AF05 Bicyclist’s Head Kinematics in Car-to-Ebike Perpendicular and Angular Impacts

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ABSTRACT: This paper focused on different types of passenger vehicles vs. small scooter type E-bike collisions for AF05 bicyclists. Detail FE bicyclist human body model (HBM) and E-bike are developed. It is observed that (i) location of head impact (WAD) matches the recent NCAP proposal and (ii) bonnet leading edge (BLE) height which varies with vehicle profile influences overall kinematics of the bicyclist. Hence, future head protection guidelines for bicyclists should be based on real-world accident statistics of that region.

KEY WORDS: Human body model, E-bike, Wrap around distance, Bonnet leading-edge, Generic vehicle Model [C1]

1. Introduction

Modes of transportation continue to evolve with advanced technology and the desire to find more economical, flexible, and environment-friendly transport mediums in small and big cities around the globe (1). In addition to electric cars, in recent years E-bikes have also appeared as a sustainable transport option, which offers several environmental, mobility, and health benefits (2). Increasing the use of E-bikes has good potential for the environment, health, and traffic load. However, there is a growing number of reports showing higher injuries to E-bicyclists (3). In China, bike/moped based traffic fatalities have increased about 11 times from 2004 to 2015 (4). Due to the poor road infrastructure of bicycle paths in the cities, cyclists are often forced to use pedestrian footpaths or share the road with motor vehicles. Canada, Europe, China, and the US have all passed legislation regarding E-bikes (max. speed, weight, and power) and categorize them separately from mopeds and motorcycles. Based on the report of CATARC (China Automotive Technology and Research Center) motorcycle accidents the most frequent two-wheeler accident type in China, followed by e-bike and bicycle accidents based on CIDAS (China In-Depth Accident Study) database (5). China has the largest number of two-wheelers on the road and the maximum number of two-wheeler accidents in the world. E-bike usage is especially high in Asian countries also. The female E-bike commuting population is quite large, especially in China, which is the leading country in terms of production and sales of E-bikes (6). Chinese E-bikes are slowly gaining popularity in the Japanese market also, especially among older people. However for old age riders, compared to normal bicycles, E-bike offers more difficulties in recovering from a sudden loss of stability due to higher speed and mass. This is one of the causes of a dramatic increase in E-bike related hospitalized casualties corresponding to a substantial increase in E-bike usage. Among all the injuries, the percentage of head injury is maximum. Hence, it is important to identify the mechanism of car-to-Ebike accidents that lead to head injury.

It is found that the 24-30 years of age group prefer E-bikes more and mainly dominated by women (7). Further, the average Chinese female population height is rather close to the AF05 human body model (HBM). Hence, this study preferred to use the AF05 human body model (8). Passenger vehicle and bicycle accident occur mainly by two scenarios i) When the vehicle was traveling straight and bicycle try to cross the road and ii) When the vehicle was turning at intersection impacts a bicycle (9) as shown in Table A1. According to another study based on CIDAS (5), E-bike impacting at the right angle (90deg) to the car is about 45%, rear impact (car hitting the E-bike from behind) is 22% and shallow angular inclined impacts (30deg), is less than 10%. The impact speed of turning scenario accidents is lower than perpendicular crossing scenario accidents (10).

Shuaishuai Hu, et al. used CIDAS database. E-bike based FE simulation, and crash tests to identify the E-bicyclist’s head kinematics. According to their study, car to E-bicycle accidents contribute to a higher proportion of Vulnerable Road User crashes in China. E-bicyclist’s head impact velocity is influenced by vehicle velocity and vehicle type. E-bicyclist’s head impact location is influenced by vehicle type and E-bicycle velocity (11). Yuan Huang et al used multi-body models of two-wheelers, vehicles, and riders to assess head injury risks. Head injury risk is influenced by vehicle velocity and the contact region’s structural stiffness (12).

