# Cyclist Crash Scenarios and Factors Relevant to the Design of Cyclist Detection Systems

Anna MacAlister, David S. Zuby

***Abstract*** Cyclists are overrepresented among motor vehicle crash fatalities. Detailed information regarding common cyclist crash scenarios and relevant crash factors is crucial to the development of cyclist detection warning and crash avoidance systems that could prevent these crashes and fatalities. Motor vehicle-cyclist crash data from federally maintained national databases were used to identify common and fatal crash scenarios between cyclists and motor vehicles. The most common fatal crash modes involved the motor vehicle-cyclist movement combinations straight-in line, straight-crossing, and straight-against. The most common crash modes involved the movement combinations straight-crossing, turning-crossing, and turning-in line. Crashes that occurred in non-daylight conditions and on roads with speed limits of 40 mi/h and greater contributed to the greatest percentage of fatalities. Cyclist detection systems that function at high speeds and in both daylight and non-daylight conditions offer the greatest potential benefit. Effective cyclist detection systems designed to function in scenarios like the three common fatal crash modes and two additional most common crash modes could help mitigate or prevent up to 47% of crashes, 48% of injuries, and 54% of fatalities, potentially saving up to 363 lives annually.

***Keywords*** Bicyclist, cyclist detection, crash avoidance, vulnerable road users

## I. INTRODUCTION

In recent years, motor vehicle-cyclist crash fatalities have begun to increase in the United States, following decades of decline since the all-time high of 1,003 cyclist deaths in 1975 [1]. The 682 cyclist deaths in 2011 represented a 10% increase from 2010, and 2012 saw an additional 6% increase to 722 cyclist fatalities [2]. Although the approximately 700 cyclists who are killed each year in crashes with motor vehicles represent a small fraction of the total annual motor vehicle crash deaths, cyclists are disproportionately likely to be fatally injured. Barely 1% of person road trips are attributed to cyclists, but these riders account for 2% of roadway fatalities [3]. Cyclists are required to follow the same regulations and traffic patterns as motor vehicles with little to none of the protection afforded to motor vehicle occupants. Cyclist protection becomes increasingly important as urban areas make efforts to reduce environmental and traffic concerns by promoting cycling as primary means of transportation.

Historically, efforts to improve cyclist safety have emphasized helmet use and adherence to riding regulations. Infrastructure can also have a substantial effect on cyclist safety. Studies have shown that cyclist-specific facilities like roundabouts and bike lanes engineered with an emphasis on cyclist safety reduce crashes and injuries to cyclists [4]. Other improvements including adequate street lighting, paved surfaces, and low-angled road grades are beneficial to cyclist safety [4].

While improvements to the road environment reduce the risk to cyclists, changes to the vehicles navigating the roadways can also help. The percentage of the passenger vehicle fleet with new collision warning and crash avoidance technologies is growing relatively quickly. Crash warning and avoidance systems already make use of different types of sensor technologies including camera-based systems, night vision technology, radar, and LIDAR systems [5]. Each of these sensor technologies has its own strengths and weaknesses. For example, camera systems require sufficient ambient light to perform well, while radar and LIDAR systems can be adversely affected by even small amounts of precipitation. Each type of system has its own effective range, which has great bearing on warning and intervention timing. The development of effective cyclist detection systems must take into account the different strengths and limitations of each sensor technology as they apply

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to different crash scenarios.

The European New Car Assessment Programme (Euro NCAP) has recently taken steps towards reducing the number of pedestrian and cyclist deaths in Europe [6]. Vulnerable road users (VRU), a category that includes pedestrians and cyclists, account for approximately half of all deaths on EU-27 roadways [6]. For this reason, Euro NCAP plans to develop protocols for testing pedestrian and cyclist detection and adopt testing procedures for autonomous emergency braking VRU systems no later than 2018 [6]. A recent study of German cyclist crashes found that the three most common motor vehicle-cyclist crash scenarios all occur when a cyclist crosses the path of a motor vehicle, either from the right while the motor vehicle travels straight or executes a right hand turn, or from the left as the motor vehicle travels straight [7]. While these data will certainly influence the development of cyclist detection systems for the European market, an understanding of the most common and most severe cyclist crash modes in the United States is necessary to the development of broadly applicable and effective cyclist detection systems. Given the different infrastructures, driving patterns, vehicle types, and cyclist cultures of Europe and the United States, it is not necessarily a valid assumption that the technologies that will produce the largest effect in one market will be equally beneficial in the other. The design and implementation of cyclist detection, collision warning, and crash avoidance systems must be guided by relevant data regarding the most common, fatal, and preventable crash modes.

## II. METHODS

Motor vehicle-cyclist crash data from federally maintained national databases were used to identify common and fatal crash scenarios between cyclists and motor vehicles, similar to a 2011 study conducted by the Insurance Institute for Highway Safety evaluating pedestrian crash scenarios [8]. Crash scenarios were defined by seven factors that describe the paths of the cyclist and motor vehicle, as well as external factors related to the crash with implications for collision warning and avoidance systems. The selected factors may affect sensor type selection and the ability of detection systems to accurately identify cyclists in a time frame that allows for driver or automated intervention to prevent a collision from occurring. Information describing the motion of a cyclist relative to the vehicle can help identify sensor ranges and fields of view, as well as help define the logic needed to develop algorithms that estimate crash risk. Obstruction of driver view is used as a proxy for the possibility that detection sensors may not have a clear view of a cyclist. Light condition provides information regarding the ability of light-dependent sensors in detecting cyclists. Speed limit, used as a proxy for vehicle speed, affects the necessary distance range of sensing technologies, as well as the time to collision and timing of warnings and interventions. Cyclist age is used as a proxy for cyclist size, an important variable in detection algorithms. Weather conditions, particularly precipitation and other particulate (blowing sand, etc.), affect the ability of the vehicle to brake, either autonomously or through driver intervention, as well as the time needed to apply an intervention. Driver braking affects the design of systems intended to autonomously brake or support and enhance driver avoidance maneuvers.

