FEM-based Methodology for Crash Severity Estimation in Frontal Crash Scenarios

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Abstract. With the technological development of forward-looking sensors, researchers are exploring their use not only for advanced driver assistance systems but also to gain important pre-crash information. Based on this pre-crash information, if the occupant motion inside the vehicle structure can be predicted for the oncoming crash scenario, then an optimal restraint strategy can be planned before the crash. This paper introduces a two-step FEM simulation based methodology for predicting the occupant severity in head-on crash scenarios. In the first step, we simulate the vehicle level model with different impact positions and relative approach angles. The results of these simulations, linear velocities in the longitudinal and lateral direction and angular velocities (roll, pitch, and yaw) during in-crash phase are the loading conditions for next simulation step (occupant level). This step simulates the motion of the driver in different crash scenarios. In this paper, we investigate the head, neck, and chest injury risks from vehicle-to-vehicle crash both traveling at 50 kilometers per hour. Prediction of the head injury criterion, identifying the cases where additional deployment of side-airbags and discussion of injury criteria with contour plots are the main outcome of this paper.

1. Introduction

Vehicle manufacturers are in continuous search of methods and techniques to reduce fatalities and thus move a step closer to realize Vision-Zero [1]. Forward-looking sensors (radar, lidar, camera, etc.) and their corresponding technology are already in-use for driver-assistance, driver-warning and collision avoidance systems. Pre-crash information such as opponent type, velocity, relative approach angle and position of the first contact define a particular crash configuration, which can be used to activate the restraint systems earlier than present traditional passive safety systems [2]. It might be required to activate restraint systems before the first contact to save the occupants. The decision to activate a restraint system or combination of restraint systems and their activation time is very complex and requires prediction of crash severity based on occupant kinematics during a particular crash configuration.

Crash severity prediction is a vital part of the above described predictive vehicle safety system. Conventional passive safety system also predicts the crash severity based on the data measured by different safety sensors (acceleration-based, pressure-based, structure-borne-sound based). Based on this prediction, the corresponding safety action is deployed. This technology has a limit on activation time of airbags depending on the response time of the passive safety sensors (about 15 milliseconds). With the information from the forward-looking sensors and
advanced crash severity prediction, there is a possibility to activate the restraint systems earlier. A number of studies used real-crash database such as Crash Analysis and Reporting System (CARS), National Automotive Sampling System (NASS) and General Estimates System (GES) for training different machine learning algorithms with the aim of predicting crash severity [3, 4]. Some studies used Artificial Neural Networks to identify and predict influential factors contributing to crash severity [5, 6]. The severity of an occupant injury in a particular crash is a combination of the physical behavior of crash management structure, occupant kinematics and the effect of restraint systems. Previous studies have considered vehicle level parameters for either training the model or classifying and predicting the severity. These studies lack the physical behavior of the occupant kinematics and restraint systems. This paper describes an approach to investigate occupant level injury scales (as per Euro-NCAP) under different crash configurations using a two-step FEM simulation. The knowledge gained from the analysis of the occupant injuries under different crash scenarios can be used to decide an appropriate pre-crash restraint strategy (restraint strategy before the crash). This knowledge would also help in investigating the limitations of standard restraint systems and highlight the crash configurations which might need advanced systems such as smart airbags to save the occupants. According to the Insurance Institute of Highway Safety (IIHS) passenger vehicle occupants accounted for 64 percent of vehicle crash deaths and about 17,662 (74.5 percent) passenger vehicle drivers died in the year 2017 [7]. Moreover, the statistics based on the crash-type show that frontal crash scenario accounts for the highest percentage of passenger vehicle occupant deaths (about 56 percent) followed by the side crash scenario at 24 percent [7]. Hence, this research work is primarily focused on frontal crash. Even though this paper discusses the results from investigations of different frontal crash scenarios, this methodology can also be applied for other crash scenarios like side and rear-end crashes.

2. Methodology

A two-step FEM simulation approach as shown in Fig. 1 is used for acquiring the occupant responses in different crash scenarios. In a first step, different crash scenarios based on different pre-crash information are simulated at vehicle level to extract the in-crash vehicle responses. These responses include high frequency components which are filtered with the standard low-pass SAE-J211 filter with 100 Hz cut-off frequency. The filtered data is then fed to a second level FEM-simulation (occupant level simulation) to extract the occupant responses. Based on these occupant responses the injury criteria for different body parts are calculated. In the end, these injury criteria are analyzed for different crash scenarios and their relationship is studied.