The present work tries to highlight the different mechanisms/stages involved in an E-bike to a vehicle collision. From prior studies, it is clear that the vehicle’s velocity is influential in determining head kinematics. So this study tries to describe the mechanism behind the non-linear relationship between vehicle velocity and head kinematics. This paper also focuses on the effect of impact orientation, vehicle type, rider stature, and vehicle’s front profile on head kinematics.

Three parameters were identified for studying the head kinematics: i) wrap around distance WAD (distance between head impact location on the vehicle from the ground), ii) head impact velocity and iii) Head impact angle while the head contacts the
vehicle. Velocity components of the bicyclist’s head are shown in Figure A1. Head injury severity is dependent on various factors such as helmet usage, contact region stiffness. Hence, head injury is not selected as a topic of comparison in this paper.

2. Data & Method

2.1. FE Model Development (Bicycle and Bicyclist)

Based on the market information and survey of the popular Chinese E-bike models introduced in the Japanese market, a typical FE model of E-bike is developed as shown in Figure 1. The detail of the FE model is tabulated in Table 1. The weight and thickness of each part are accurately incorporated to match the mass, CG, and inertial properties of the bicycle. Six kinematic joints are defined at the handle, pedals, and two wheels. The in-wheel electric motor is located at the hub of the rear wheel. These types of E-bikes have pedals and also a footrest in the middle. In general, e-bicyclists put both their feet on the footrest as shown in in top part of Figure 2.

![Figure 1. Isometric view of the developed FE model.](image1)

| Bicycle Model Details | Numbers | Weight (kg) | Element Size |
|-----------------------|---------|-------------|--------------|
| Nodes                 | 65224   |             |              |
| Shell Elements        | 34105   | 35 (including Li-ion battery of 10kg*) | Global average element size (10 mm) |
| Solid Elements        | 170215  |             |              |
| Parts                 | 69      |             |              |
| Kinematic Joints      | 6       |             |              |
| Material              | 5       |             |              |

* The weight will change for other types of batteries.

3. Results

Using a simplified GHBMC (Global Human Body Model Conference) human body AF05 model, the corresponding AF05 bicyclist model is developed to match the driving posture of a bicyclist to fit into the E-bike with both toes resting on the footrest. This section describes the results obtained from a typical PV vs. E-bike with AF05 bicyclists. CAE simulation focuses on head kinematic responses e.g., location of impact WAD, speed, and angle of impact of the head.

3.1. Head kinematics of AF05 bicyclist with vehicle @ 90deg

A commercial SUV type vehicle was selected for the present study. Figure 2 shows the comparison of the difference in trajectories of the head from lower to a higher speed of impacts. At a lower speed of impact, the head trajectory goes down and then goes straight. For high speed of impact, the head moves straight and then rotates before hitting the windshield (refer to Figure 2). Bicyclist interaction with passenger vehicle tends to follow four kinematic stages as shown in Figure A2, i) E-bike with bicyclist impacts the passenger vehicle, ii) bicyclist slides over the hood and the head travels in a straight line, iii) hip region deceleration starts due to friction and the upper body of the bicyclist along with head tends to rotate (pitching), iv) head trajectory starts moving in the lateral direction (yaw). At lower speeds, before the head contacts with the vehicle, all four stages were experienced by the bicyclist. However, at higher speeds, head contact happens before the fourth stage (also refer to the bottom of Figure A2).

![Figure 2. Comparison of head trajectories of PV vs. E-bike in side-impact (Pink: lower speed and Blue: higher speed) for AF05](image2)

Figure 3a shows the variation in head impact speed concerning vehicle impact speed. It shows a slightly non-linear trend. However, as shown in Figures 3b and 3c, the trend of WAD and head impact angle variations are different, particularly for the velocity of impact below 37.5kph where the head impact velocity response is more non-linear. In the 30-37.5kph range, the head impact angle is very low and almost constant. WAD is almost constant from 30kph to 37.5kph. In the 30-37.5kph range, the bicyclist experienced all 4 stages and beyond 37.5kph only 3 stages were exhibited (refer to Figure A2 & Figure A4).