Data were extracted from two national crash databases maintained by the National Highway Traffic Safety Administration (NHTSA) in the United States. The National Automotive Sampling System General Estimates System (NASS GES) is a nationally representative sample of police-reported motor vehicle crashes that occur on public roads. The cases are weighted by the inverse of their selection probability to provide a sample that is representative of approximately 6 million annual motor vehicle crashes nationwide. While NASS GES weights can be used to estimate fatal crash counts, information about these crashes was extracted from the Fatality Analysis Reporting System (FARS). FARS is a census of motor vehicle crashes in which at least one occupant or other involved person was fatally injured and died within 30 days of the crash.

All person-level records for cyclists in the 2008-2012 NASS GES and FARS files were extracted and combined with their corresponding crash-level records. For crashes involving a single motor vehicle, the cyclist and crash data were again merged with the corresponding driver and vehicle records. Crashes involving more than one motor vehicle were not included in the study to restrict the analysis to primary motor vehicle-cyclist crashes and eliminate the confounding factors that could be introduced when a cyclist crash occurred as a result of a previous vehicle-vehicle crash. NASS GES cases were weighted by their case weights to produce national estimates of motor vehicle-cyclist crash incidences.

Crashes involving the front of the vehicle were further analyzed to isolate the effects of crash factors on scenarios that could be preventable with a cyclist detection algorithm. Cyclist crashes were classified according to the seven primary accident factors (Table 1).

TABLE 1
CLASSIFICATION OF CYCLIST AND VEHICLE MOVEMENT, DRIVER VIEW OBSTRUCTION, LIGHT CONDITIONS, INCLEMENT WEATHER, CYCLIST AGE, SPEED LIMIT, AND VEHICLE BRAKING USING NASS GES AND FARS RECORDS, 2008-2012

| | NASS GES | FARS |
|---|---|---|
| Cyclist movement | | |
| Cyclist in-line with traffic | PED_ACC = 13, 15-17, 22-24, 27, 35, 39, 61, 62 *OR* MPR_ACT = 5 | LOCATION = 11-13, 15, 16 *AND* P_CF1-3 ≠ 3, 47-50 *OR* MPR_ACT = 5 |
| Cyclist against traffic | PED_ACC = 26, 30 *OR* MPR_ACT = 6 | P_CF1-3 = 49, 50 *OR* MPR_ACT = 6 |
| Cyclist crossing traffic | PED_ACC = 1, 2, 4-10, 12, 18, 19, 21, 25, 31-34, 48, 49, 50, 55, 60, 90 *OR* MPR_ACT = 3 | P_CF1-3 = 3, 47, 48 *OR* MPR_ACT = 3 |
| Vehicle movement | | |
| Vehicle traveling straight | P_CRASH1 = 1-4, 6, 14-16 | VEH_MAN = 1-5, 9, 16, 17 *OR* P_CRASH1 = 1-4, 6, 14-16 |
| Vehicle turning | P_CRASH1 = 10-12 | VEH_MAN = 10-14 *OR* P_CRASH1 = 10-12 |
| Driver view obstruction reported | VIS_OBSC = 1-15, 97, 98 *OR* MVISOBSC = 1-14, 97, 98 | DR_CF1-4 = 61-76 *OR* MVISOBSC = 1-14, 97, 98 |
| Non-daylight conditions | LGHT_CON = 2-5 *OR* LGT_COND = 2-6 | LIGHT = 2-6 *OR* LGT_COND = 2-6 |
| Inclement weather | WEATHER = 2-8, 10, 11 *OR* WEATHER1-2 = 2-8, 10, 11 | WEATHER = 2-8, 10, 11 *OR* WEATHER1-2 = 2-8, 10, 11 |
| Cyclist age 12 years or younger | AGE = 0-12 | AGE = 0-12 |
| Speed limit less than 40 mi/h | SPD_LIM = 1-39 *OR* VSPD_LIM = 1-39 | SP_LIMIT = 1-39 *OR* VSPD_LIM = 1-39 |
| Vehicle braking reported | IMPACT1 = 1, 11, 12, 21, 31, 32 *AND* P_CRASH3 = 2-5, 8, 9 | IMPACT1 = 1, 11, 12 *AND* P_CRASH3 = 2-5, 8, 9 |

Cyclist movement was classified as in-line with traffic, against traffic, or crossing traffic. Motor vehicle movement prior to the crash was classified as traveling straight or turning. Six movement combinations obtained using the three cyclist movement types and two vehicle movement types were used to classify crash scenarios (Figure 1). Cases that occurred in non-daylight conditions or during inclement weather, as well as cases in which the driver's view was obstructed, were identified using variables coded within each database (Table1).

