyclists because the bicyclists can be pushed by lateral forces. Accordingly, in addition to position control, measuring other bicyclists' behaviors, such as changes in direction and speed, can provide additional data on this research topic. The use of an appropriately designed instrumented bicycle for the recruited bicyclists to ride on a planned route in real traffic can directly measure interactive behaviors and additional potential factors related to the bicyclists, other road users, and the road environment under conditions similar to natural riding.

The purpose of the present study aimed to demonstrate how an instrumented vehicle, a bicycle, can objectively measure the motorized vehicle-related factors, road-related factors, and bicyclist-related factors to explore the concerned traffic safety issues, taking the factors influenced motorists' decisions about initial passing distances for a bicyclist as an example.

II. Methods

Apparatus and participants

An urban-style bicycle was fitted with one global positioning system, one multi-function logger (including a 3-axis accelerometer, a gyroscope, and a compass), two ultrasonic distance sensors, eight proximity switches, one variable resistor, and five car camera DVR black boxes. The ultrasonic distance sensors (one for the left side and one for the right side on the rear rack) were placed with their centers 0.65 m from the ground, facing perpendicular to the direction of travel. All the instruments fed into a laptop computer running Labview software via an NI card associated with the sensor. The computer simultaneously received the input from all of the instruments. Table 1 presents the physical measures logged by each instrument, the calculated bicyclist behavior indicators, and the behaviors that could be investigated. In the present study, the behavior indicators from the left-side ultrasonic distance sensor, the proximity switches, and the variable resistor were analyzed.

The participants were recruited from a university campus. For the sixteen male participants (age: mean = 23.56 years, standard deviation = 2.80 years), the mean riding experience was 173 minutes per week (standard deviation = 273 minutes per week), and five of them rode a bicycle at least 60 min daily. Among the male participants, fifteen had a motorcycle license (ownership: mean = 5.78 years, standard deviation = 2.53 years), and ten used a motorcycle for daily life. For the eighteen female participants (age: mean = 22.39 years, standard deviation = 3.11 years), the mean riding experience was 26 minutes per week (standard deviation = 52 minutes per week). Among the female participants, thirteen had a motorcycle license (ownership: mean = 3.46 years, standard deviation = 2.37 years), and four used a motorcycle for daily life. Generally, the male participants appeared to have more experience riding a bicycle and a motorcycle.

There have been studies indicating that drivers may believe bicyclists wearing helmets are more predictable than those without helmets [7]. To reduce probable confounding factors associated with helmets, and for safety reasons, the participants in the present study wore helmets. Each participant was also insured. Before each departure, all the instruments were checked, calibrated, and synchronized, and the participant was checked to make sure his or her helmet fit well.

Data processing

A data review and editing program was used in the present study to cut the five video recordings into time-series pictures (ten frames per second) for synchronization with the logged numerical data (the raw data were averaged into ten data points per second). This program enabled frame-by-frame review of the five video feeds along with the numeric data every 0.1 second. The program also assisted in the data processing.

I. INSTRUMENTS, MEASURES, AND CALCULATED BEHAVIOR INDICATORS

Instruments	Physical measures	Samples	Behavior indicator	Studiedbehavior
Global positioning system	Latitude and longitude (degree)	1 per second	Location (degrees)	d, e
Multi-function logger	Accelerometer: lateral, longitudinal, and vertical acceleration (G)	60-70 per second	Accelerometer: lateral, longitudinal, and vertical acceleration (G)	b, c, e, f, g
	Gyroscope: lateral, longitudinal, and vertical angle	60-70 per second	Lateral, longitudinal, and vertical angle acceleration (degree/s)	c, e, f, g

	acceleration (degree/s)			
	Compass: lateral, longitudinal, and vertical magnetic field vector (Gauss)	60-70 per second	Magnet bearing (degrees) (absolute angle)	c, e, f, g
Ultrasonic distance sensor	Distance (cm)	60-70 per second (max. range 650 cm)	Passing distances (cm)	a, f
Proximity switch	Pulse (On/Off)	8 signals per turn of the rear wheel	Travel speed (km/hr)	b
Variable resistor	Variable resistor value	60-70 per second	Wheel angle (degrees) (relative angle of stem to frame)	c, e, f, g
Car camera DVR black box	Image (view of front, rear, left, right, and face)	860x640 pixels (30 fps, MPG file format)	Image	a, c, d, e, f, g, h

[a] Position: lateral and longitudinal positions. [b] Changing speed: braking, stopping, stopping pedaling. [c] Changing direction: including lane change, pulling onto the path from the sidewalk. [d] Cruising. [e] Making right/left turn. [f] Passing and weaving in slow moving or queued traffic. [g] Wobbling and swerving. [h] Turning head to see.