![Figure 3a. Percentage variation of head impact speed with respect to the speed of impact of PV](image3)
This section explains the effect of turning scenarios on head kinematics. From literature studies, it is evident that impact speed reduces with the angle of turning. This study evaluated two test angled configurations namely, configuration-1: impact angle 30deg, 25kph while turning at cross-section with lower speed (Figure 4), and configuration-2: impact angle 15deg, speed 40kph (Table A2). From the comparison table of those head kinematic responses, it is observed that the head impact velocity and WAD will be less for angular impacts compared to perpendicular impacts. The corresponding changes in head impact velocity value is more than those of the location of head impact WAD and it is direction-dependent.

3.2. Head kinematics of AF05 bicyclist in inclined impact

3.3. Effect of Vehicle type:

This section explains the effect of different vehicle types on head kinematics. This study uses Generic Vehicle Models (recommended by Euro-NCAP for active hood evaluation) for portraying different vehicle types. There are 4 different types of generic vehicles (RDS: road star, FCR: the family car, MPV: multi-purpose, and SUV: sports utility). Figure 5a shows the superimposed schematic diagram of an E-bike bicyclist impacting General Vehicle Models (GVMs). These simplified numerical FE vehicles are representative of the vehicles in the market in corresponding categories. Typical BLE heights of RDS, FCR, MPV, and SUV type GVM vehicles are 634, 690, 760 & 854mm, respectively. The BLE height of the commercial PV vehicle model discussed in the previous section is 720 mm.

Wrap around distance, head impact velocity, and angle variation across different vehicle types for perpendicular impacts are plotted in Figure 5b, 5c & 5d. The WAD, head velocity, and head impact angle are highest for a vehicle with low-BLE (RDS-type) and lowest for a vehicle with high-BLE (SUV-type). The responses of FCR & MPV are in between RDS & SUV types.

The head kinematics of the RDS & SUV vehicle types are explained in Figure A3. As the BLE height of the SUV type vehicle matches close to the bicyclist’s seating pelvis height, the pelvis of the bicyclist will directly hit the BLE first where a considerable amount of initial kinetic energy of the bicyclist is lost. Then the hand will come in contact with the hood followed by the head contacting the vehicle. On the other hand, as the BLE height of the RDS-type vehicle is below the bicyclist’s seating pelvis height, the pelvis of the bicyclist slides on the hood without any initial contact at BLE. Hence, its initial kinetic energy is only partially lost before the head hits the vehicle at a relatively higher speed. WAD, head impact velocity, and head impact angle are highly influenced by BLE height. The overall effect of BLE of a vehicle on head kinematics of the present study is similar to the prior studies of BASI (10).

Figure 3b. Percentage variation of WAD with respect to the speed of impact of PV

Figure 3c. Percentage variation of head impact angle vs. speed of impact of PV

| Impact Angle (deg) | Impact velocity (kph) | % Change in head responses with respect to 25kph impact. | Ref. 90 deg |
|-------------------|----------------------|----------------------------------------------------------|------------|
| Angled (+30)      | 25                   | 66%                                                      | 82%        | 100%        |
| Angled (-30)      | 25                   | 79%                                                      | 80%        | 100%        |

Figure 4. Head kinematic responses for angular impact (configuration 1: higher impact angle 30 deg., lower impact speed 25kph while turning at cross-section).

Figure 5a. A schematic diagram of the bicyclist impacting General Vehicles proposed by Euro-NCAP

Figure 5b. Percentage variation of head impact location WAD with respect to the Vehicle types @40kph
4. Discussion and Limitations

4.1. Mechanism of low head impact angle at a lower vehicle speed

As shown in Figure 3c, the values of the head impact angle are very low at lower speeds in 90deg impact cases. The head impact angle is measured in the directions of length and height of the vehicle (refer to Figure A1). Bicyclist’s impact behavior for low 30kph and high-speed 50kph of impact is shown in Figure A2: i) E-bike with bicyclist impacts the passenger vehicle, ii) bicyclist slides over the hood and the head travels in a straight line, iii) hip region gets restrained (due to friction or hood profile) and because of the inertia of the upper body, the hip region gets lifted upwards from the hood. Meanwhile, the bicyclist’s head starts rotating (pitching) with respect to the pelvis and it tries to rotate till it reaches almost the same datum height of hip and this is the starting point of fourth stage iv) head starts moving in the lateral direction (yaw).