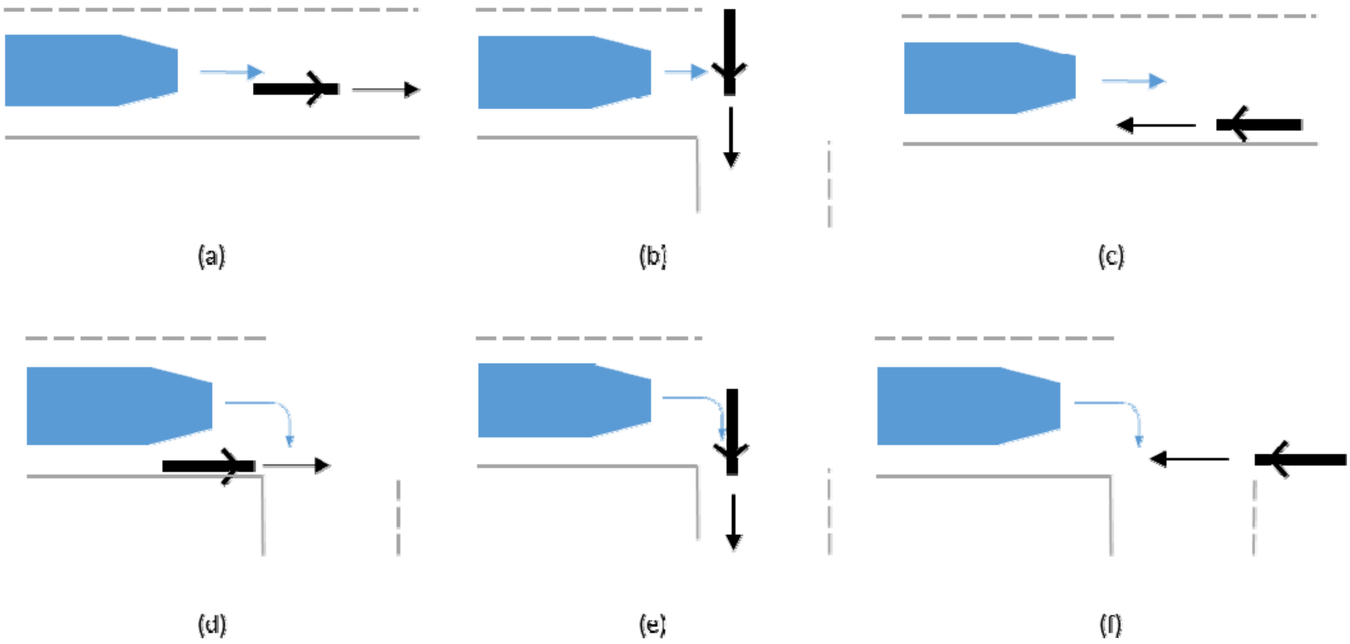

Fig. 1 Depictions of motor vehicle and cyclist movement combinations for crash scenarios (a) vehicle moving straight and cyclist traveling in line with traffic, (b) vehicle moving straight and cyclist crossing traffic, (c) vehicle moving straight and cyclist moving against traffic, (d) vehicle turning and cyclist moving in line with traffic, (e) vehicle turning and cyclist crossing traffic, and (f) vehicle turning and cyclist moving against traffic.

## III. RESULTS

From 2008 to 2012, there were 7,835 cyclist records in NASS GES, representing approximately 275,000 cyclists with case weights applied and rounded to the nearest thousand. During the same time frame, 3,367 cyclist fatalities were documented in FARS. During this 5-year period, an average of 55,000 cyclists were involved in police-reported motor vehicle crashes each year, and an average of 673 cyclists per year sustained fatal injuries in motor vehicle crashes. Cyclist crashes involving a single motor vehicle accounted for 99% of all cyclist motor vehicle crashes and 95% of cyclist fatalities for a total of 274,000 cyclist-motor vehicle crashes and 3,201 deaths during the 5-year study period. The distribution of cyclist crashes, injuries, and fatalities by various vehicle, environmental, and cyclist characteristics are shown in Table 2.

***Front impacts to single passenger vehicles***

During the 5-year study period, cyclist crashes involving the front of a passenger vehicle accounted for 63% (172,000) of all single motor vehicle cyclist crashes and 74% (2,363) of fatal cyclist crashes. The distribution of cyclist crashes, injuries, and fatalities by vehicle, environmental, and cyclist characteristics for crashes involving the fronts of passenger vehicles are shown in Table 3. Sixty-four percent of passenger vehicle-cyclist crashes with the front of the vehicle occurred on roads with speed limits of less than 40 mi/h, while only 35% of fatal crashes occurred on roads with the same speed limits. Twenty-three percent of cyclist crashes and 50% of fatal crashes occurred during non-daylight conditions. Inclement weather was present in 11% of all cyclist crashes and 13% of fatal cyclist crashes. Children 12 and younger accounted for 12% of cyclist crashes but only 7% of cyclist fatalities.