For vehicle level simulation, the vehicle model of Toyota Yaris made available by Collision Safety and Analysis (CCSA) of George Mason University was used. The severity for head-on frontal crash is greater as compared to in-line collision. Moreover, most of the frontal collisions occur when driving on city roads, where the speed is limited to 50 kilometers per hour (e.g. Germany). Hence for vehicle level simulation, head-on collision crash scenarios were selected with both vehicles traveling at 50 kilometers per hour. Considering different loading conditions on CMS as discussed in section II-A, 13 different impact positions were selected (6 on driver side, 6 on passenger side and a central impact position). For each position, 11 relative angular cases (5 positive angles, 5 negative angles and a 0 degree angle) with a variation of 15 degrees between each case were chosen for simulation. Considering front curvature of the vehicles, collision at extreme impact position with angular cases is geometrically not possible and hence were not simulated. Based on these conditions, a total of 131 different scenarios were simulated. The results of these simulations, mainly the motion such as linear and angular velocities of vehicle during the crash is then given to the occupant level simulation. Since the driver is more prone to injuries, this study focuses on driver injuries in the occupant-level simulation. The occupant-level simulation includes restraint systems such as driver-airbag and seat-belt with pre-tensioner
Input: Pre-crash information
- Impact velocity of EGO-vehicle and opponent
- Position of first contact
- Relative approach angle
- Opponent type

Vehicle level Simulation

In-crash vehicle level responses
- Velocity response in lateral and longitudinal direction.
- Pitch rate
- Yaw rate
- Roll rate

Analysis and relating to Injury Severity Classes
- Good 4 points
- Adequate 3 points
- Marginal 2 points
- Poor 1 point
- Weak 0 point

Occupant responses (Injury Scales)
- Head Injury Criterion
- Neck Injury metrics
- Chest injury metrics

Occupant level Simulation

Figure 1. Methodology for data generation and analysis (vehicle level simulation blocks displays the sign conventions used for impact position and relative approach angle)

and retractor. In most of the European vehicles, frontal airbags are installed voluntarily by the manufacturers. We have chosen these restraint systems complying to the least possible configuration of restraint systems available for purchase in Europe. In our study, we activate seat belt retractor at 1 millisecond and is set to a maximum force of 3.25 kilo Newtons, while the front airbag is activated after 15 milliseconds and fully inflated at 45 milliseconds after T0. The restraint system activation parameters were the same for all the occupant-level simulations in order to compare the severity on the occupant body parts.

3. Results and discussion

Figure 2. Longitudinal and lateral velocity from vehicle level simulation.

Figure 3. Angular velocity (roll, pitch and yaw rates) from vehicle level simulation.

The results from vehicle level simulations vary with the position of impact and relative approach angle. The simulations with both impact position and relative approach angle near or equal to zero show very little increase in lateral velocity, yaw rate and roll rate. As the impact position or angle changes, the vehicle moves laterally along with angular motions. Fig. 2 and
Table 1. Parameters of curve fit for different impact positions

| Position  | Parameters of Gaussian fit | Goodness of fit |
|-----------|----------------------------|-----------------|
|           | Distance from center (mm)  | a              | b               | c               | R²  |
| P3        | 364                        | 0.43           | 727.20          | 11.38           | 0.97|
| P2        | 245                        | 0.29           | 362.70          | 45.20           | 0.98|
| P1        | 122                        | 0.14           | 341.20          | 33.44           | 0.97|
| P0        | 0                          | 0.00           | 335.90          | 15.75           | 0.98|
| -P1       | -122                       | -0.14          | 324.40          | 12.32           | 0.95|
| -P2       | -245                       | -0.29          | 326.00          | 6.33            | 0.96|
| -P3       | -364                       | -0.43          | 224.50          | 5.14            | 0.94|
| -P4       | -485                       | -0.57          | 196.30          | -9.95           | 0.89|

Table 2. Coefficients for equation of Gaussian curve parameters

| Coefficient number | Parameter of Gaussian equation |
|--------------------|--------------------------------|
| i                  | a     | b     | c     |
| 1                  | 5605  | -1422 | -458.4 |
| 2                  | 8350  | -1665 | -1383  |
| 3                  | 2798  | -158.8| -550.3 |
| 4                  | -788  | 256.1 | 192.6  |
| 5                  | -139.5| 86    | 75.2   |
| 6                  | 344.3 | 17    | 52.9   |

Fig. 3 show the vehicle responses during crash from one of the crash scenario simulated (impact position at 485 mm from the center at an angle of -45 degree).