As discussed in the previous section, bicyclist with low impact speed complete all four stages and the head impact angle (refer to Figure A2) measured in the 4th stage will be less for low-speed impacts. Bicyclist engaging in higher impact speeds with a vehicle, exhibit head contacting vehicle in the 3rd stage (pitching) itself, and the head impact angle measured in the pitching stage will be high.

4.2. Effect of Human size

This section attempted to evaluate the effect of human size on bicyclist kinematics. GHMBMC – AM50 & AF05 human models were used as a bicyclist to impact against the passenger vehicle (40kph) and the characteristics are shown in Figure A5. Moving from AF05 to AM50, WAD, impact angle, and head impact velocity increase. The trend of head kinematics of this study is similar to that of BASI’s study (10). Since AM50 sits at a higher datum compared to AF05, it experiences a more sliding phase than AF05 (similar to the mechanism explained in Figure A3).

4.3. Car to Normal bicyclist vs Car to E-bicyclist

This section explains the kinematical difference between normal & e-bicyclist. During impact, e-bicyclist tend to rotate more in longitudinal direction with back of the head impacting the vehicle (Figure A6). E-bicyclist upper body slides over the vehicle but the legs get impacted against vehicle’s front structure and experience eccentric force. This initial eccentric contact force exerted on the leg, triggers high rotation for e-bicyclist as shown in Figure A7. On the other hand, the normal bicyclist’s leg is trapped in between the car and the normal bicycle (Figure A7). Hence, normal bicyclist do not rotate like e-bicyclist. It is also observed from Figure A8, the head impact velocity for the normal bicyclist is more than the e-bicyclist.

4.4. Effect of vehicle front profile

This section explains the influence of vehicle front-end profile on head kinematics. Nine profile parameters were selected to generate different vehicle front-end profiles as shown in Figure 6a. Vehicle profile dimensions are modified using mesh morphing technique to develop 90 different designs (Figure 6b) and impacted against E-bicycle at 40kph. Using a standard normalized regression technique, most influential parameters were identified. It is observed from Figure 6c, BLE height, windshield angle, bumper lead upper, hood angle are the dominant parameters in determining the head kinematics.

Head impact velocity has inverse relationship with BLE height. In an e-bicyclist vs high BLE height vehicle impact scenario (refer Figure A3), larger area of E-bicyclist’s lower body region interacts with vehicle front profile and accelerated towards vehicle’s travel direction. Hence head velocity, which is measured in opposite to vehicle travel direction, will be less for higher BLE vehicles.
4.5. Limitations & Future tasks

This study mainly focused on AF05 female bicyclist’s head kinematics in scooter type E-bike. The different populations of bicyclists in scooter type E-bike will be studied in the future. A similar study to evaluate head kinematics using a normal bicycle (pedal type) will also be studied in the future. With more and more market penetration and introduction of higher sensing capability of recent ADAS systems (for ex. AEB for bicyclists) in different segments of vehicles, proper consideration for the effectiveness of such systems in real-world safety has to be estimated before finalizing the procedure for future passive safety protocols for VRU.

5. Summary and Conclusion

This paper focused on bicyclist head kinematic response (WAD, Head impact angle, and speed) of small females in car-to-E-bike (scooter type). The present study used the GHBMC AF05 model as bicyclist impacting passenger vehicles at different speeds and orientations. The influence of vehicle type and occupant size on head kinematics were also analyzed.

a) Vehicle impact speed and impact angle are influential parameters in determining the head kinematics.

b) BLE is an influential factor in determining bicyclist's head kinematic responses.

c) Bicyclists are expected to follow four stages in impacting the vehicle, namely the initial stage, sliding stage, detachment stage, and head impact stage.

d) The E-bicyclist is rotated more about the vehicle length axis hitting the back of the head on the vehicle, since their legs on the footrest are not trapped between the impacting vehicle & E-bicycle. As the head impact velocity is more for a normal bicyclist compared to an E-bicyclist, there is hardly any need to change the existing impact velocity level for the current test procedure.