TABLE 2
PERCENT DISTRIBUTION OF CYCLISTS IN SINGLE-VEHICLE CRASHES BY VEHICLE, ENVIRONMENT, AND CYCLIST CHARACTERISTICS, 2008-2012

| | All cyclists N=274,000 | Injured cyclists N=147,000 | Fatally injured cyclists N=3201 |
|---|---|---|---|
| Vehicle type | | | |
| Passenger vehicle | 97.6 | 97.3 | 83.0 |
| Heavy truck or bus | 1.7 | 2.1 | 11.1 |
| Motorcycle | 0.7 | 0.6 | 0.9 |
| Other or unknown | 0.0 | 0.6 | 5.1 |
| Point of initial impact on vehicle | | | |
| Front | 63.8 | 64.3 | 83.6 |
| Right | 22.9 | 23.0 | 7.0 |
| Left | 9.0 | 9.2 | 2.8 |
| Rear | 4.1 | 3.4 | 2.1 |
| Other or unknown | 0.3 | 0.1 | 4.5 |
| Speed limit | | | |
| No limit | 6.7 | 7.1 | 0.0 |
| <30 | 30.3 | 30.6 | 10.6 |
| 30-39 | 32.9 | 34.1 | 27.1 |
| 40-49 | 11.8 | 13.2 | 30.6 |
| >49 | 3.8 | 3.1 | 26.6 |
| Unknown | 14.6 | 11.9 | 5.0 |
| Light condition | | | |
| Daylight or unknown | 77.9 | 79.0 | 53.2 |
| Dark | 3.6 | 4.1 | 20.0 |
| Dark but lighted | 13.6 | 13.2 | 21.3 |
| Dawn/dusk | 4.8 | 3.8 | 5.5 |
| Inclement weather | 11.4 | 11.3 | 13.1 |
| Cyclist age | | | |
| <6 | 0.7 | 0.8 | 0.9 |
| 6-12 | 10.5 | 11.3 | 5.6 |
| 13-17 | 16.0 | 15.1 | 7.0 |
| 18-64 | 68.4 | 68.5 | 74.4 |
| >64 | 4.4 | 4.2 | 12.1 |
| Unknown | 0.0 | 0.0 | 0.0 |
| Male cyclists | 79.1 | 79.0 | 86.8 |
| Cyclist location | | | |
| Intersection | 35.3 | 33.5 | 32.1 |
| Roadway, non-intersection | 31.7 | 31.6 | 60.9 |
| Dedicated bike lane* | 1.4 | 1.7 | 1.4 |
| Unknown | 31.6 | 33.2 | 5.6 |
| Cyclist wearing helmet | 16.5 | 18.4 | 12.8 |

*Prior to 2010, information on dedicated bike lanes was not available in the NASS GES and FARS databases.

TABLE 3
PERCENT DISTRIBUTION OF CYCLISTS IN SINGLE-VEHICLE CRASHES INVOLVING FRONTS OF PASSENGER VEHICLES BY VEHICLE, ENVIRONMENT, AND CYCLIST CHARACTERISTICS, 2008-2012

| | All cyclists N=172,000 | Injured cyclists N=93,000 | Fatally injured cyclists N=2363 |
|---|---|---|---|
| Speed limit (mi/h) | | | |
| No limit | 8.1 | 8.1 | 0.0 |
| <30 | 30.4 | 31.7 | 9.4 |
| 30-39 | 33.1 | 32.7 | 25.1 |
| 40-49 | 11.3 | 13.8 | 32.8 |
| >49 | 3.3 | 2.6 | 29.1 |
| Unknown | 13.8 | 11.2 | 3.6 |
| Light condition | | | |
| Daylight or unknown | 76.5 | 76.7 | 49.9 |
| Dark | 3.9 | 4.7 | 22.4 |
| Dark but lighted | 14.7 | 14.7 | 22.6 |
| Dawn/dusk | 4.8 | 3.9 | 5.2 |
| Inclement weather | 11.4 | 11.6 | 13.2 |
| Cyclist age | | | |
| <6 | 0.9 | 1.0 | 0.6 |
| 6-12 | 11.3 | 12.2 | 5.9 |
| 13-17 | 17.7 | 15.9 | 7.5 |
| 18-64 | 65.6 | 66.4 | 74.0 |
| >64 | 4.5 | 4.5 | 11.9 |
| Unknown | 0.0 | 0.0 | 0.0 |
| Male cyclists | 78.2 | 78.2 | 87.5 |
| Cyclist location | | | |
| Intersection | 35.1 | 33.4 | 30.3 |
| Roadway, non-intersection | 27.8 | 26.9 | 63.1 |
| Dedicated bike lane* | 0.8 | 1.0 | 1.5 |
| Unknown | 36.3 | 38.6 | 5.2 |
| Cyclist wearing helmet | 13.6 | 14.8 | 12.8 |
| Vehicle movement | | | |
| Traveling straight | 50.1 | 50.6 | 93.3 |
| Turning | 44.0 | 44.9 | 6.1 |
| Other or Unknown | 5.9 | 4.4 | 0.6 |
| Cyclist movement | | | |
| Crossing traffic | 54.2 | 54.1 | 24.1 |
| Moving in-line with traffic | 20.8 | 23.2 | 47.0 |
| Moving against traffic | 6.7 | 5.5 | 6.7 |
| Other or unknown | 18.3 | 17.2 | 22.3 |
| Driver view obstruction reported | 9.1 | 10.2 | 6.0 |
| Vehicle braking reported | 6.3 | 7.0 | 10.4 |

*Prior to 2010, information on dedicated bike lanes was not available in the NASS GES and FARS databases.

Seventy-eight percent of cyclists involved in crashes and 88% of cyclists fatally injured in crashes were male. The majority of fatal cyclist crashes (63%) occurred on roadways outside of intersections, where only 28% of all crashes occurred. Fourteen percent of cyclists involved in a crash were reported to be wearing a helmet, as were 13% of fatally injured cyclists. About half of all vehicle-cyclist crashes involved a vehicle traveling straight. The same vehicle movement was present in 93% of fatal vehicle-cyclist crashes. While half of all cyclist crashes occurred when the cyclist was crossing traffic, less than a quarter of all fatalities occurred when cyclists crossed traffic. In 9% of vehicle-cyclist crashes and 6% of fatal crashes, the driver's view was reportedly obstructed. Vehicle braking was reported in 6% of all cyclist crashes and 10% of fatal crashes.