There was a considerable amount of data collected as a result of continuous logging by the instruments. We hypothesized that many of these data were not correlated with the situations relevant to bicycling risk and thus needed to be eliminated. The critical incident technique is a procedure for collecting observed events with special significance that meets systematically defined criteria. In general, it is most useful for quickly separating major situations of interest. The present study used the critical incident technique to develop a set of a priori criteria to detect the presence of a potential event, which was defined as a set of physical measures that exceeded the trigger criteria and that may indicate an external event or potentially hazardous riding behavior. When the values of the physical measures in a data point exceeded the a priori criteria, the data point was automatically marked by the data review and editing program as an instance of a potential event. The marked data points cued the observers to view the video images more extensively and note the events.

In the present study, a data experiment on reduction rules (not reported here) was performed with two independent datasets, one for analyzing and one for validating, to build up the a priori criteria. After the data experiment, three rules for the a priori criteria were established. Combining these three rules, nearly 90% of the events observed in the video images could be successfully found using the marks in the two datasets.

Rule 1: Trigger at least three of the following five criteria:

Wheel angle □ 88 or □ 92 degrees;

Lateral acceleration □ -0.1 or □0.05 G;

Longitudinal acceleration □ -0.15 or □0.1 G;

Left-side passing distance □ 150 cm;

Right-side passing distance □ 150 cm.

Rule 2: Simultaneously trigger the following two criteria:

Wheel angle □ 88 or □ 91 degrees;

Longitudinal acceleration □ -0.06 G.

Rule 3: Simultaneously trigger the following two criteria:

Wheel angle □ 88 or □ 92 degrees;

Lateral acceleration □ -0.1 or □ 0.08 G.

To reduce the amount of data, the bicyclists' riding data (in 0.1 second intervals) were first read by the data review and edit program. Then, the data points were marked by the program according to the above-mentioned rules 1-3. Because one data point represented the data for 0.1 s, rules 1-3 served to highlight successive data points for a potential event. Potential events commonly lasted for several seconds, resulting in consecutive marks that required the observers to watch the same event repeatedly. Therefore, the program combined the consecutive marks into one representative mark to cue a potential event to further reduce the video observation process.

Following the marks, the observers watched the synchronized video images and the marked data in the data review and editing program to record seventeen different types of events and their related data. These events included event types (left-side passing, right-side passing, road-side parking, etc.) and events involving certain vehicles (motorcycle, car, bus, etc.). Each event had definitive observation rules. For example, a left-side passing event required at least one vehicle to appear in the videos, moving from the rear to the left side and then to the front, and the values from the left-side ultrasonic distance sensor must also have been reduced during this period.

In addition, the program also defined road sections according to changes in the road environment using the GPS data. After observers confirmed the road sections defined for each participant's riding data, the program automatically read infrastructure tables to record data concerning the infrastructure (e.g., lane separation, division between different directions, etc.). Finally, the program output the selected scope of the data and the variables for further analysis; in the present study, we were interested in left-side passing events and specific influential factors.

Measurements and statistical analysis

The present study collected and investigated 1,380 incidents of left-side passing by motorists. Because a passing event occurs over a continuous time period, three stages were defined: 1) before passing (t1 stage), 0.5 s before the t2 stage; 2) while passing (t2 stage), the period in which the passing distance (i.e., the data from the left-side ultrasonic distance sensor) decreased; and 3) after passing (t3 stage), 0.5 s after the t2 stage. The data in the t1 and t2 stages were used in the present study. In the study area, most motorcycles have an engine size less than 250 cm3 In addition, there was a solid white line (10 cm wide) on the road that separated the cars from the bicycles, named slow traffic separation in the present study. According to regulations, car drivers must drive on the left side of the solid white line unless they plan to turn at an approaching intersection or park on the roadside, and bicyclists must ride on the right side of the solid white line. Motorcyclists can ride on either side of the solid white line. A forward-oriented wheel angle was recorded as 90 degrees, an angle deflected to the left was recorded as greater than 90 degrees, and an angle deflected to the right was recorded as less than 90 degrees.