In determining the future global harmonized evaluation of head impact protection for bicyclists including scooter type E-bikes, one needs to conduct a further comprehensive and in-depth study.

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Appendix

Table A1. Impact scenarios with passenger car and bicyclist

| Scenario | In GIDAS (n=2840) all collision with passenger car and bicyclist |
|----------|---------------------------------------------------------------|
| A vehicle driving straight ahead bicycle crossing from left and right | 51% |
| Vehicle Turning left and right | 21% |
| others | 28% |

Table A2. Relative comparison head kinematic response for angular impact (Configuration 2).

| Vehicle Impact | Head Impact response in % w.r.t 90deg impact. |
|----------------|---------------------------------------------|
| Orientation Velocity Velocity WAD Ref. 90deg |
| deg | kph | | |
| 105(90+15) | 40 | 86% | 99% | 100% |
| 75(90-15) | 40 | 95% | 97% | 100% |

Figure A1 Velocity components of bicyclist’s head
|                  | Impact Stage | Sliding Stage | Detachment Stage | Head Impact Stage |
|------------------|--------------|---------------|-----------------|------------------|
| **Top view**     |              |               |                 |                  |
| 30kph            |              |               |                 |                  |
| Side view        |              |               |                 |                  |
| 50kph            |              |               |                 |                  |
| Side view        |              |               |                 |                  |

Figure A2. Comparison of bicyclist kinematics in side view and plan view at low speed 30kph and high speed 50kph impact

|                  | Impact Stage | Sliding Stage | Detachment Stage | Head Impact Stage |
|------------------|--------------|---------------|-----------------|------------------|
| **SUV**          |              |               |                 |                  |
|                  |              |               |                 |                  |
| **RDS**          |              |               |                 |                  |

Figure A3. Head kinematics in side-view for RDS and SUV impact during 4 distinct different phases

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Figure A4 Different stages of Bicyclist kinematics superimposed on the schematic head velocity vs. time graph.

- **Start of impact**
  - Pelvis restrained by hood
  - Velocity will start increasing

- **Pitching of head**
  - Velocity component in Y-Z plane is high

- **Detachment Stage**
  - Yaw of head
  - Velocity component in Y-Z plane low

- **Head Impact Stage during pitching motion**
  - (High speed V>37.5kph)

- **Head Impact Stage during yaw motion**
  - (Low speed V=30.0~37.5kph)

Figure A5 Head impact Characteristics comparison for AM50 and AF05.

- **% Change in WAD**
  - AF05: 95% to 115%
  - AM50: 90% to 110%

- **% Change in head impact angle**
  - AF05: 50% to 100%
  - AM50: 150% to 250%

- **% Change in head impact speed**
  - AF05: 50% to 100%
  - AM50: 100% to 200%
Table A3. Definitions/Abbreviations

| AM50/AF05 | American Male 50th %ile | American Female 5th %ile | GIDAS | German In-Depth Accident Study database |
|-----------|--------------------------|--------------------------|-------|----------------------------------------|
| BASit     | The Federal Highway Research Institute Germany | | GVM(SUV, RDS, FCV, MPV) | Generic Vehicle Model |
| BLE       | Bonnet Leading Edge | | HBM | Human Body Model |
| CIDAS     | Chinese In-Depth Accident Study database | | NCAP | New Car Assessment Program |

Figure A6  Impact characteristics comparison for normal and e-AF05 bicyclist

Figure A7  Mechanism of normal bicycle and E-bike with AF05 bicyclist.

Figure A8  Head impact velocity for normal & e-bicyclist.

Table A3. Definitions/Abbreviations

| AM50/AF05 | American Male 50th %ile | American Female 5th %ile | GIDAS | German In-Depth Accident Study database |
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