***Crash modes and movement combinations***

Cyclist and vehicle movement combinations are presented in Table 4. The three crash modes leading to the most fatalities involved the following motor vehicle-cyclist movement combinations: straight-in-line (1072 fatalities), straight-crossing (530 fatalities), and straight-against (139 fatalities). The most common crash mode involved the same vehicle-cyclist movement combination as the second most fatal crash mode, straight-crossing, accounting for 50,000 crashes. The next most common crash modes involved the following vehicle-cyclist movement combinations: turning-crossing (39,000 crashes) and turning-in-line (18,000 crashes). Crashes that produced injuries, but not fatalities, followed the same vehicle-cyclist movement patterns as all cyclist crash involvements.

***Crash factors***

Summaries of the influence of crash factors for each of the three crash scenarios that result in the greatest numbers of fatalities are presented in Tables 5 and 6. Sixteen percent of involved cyclists were children ages 12 and younger, but only 6% of fatal crashes involved children of this age group. Twenty-nine percent of cyclists involved in the three most common fatal crash scenarios crashed in nighttime conditions, whereas more than half of fatal crashes were at night. Inclement weather was a factor in 13% of all crashes, with 14% of all fatal crashes occurring in these scenarios. Driver view obstruction was reported in 9% of the three most frequent fatal crash scenarios and 6% of fatal crashes included these types. Two-thirds (67%) of cyclist crashes of the three common fatal crash modes occurred on roads with speed limits of less than 40 mi/h, while less than one-third (30%) of fatal crashes occurred on these roads. Sixty-six percent of fatal crashes in these modes occurred on roads with speed limits of less than 50 mi/h. Lastly, vehicle braking was reported in 8% of crashes and 11% of fatal crashes.

Summaries of the influence of crash factors for each of the three most common crash scenarios are presented in Tables 7 and 8. Thirteen percent of cyclists involved in the three most common motion scenarios were children ages 12 and younger, but only 8% of fatal crashes in these scenarios involved children of this age group. Twenty-four percent of the crashes in the most common scenarios occurred at night, as did approximately half of fatal crashes. Inclement weather was a factor in 11% of all common crashes and 15% of all fatal common crashes. Driver view obstruction was reported in 8% of the most common crash scenarios and 7% of fatal crashes occurring in these three scenarios. More than two-thirds (69%) of common cyclist crashes and 42% of common crashes leading to cyclist fatalities occurred on roads with speed limits of less than 40 mi/h. Finally, vehicle braking was reported in 7% of crashes and 16% of fatal crashes.

Some crash scenarios involved more than one crash factor. Table 9 shows hierarchical distributions of the number of crashes and fatalities that could be addressed by cyclist detection, collision warning, and crash avoidance systems designed to take into account each of the crash factors for the three most common fatal crash scenarios and two additional common crash scenarios. During the 5-year study period, 54% of all fatal cyclist crashes with the front of a single passenger vehicle occurred in the three most common fatal crash modes or the remaining two most common modes. These same five crash modes accounted for approximately 74% of all cyclist crashes with the fronts of single passenger vehicles.

TABLE 4

VEHICLE AND CYCLIST MOVEMENT COMBINATIONS FOR CYCLIST INVOLVEMENTS, INJURIES, AND DEATHS IN SINGLE-VEHICLE CRASHES WITH FRONTS OF PASSENGER VEHICLES, 2008-2012

| | Cyclist movement | | | | | | | | | | | | Total | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Crossing traffic | | | In-line | | | Against | | | Other/unknown | | | | | |
| Vehicle movement | All | Injured | Fatal | All | Injured | Fatal | All | Injured | Fatal | All | Injured | Fatal | All | Injured | Fatal |
| Straight | 50000 | 27000 | 530 | 16000 | 10000 | 1072 | 5000 | 2000 | 139 | 15000 | 7000 | 460 | 86000 | 47000 | 2205 |
| Turning | 39000 | 21000 | 38 | 18000 | 11000 | 30 | 6000 | 2000 | 18 | 13000 | 7000 | 57 | 76000 | 42000 | 143 |
| Other/unknown | 3000 | 2000 | 1 | 2000 | 1000 | 8 | 1000 | 0 | 1 | 4000 | 1000 | 5 | 10000 | 4000 | 15 |
| Total | 93000 | 50000 | 569 | 36000 | 22000 | 1110 | 12000 | 5000 | 158 | 31000 | 16000 | 522 | 172000 | 93000 | 2363 |