The upper-body (head, chest and neck) of a human is more sensitive and prone to fatal injuries than the lower-body (femur, tibia, knee and feet). Therefore, we are focusing our study on the behavior of upper-body injuries with different crash scenarios. The following section discusses the results from occupant level simulation.

3.1. Head

The first criterion considered for head injury is \( A - 3ms \). As per the EuroNCAP norms, a hard contact of head is defined by a value higher than or equal to 80 g. Fig. 4 shows a contour plot of this criterion with different positions and angles. It can be observed that a hard contact occurs at extreme positions (normalized position above 0.57) and angles as shown by red region in the contour plot. There are two cases for a hard contact. The first case consists of the crash scenarios causing the driver to move diagonally towards the A-pillar and side structures. In this case, fatal injuries are highly probable due to direct contact of head with the structures. The other case includes the driver diagonal movement towards the airbag. The driver’s head in this case contacts with airbag at an offset position (out-of-position) and does not have the required stiffness to stop further movement of the head. Therefore after some time, the head comes in contact with steering wheel through airbag cloth causing a hard impact.

Figure 4. \( A - 3ms \) contour plot (color map of plot is as per EuroNCAP injury rating scheme [8]).

\[ HIC - 15 \] is the second criterion considered. The value of this criterion for a particular impact position is high at angles near zero and reduces with increase in the angle (both positive
and negative increment) and can be represented by a Gaussian equation

\[ HIC = a \cdot e^{-\left(\frac{\alpha}{b} - c\right)^2} \]  

(1)

where \(a\), \(b\) and \(c\) are the real arbitrary parameters of the Gaussian curve and \(\alpha\) is the relative approach angle in degrees. Hence, to analyze the behavior of this criterion, a number of Gaussian curves with each curve corresponding to a particular position was fitted. Fig. 5 shows the fitted curve for a particular impact position. The crash scenarios with extreme impact positions include large number of data points which fall in the first case of hard contact. Hence, the data points for these impact positions were not considered for curve fitting analysis. For the impact positions, where very few data points represent hard contact were treated as outliers and hence neglected during the curve-fitting process. Table 1 displays the results from the Gaussian curve fitting process for different impact positions. The behavior of these parameters obtained was approximated by polynomial equations as given below

\[ a = d_1 \cdot P^5 + d_2 \cdot P^4 + d_3 \cdot P^3 + d_4 \cdot P^2 + d_5 \cdot P + d_6 \]  

(2)

\[ b = e_1 \cdot P^5 + e_2 \cdot P^4 + e_3 \cdot P^3 + e_4 \cdot P^2 + e_5 \cdot P + e_6 \]  

(3)

\[ c = f_1 \cdot P^5 + f_2 \cdot P^4 + f_3 \cdot P^3 + f_4 \cdot P^2 + f_5 \cdot P + f_6 \]  

(4)

where \(d_i\), \(e_i\) and \(f_i\) are the coefficients of the polynomial equation and \(P\) is the normalized position of impact. Substituting the above polynomial equations in (4), we get

\[ HIC = \left( d_1 \cdot P^5 + d_2 \cdot P^4 + d_3 \cdot P^3 + d_4 \cdot P^2 + d_5 \cdot P + d_6 \right) \cdot e^{-\left(\frac{a - e_1 \cdot P^5 + e_2 \cdot P^4 + e_3 \cdot P^3 + e_4 \cdot P^2 + e_5 \cdot P + e_6}{f_1 \cdot P^5 + f_2 \cdot P^4 + f_3 \cdot P^3 + f_4 \cdot P^2 + f_5 \cdot P + f_6}\right)^2} \]

(5)

This equation represents the surface of \(HIC - 15\) for different positions and angle, which is valid for limits \(P > -0.57\) to \(P < 0.43\). Table 2 gives the coefficients of the polynomial equations obtained by curve fitting. \(HIC - 15\) for positions beyond the limits of the above equation is very high due to the direct contact of the occupant with side-structures or improper position of contact with airbag (out-of-position). This highlights the need of other airbags such as curtain airbag or torso airbag to reduce the probability of fatal injuries to the occupant.