The motorists' initial passing distance in the t2 stage was analyzed with the studied factors used as between-subjects factors in the univariate analyses of variance (ANOVA). A significance level of 0.05 was used. Bonferroni adjustments were used for post-hoc pairwise comparisons of the estimated marginal means and were calculated as α = 0.05 / total number of pairs. Statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS) version 15.

III. RESULTS

Table 2 shows the ANOVA results, including the means and the standard deviations of the studied factors influencing the motorists' initial passing distances. The results indicated that passing vehicle types, road surface conditions in the t1 stage, lane separation, slow traffic separation, the bicyclist's gender, and the bicyclists' mean wheel angle, mean speed, and speed variation control in stage t1 were significant factors for the motorists' initial passing distances. The pairwise comparisons revealed that the initial passing distances chosen by motorcycles were significantly smaller than those chosen by cars, small trucks, and large trucks. However, the initial passing distances chosen by motorcycles still averaged 152.15 cm.

The initial passing distance when there were poor surface conditions in the t1 stage was significantly smaller than when the surface conditions were good. As shown in Table 3, poor surface conditions reduced the motorists' initial passing distances from 161.51 cm under good surface conditions to 134.55 cm. In addition, without lane and slow traffic separations, the initial passing distances were significantly smaller than they were on roads that did have separations. Moreover, motorists chose a significantly smaller initial passing distance when passing male bicyclists as compared to female bicyclists. The initial passing distances tended to be smaller when the motorists passed bicyclists who handled their bicycles with smaller wheel angles, at lower speed, and with smaller speed variation in the t1 stage. In particular, the initial passing distances were reduced from 180.64 cm when the mean wheel angle was greater than (or equal to) 95 degrees to 132.87 cm when the mean wheel angle was less than 85 degrees.

IV. Discussion

Motorized vehicle factors

The present study supports previous studies showing that motor vehicle type affects passing distance [7-8]. The initial passing distance chosen by motorists was smaller when motorcyclists passed than when cars and small trucks passed. Previous studies found that bus drivers pass closer than drivers of others types of vehicles. The results of the present study also showed that buses drivers selected the smallest initial passing distances, although the results did not reach statistical significance.

II. ANOVA SHOWING THE MEANS AND STANDARD DEVIATIONS OF INITIAL PASSING DISTANCES

Factors $[F(\nu_1, \nu_2=1287)]^b$	**Categories**	**N (%)** (n=1380)	**Mean**	**Std.** [a]
Passing vehicle [11.524(4)]*	Motorcycle	48.44	152.15	52.93
	Car	34.28	168.14	49.79
	Small truck	10.89	171.78	55.61
	Bus	2.18	150.33	67.67
	Large truck	4.21	172.97	45.91
Road surface_t1 [8.618(1))]‡	Good	96.81	161.51	53.11
	Poor	3.19	134.55	37.88
Lane separation [6.677(1)]#	Yes	31.21	164.15	60.08
	No	68.79	158.28	48.07
Slow traffic separation [23.762(1)]*	Yes	53.99	166.68	49.55
	No	46.01	152.40	54.10
Gender [20.758(1)]*	Male	38.91	150.66	46.69
	Female	61.09	167.01	55.59
Angle mean_t1[c] [16.090(1)]*	a ＜ 85	-	132.87	41.04
	85 ≦ a ＜ 90	-	159.80	53.20
	90 ≦ a ＜ 95	-	162.98	53.50
	95 ≦ a	-	180.64	36.86
Angle variance_t1[c] [0.418(1)]	a ＜ 5	-	161.13	53.68
	5 ≦ a ＜ 10	-	155.36	46.98
	10 ≦ a ＜ 20	-	163.58	56.63
	20 ≦ a	-	164.06	48.45
Speed mean_t1[c] [5.528(1)]#	s ＜ 5	-	159.62	54.11
	5 ≦ s ＜ 10	-	153.28	55.86
	10 ≦ s ＜ 15	-	160.06	49.23

	15 ≦ s	-	172.15	51.63
Speed variance_t1[c] [7.204(1)][‡]	s < 10	-	158.34	52.07
	10 ≦ s < 20	-	164.57	54.88
	20 ≦ s < 40	-	164.74	51.81
	40 ≦ s	-	180.55	60.89

Note. [a] Standard deviation. [b] The data in the square brackets are the statistics $F(\nu_1, \nu_2)$. Only the ν_1 is displayed. All ν_2 values were 1287. [c] The factors were treated as continuous variables in the ANOVA; the categories are only for describing the data. [*] $p < 0.001$. [‡] $p < 0.01$. [#] $p < 0.05$.