TABLE 5

CYCLIST INVOLVEMENTS AND FATALITIES IN SINGLE-VEHICLE CRASHES WITH FRONTS OF PASSENGER VEHICLES BY CYCLIST AND ENVIRONMENT CRASH FACTORS FOR THREE MOST COMMON FATAL CRASH SCENARIOS WITH GREATEST NUMBER OF FATALITIES, 2008-2012

| | Totals | | Children 12 and younger | | Non-daylight conditions | | Inclement weather | |
|---|---|---|---|---|---|---|---|---|
| Vehicle-cyclist | Involvements | Fatalities | Involvements | Fatalities | Involvements | Fatalities | Involvements | Fatalities |
| movement | N | N | N (%) | N (%) | N (%) | N (%) | N (%) | N (%) |
| Straight-in line | 16000 | 1072 | 1000 (7.7) | 37 (3.5) | 6000 (34.7) | 573 (53.5) | 2000 (15.0) | 145 (13.5) |
| Straight-crossing | 50000 | 530 | 10000 (19.7) | 46 (8.7) | 14000 (27.9) | 276 (52.1) | 6000 (11.3) | 80 (15.1) |
| Straight-against | 5000 | 139 | 500 (9.8) | 12 (8.6) | 1000 (23.4) | 75 (54.0) | 1000 (17.8) | 21 (15.1) |
| Total | 71000 | 1741 | 12000 (16.3) | 95 (5.5) | 21000 (29.2) | 924 (53.1) | 9000 (12.6) | 246 (14.1) |

TABLE 6

CYCLIST INVOLVEMENTS AND FATALITIES IN SINGLE-VEHICLE CRASHES WITH FRONTS OF PASSENGER VEHICLES BY VEHICLE CRASH FACTORS FOR THREE MOST COMMON FATAL CRASH SCENARIOS WITH GREATEST NUMBER OF FATALITIES, 2008-2012

| | Totals | | Driver view obstruction | | Speed limit <40 mi/h | | Speed limit <50 mi/h | | Vehicle braking | |
|---|---|---|---|---|---|---|---|---|---|---|
| Vehicle-cyclist | Involvements | Fatalities | Involvements | Fatalities | Involvements | Fatalities | Involvements | Fatalities | Involvements | Fatalities |
| movement | N | N | N (%) | N (%) | N (%) | N (%) | N (%) | N (%) | N (%) | N (%) |
| Straight-in line | 16000 | 1072 | 1000 (6.8) | 60 (5.6) | 9000 (57.3) | 277 (25.8) | 13000 (77.0) | 633 (59.0) | 1000 (6.0) | 77 (7.2) |
| Straight-crossing | 50000 | 530 | 4000 (8.5) | 36 (6.8) | 36000 (71.0) | 202 (38.1) | 42000 (83.5) | 423 (79.8) | 4000 (7.7) | 92 (17.4) |
| Straight-against | 5000 | 139 | 1000 (13.1) | 5 (3.6) | 2000 (51.9) | 44 (31.7) | 3000 (60.0) | 84 (60.4) | 1000 (16.8) | 21 (15.1) |
| Total | 71000 | 1741 | 6000 (8.7) | 101 (5.8) | 48000 (66.6) | 523 (30.0) | 57000 (80.5) | 1140 (65.5) | 6000 (7.9) | 190 (10.9) |

TABLE 7

CYCLIST INVOLVEMENTS AND FATALITIES IN SINGLE-VEHICLE CRASHES WITH FRONTS OF PASSENGER VEHICLES BY CYCLIST AND ENVIRONMENT CRASH FACTORS FOR THREE MOST COMMON CRASH SCENARIOS, 2008-2012

| | Totals | | Children 12 and younger | | Non-daylight conditions | | Inclement weather | |
|---|---|---|---|---|---|---|---|---|
| Vehicle-cyclist | Involvements | Fatalities | Involvements | Fatalities | Involvements | Fatalities | Involvements | Fatalities |
| movement | N | N | N (%) | N (%) | N (%) | N (%) | N (%) | N (%) |
| Straight-crossing | 50000 | 530 | 10000 (19.7) | 46(8.7) | 14000 (27.9) | 276 (52.1) | 6000 (11.3) | 80 (15.1) |
| Turning-crossing | 39000 | 38 | 3000 (6.9) | 3 (7.9) | 7000 (18.9) | 12 (31.6) | 4000 (9.9) | 3 (7.9) |
| Turning-in line | 18000 | 30 | 1000 (5.1) | 1 (3.3) | 5000 (26.0) | 7 (23.3) | 2000 (9.9) | 4 (13.8) |
| Total | 107000 | 598 | 14000 (13.1) | 50 (8.4) | 26000 (24.3) | 295 (49.3) | 12000 (11.2) | 87 (14.5) |

TABLE 8

CYCLIST INVOLVEMENTS AND FATALITIES IN SINGLE-VEHICLE CRASHES WITH FRONTS OF PASSENGER VEHICLES BY VEHICLE CRASH FACTORS FOR THREE MOST COMMON CRASH SCENARIOS, 2008-2012

| | Totals | | Driver view obstruction | | Speed limit <40 mi/h | | Speed limit <50 mi/h | | Vehicle braking | |
|---|---|---|---|---|---|---|---|---|---|---|
| Vehicle-cyclist | Involvements | Fatalities | Involvements | Fatalities | Involvements | Fatalities | Involvements | Fatalities | Involvements | Fatalities |
| movement | N | N | N (%) | N (%) | N (%) | N (%) | N (%) | N (%) | N (%) | N (%) |
| Straight-crossing | 50000 | 530 | 4000 (8.5) | 36(6.8) | 36000 (71.0) | 202 (38.1) | 42000 (83.5) | 423 (79.8) | 4000 (7.7) | 92 (17.4) |
| Turning-crossing | 39000 | 38 | 2000 (6.1) | 3 (5.3) | 27000 (68.9) | 31 (81.6) | 31000 (77.7) | 34 (89.5) | 2000 (3.8) | 2 (5.3) |
| Turning-in line | 18000 | 16 | 2000 (12.4) | 6 (20.0) | 11000 (64.2) | 17 (56.7) | 14000 (77.1) | 23 (76.7) | 1000 (4.0) | 1 (3.3) |
| Total | 107000 | 598 | 8000 (7.5) | 44 (7.4) | 74000 (69.2) | 250 (41.8) | 87000 (81.3) | 480 (80.3) | 7000 (6.5) | 95 (15.9) |