3.2. Neck

NCAP-protocol specifies time-based cumulative limits for neck forces. In our study for all the crash scenarios, the neck forces were in the safe region (green) up to time corresponding to the end of the cumulative limits (45 milliseconds for shear force and 60 milliseconds for tension) [9, 8]. Beyond this time, the neck forces can only be classified as good (green region: when the force is below 1.1 kilo-newtons) or poor (red region: when the force is equal to or above 1.1 kilo Newtons). Fig. 6 shows the contour plot for neck shear forces. It can be observed that as the normalized overlap position increases along with the relative approach angle, the neck force changes from good region to fatal (poor) region. The primary cause for this transition is the direction of resultant velocities acting on occupant body. Due to smaller overlaps and higher approach angles, the lateral velocity, yaw, pitch and roll components increase in magnitude and cause the occupant dummy to move in a direction that reduces the effective interception with airbags. In some cases, this leads to a hard contact with internal car structure and results in high neck forces. However, in some cases it causes the occupant body to change the direction of motion abruptly and due to inertial effect between head and the body, the forces on neck increase. The neck tension force and extension moment show similar behavior as that of the neck shear force.
Chest compression during a crash mainly depends on the effective impact on the vehicle and the mechanics of the restraint systems relative to motion of the occupant. This behavior can be observed in the contour plot (Fig. 7). There are two cases which cause an incremental transition in the injury values based on chest compression.

Case-1: This case consists of crash scenarios with extreme negative positions and negative approach angles (Region-1 in Fig. 7). The increase in chest compression is caused due to the relative dynamics of vehicle and occupant during the crash. The lateral velocity and rotational motion induced due to the combination of positions and angles of vehicles during crash, cause the occupant to move in directions that would not effectively intercept the inflated airbag. Hence the damping efficiency is reduced, and the occupant moves a larger distance before beginning the rebound phase. This causes the seat belt to provide higher reaction forces onto the chest of the occupant, which increases the chest compression.

Case-2: This case consists of crash scenarios with positive positions and relative approach angle near zero degree (Region-2 in Fig. 7). For these crash scenarios, we observe that the effective energy transferred during the crash is maximum. Hence the occupant velocity would be higher. The restraint systems have higher forces to dampen, to decelerate the occupant. As a result, the overall deflection of the chest increases.

4. Conclusion
Following points can be concluded based on the analysis of the results carried out in section IV.

- In crash scenarios with extreme positive positions and positive relative approach angle, the occupant’s head and neck have a higher risk of fatal injuries. For these crash scenarios, activating side airbags (if it’s installed in the vehicle) would reduce the occupant injuries. A safest possible boundary line can be defined based on the contour plot for both head and neck injury criterion ($A - 3ms$ and neck forces). An arc representing the boundary of the fatal region can be used to predict the possibility of a fatal crash based on the angle and position of crash (shown by a dashed arc in Fig. 4 and Fig. 6). Based on the simulations conducted in the scope of this research, this boundary arc can be represented by following equation

$$\left(\alpha - 85.35\right)^2 + \left(P - 7283.02\right)^2 = 7283.1^2$$

This arc would help to distinguish between the crash scenarios which require activation of frontal airbags only and those which require activation of side curtain airbag and torso airbag additionally.

- For the crash scenarios with proper contact with airbag, a methodology to predict the HIC-15 values based on the position of impact and relative approach angle is formulated. This
methodology would help in predicting the head injuries in a particular crash scenario before the crash. 

- It can be observed that the higher risk region is developing in the extreme negative positions and negative angles for chest compression. A prior understanding of the transitional behaviour can be used to trigger the torso airbags (if equipped) to restrict the motion of the occupant and hence mitigate the possibilities of higher chest deflection.

5. Future work
In this paper, we have analyzed the different frontal head-on crash scenarios with both the vehicles traveling at 50 kilometers per hour. The study can be extended to different velocities and opponents to get information about the occupant injuries by these parameters. This information can be used to build an occupant injury prediction model comprising of different models for each criterion. This prediction can help in deciding which combination of the restraint systems to be activated and at what times. These steps are planned as future research work.

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