Road factors

Some studies have reported that a marked bicycle lane (generally marked by a solid line) in a low-speed area (e.g., an area with a speed limit of 48 km/hr) does not seem to affect motorists' passing distances [8]. However, some studies have indicated that a marked bicycle lane does have safety benefits [10]. Bicyclists also perceive a road with a solid line marking the separation between motorists and bicyclists to be safer than a road with no such separation [11]. The results of the present study revealed that longitudinal markings (for lane separation or slow traffic separation) can encourage greater passing distances when motorized vehicles pass bicyclists. Moreover, a solid line (for slow traffic separation) to separate cars from bicyclists can further reduce the percentage of passes that occur at less than 100 cm to 9%, for the initial passing distances selected by the motorists. The test roads in the present study all had a speed limit under 50 km/hr, which may support the concept that a clear and longitudinal solid line separation can help to maintain a greater lateral distance between motorists and bicyclists on average.

Bicyclist-related factors

Walker [7] found that motorists are more likely to provide additional passing distance for a female bicyclist (simulated by the surveyor-cyclist's clothing) than for a male bicyclist. The present study also demonstrated the same results among the participating bicyclists. Physical appearance seems to be an important cue for motorists to predict the behaviors of a bicyclist when approaching the bicyclist. The data from the present study revealed that there were differences in lateral control (distance and wheel angle) between the male and female bicyclists. The male bicyclists in the present study had more experience driving motorized vehicles and riding bicycles than the females, and this discrepancy regarding experience may offer one explanation for the differences in control observed between the males and the females, as perceived risk is associated with bicyclists' biking experience.

Furthermore, the bicyclists' handling of wheel angle and speed, as well as speed variation before the pass, can affect the motorists' initial passing distance. The wheel angle showed the most substantial influence; initial passing distances decreased approximately 50 cm (approximately 25%) between a bicyclists' wheel angle oriented 5 degrees to the left and a wheel angle oriented 5 degrees to the right. When the bicyclists oriented the wheel angle more to the right and displayed a more stable speed, the motorists chose a smaller initial passing distance. This behavior likely occurs because the motorists predicted the bicyclists to continue to move to the right and depart from the motorists' path; consequently, the motorists decided not to increase the passing distance. Stable control by the bicyclists may further increase the motorists' confidence in such a prediction.

Instrumented vehicle

An instrumented vehicle can collect rich data on bicyclists' behaviors, and these data can potentially be applied to various types of studies. First, using individual level data from a first-person perspective, the data can be used to provide objective evidence for various safety measures that have been subjectively evaluated. In addition to the road-related factors that have been discussed in the present study, there are many other traffic parameters that can be evaluated in the future using measuring technology for the recorded images to investigate their influences on bicyclists' behaviors. Second, the collected individual-level data could be used to explore important issues that are less-often explored, including whether motorists pull into the bicyclists' path from the roadside, whether parked motorized vehicles open their doors, and so on. Third, the passing motorized vehicles' spatial and time dimensions demonstrated complicated effects on bicyclists' behaviors at different passing stages, and this issue merits further study. The use of cars as a benchmark to compare buses and motorcycles may clearly demonstrate the effect of these parameters in mixed traffic. Finally, subjective rating scales may be an artifact of the traditional ways used to represent perceived risk numerically [12], whereas objective behaviors could be used to create a surrogate safety index. However, there are some research disadvantages. It requires a large number of participants and riding routes to cover more populations, roads, and traffic environments. In addition, the data collected through this method require considerable time and effort to process. In the present study, with assistance from the self-developed data review and editing program, it still took one person-day to record the events and road facilities for every half an hour of riding data.

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