TABLE 9
CYCLIST INVOLVEMENTS, INJURIES, AND FATALITIES IN SINGLE-VEHICLE CRASHES BY THREE MOST COMMON FATAL AND TWO ADDITIONAL MOST COMMON CRASH SCENARIOS THAT COULD BE ADDRESSED IF CYCLIST DETECTION SYSTEMS WERE ABLE TO FUNCTION IN NON-DAYLIGHT CONDITIONS, AT SPEEDS GREATER THAN 40 MI/H, IN INCLEMENT WEATHER, AND WITH DRIVER VIEW OBSTRUCTION, 2008-2012

| | Cyclists involved | Cyclists injured | Cyclist fatalities |
|---|---|---|---|
| *Vehicle traveling straight, cyclist moving in line* | | | |
| Crashes addressed by base system | | | |
| Speed limit <40 mi/h, daylight, clear weather, no view obstruction | 5000 | 3000 | 112 |
| Potential crashes addressed | | | |
| Non-daylight conditions and speed limit ≥40 mi/h | 8000 | 6000 | 769 |
| Inclement weather | 2000 | 1000 | 131 |
| Driver view obstruction | 1000 | 1000 | 60 |
| Subtotal for scenario | 16000 | 10000 | 1072 |
| *Vehicle traveling straight, cyclist crossing* | | | |
| Crashes addressed by base system | | | |
| Speed limit <40 mi/h, daylight, clear weather, no view obstruction | 22000 | 12000 | 94 |
| Potential crashes addressed | | | |
| Non-daylight conditions and speed limit ≥40 mi/h | 19000 | 10000 | 327 |
| Inclement weather | 5000 | 2000 | 73 |
| Driver view obstruction | 4000 | 3000 | 36 |
| Subtotal for scenario | 50000 | 27000 | 530 |
| *Vehicle traveling straight, cyclist moving against* | | | |
| Crashes addressed by base system | | | |
| Speed limit <40 mi/h, daylight, clear weather, no view obstruction | 1000 | 1000 | 20 |
| Potential crashes addressed | | | |
| Non-daylight conditions and speed limit ≥40 mi/h | 2000 | 1000 | 94 |
| Inclement weather | 1000 | 1000 | 20 |
| Driver view obstruction | 1000 | 0 | 5 |
| Subtotal for scenario | 5000 | 2000 | 139 |
| *Vehicle turning, cyclist crossing* | | | |
| Crashes addressed by base system | | | |
| Speed limit <40 mi/h, daylight, clear weather, no view obstruction | 19000 | 10000 | 17 |
| Potential crashes addressed | | | |
| Non-daylight conditions and speed limit ≥40 mi/h | 15000 | 8000 | 16 |
| Inclement weather | 4000 | 2000 | 3 |
| Driver view obstruction | 2000 | 2000 | 2 |
| Subtotal for scenario | 39000 | 21000 | 38 |
| *Vehicle turning, cyclist traveling in line* | | | |
| Crashes addressed by base system | | | |
| Speed limit <40 mi/h, daylight, clear weather, no view obstruction | 6000 | 4000 | 9 |
| Potential crashes addressed | | | |
| Non-daylight conditions and speed limit ≥40 mi/h | 7000 | 4000 | 11 |
| Inclement weather | 2000 | 1000 | 4 |
| Driver view obstruction | 2000 | 1000 | 6 |
| Subtotal for scenario | 18000 | 11000 | 30 |

## IV. Discussion

Crashes in which the vehicle was traveling straight and the cyclist was moving in line with traffic were found to result in the greatest number of cyclist fatalities, followed by crashes in which the vehicle was traveling straight and the cyclist was either crossing traffic or moving against traffic, respectively (Table 4). These three crash modes alone account for 74% of cyclist fatalities in crashes to the fronts of passenger vehicles. Including the additional 460 cyclists with unknown movement patterns who were fatally injured by straight-moving vehicles, more than 93% of cyclist fatalities in crashes to the fronts of passenger vehicles occurred when the vehicle was traveling straight. The most common crashes followed a different pattern. Although the most common crash mode, in which the vehicle was traveling straight and the cyclist was crossing traffic, also was the second most common fatal crash scenario, the remaining two common crash modes were not among the most common fatal scenarios. The second and third most common crash modes involved the vehicle turning and the cyclist either crossing traffic or moving in line with traffic, respectively. The difference in crash patterns leading to the greatest number of fatalities and those leading to the greatest number of crashes means that cyclist detection systems must focus on a variety of crash scenarios. Additionally, crash factors affect the numbers of fatalities and the total number of crashes differently. For example, while the majority of crashes occur at vehicle speeds less than 40 mi/h, only one-third of fatalities occur below 40 mi/h (Table 3). To prevent the majority of crashes and fatalities, cyclist detection systems must function at vehicle speeds up to and greater than 50 mi/h. Cyclist detection systems that function at high speeds and in both daylight and non-daylight conditions have the greatest potential to prevent cyclist fatalities. Existing forward collision prevention systems may have the potential to address the most common fatal cyclist crash scenario, straight-in line, with only minor modifications. These systems already have been demonstrated to be effective at reducing the frequency of property damage and bodily injury liability insurance claims [9]. A more recent study indicates that low-speed (≤50 km/h) autonomous emergency braking systems reduce real-world rear impact crashes by 38% [10]. Extending the function of these systems to include the capability to identify cyclists may be possible with the sensing technology already deployed in many front crash prevention systems. This one crash scenario accounts for 6% of all cyclist crashes and 32% of fatal cyclist crashes (Table 9).

Although impacts to the front of the vehicle make up the largest portion of cyclist crashes and fatalities, there is a non-trivial number of crashes and fatalities that occur to the right side of the vehicle (Table 2). A detailed analysis of crashes to the sides of vehicles could guide the development of new technologies designed to prevent or mitigate another significant portion of cyclist crashes and fatalities.

While this study provides guidance for the development of cyclist detection and collision warning and avoidance systems, it is subject to limitations. First, the data used in this study were obtained from two databases, NASS GES and FARS, and are therefore subject to the limitations of the databases. Any errors made during the initial coding of each case cannot be determined and are present in the data set. Second, discrepancies exist between the two databases. For crashes occurring in 2010 and later, the NASS GES and FARS databases use the same variables and field codes. For crashes occurring prior to 2010, each database follows a unique coding procedure and variables in one dataset do not necessarily correspond directly to variables in the other. Third, the variables coded in NASS GES and FARS do not provide a comprehensive view of the crash. For example, the variable driver view obstruction can take on many values describing what blocked the view of the driver, but the field does not provide information regarding to what degree the driver's view was obstructed or for what period of time leading up to the crash. This type of detailed information would be beneficial to the development of cyclist detection systems. Finally, one fundamental limitation of all cyclist data in the NASS GES and FARS databases is the way in which cyclist movement is coded. In both databases, before and after standardization, cyclists and pedestrians are treated collectively as "non-motorist" person types. While there are some concessions made to account for their differences, like the bicycle helmet usage field, their movement patterns are characterized similarly. Codes for non-motorist movement are primarily derived from pedestrian movement styles, rather than the movement patterns of cyclists. More detailed information regarding crash scenarios could be attained if the NASS GES and FARS databases coded cyclist movement in a manner similar to vehicle movement, reflecting the movement patterns cyclists are legally obligated to obey.

## V. CONCLUSIONS

The majority of all crashes involving a cyclist and motor vehicle occur to the front of passenger vehicles. Crashes in which the cyclist crosses the path of traffic are the most common in the United States, while the most common fatal crash mode involves a motor vehicle striking a cyclist moving along with traffic. Changes to traffic infrastructure and cyclist safety culture are vital in the effort to reduce these overrepresented traffic fatalities, but vehicle safety systems including cyclist detection and collision warning and avoidance also have the potential to greatly improve the safety of roadways for cyclists. For these types of systems to have the greatest possible benefit, it is important that they are designed with the most common and most severe crash scenarios in mind. Cyclist detection algorithms coupled with collision warning and crash avoidance systems designed with the three most common fatal scenarios and factors in mind could help mitigate or prevent up to 26% of crashes and cyclist injuries and 52% of fatalities. Systems designed with the remaining two most common crash modes in mind have the potential to mitigate or prevent up to an additional 21% of crashes, 22% of cyclist injuries, and 2% of cyclist fatalities, affecting a total of up to 47% of cyclist crashes, 48% of cyclist injuries, and 54% of cyclist fatalities.

## VI. REFERENCES

[1] National Highway Traffic Safety Administration. 2012 bicyclists and other cyclists traffic safety fact sheet. Report no. DOT HS-812-018. Washington, D.C.: U.S. Department of Transportation; 2014.

[2] Insurance Institute for Highway Safety. Pedestrian and bicyclists fatality facts. Insurance Institute for Highway Safety, Arlington VA, 2014.

[3] Pucher J, Buehler R, Merom D, Bauman A. Walking and cycling in the United States, 2001-2009: evidence from the National Household Travel Surveys. *American Journal of Public Health,* 2011, 101(S1): S310-S317.

[4] Reynolds C, Harris M, Teschke K, Cripton P, Winters M. The impact of transportation infrastructure on bicycling injuries and crashes: a review of the literature. *Environmental Health*, 2009, 8(1):47-65.

[5] Jermakian J. Crash avoidance potential of four passenger vehicle technologies. *Accident Analysis and Prevention,* 2011, 43(3):732-740.

[6] European New Car Assessment Programme. *2020 Roadmap*. Brussels, Belgium. 2014.

[7] Kuehn M, Hummel T, Lang A. Cyclist-car accidents – their consequences for cyclists and typical accident scenarios. *Proceedings of the 24th International Conference on the Enhanced Safety of Vehicles*, 2015, Gothenburg, Sweden.

[8] Jermakian J, Zuby, D. *Primary pedestrian crash scenarios: factors relevant to the design of pedestrian detection systems.* Insurance Institute for Highway Safety, Arlington VA, 2011.

[9] Moore M, Zuby D. Collision Avoidance Features: Initial results. *Proceedings of the 23rd International Conference on the Enhanced Safety of Vehicles*, 2013, Seoul, Republic of Korea.

[10] Fildes B, et al. Effectiveness of low speed autonomous emergency braking in real-world rear-end crashes. *Accident Analysis & Prevention,* 2015, 81:24-29.