Analysis of female occupant injuries from crash test data for Full Frontal Crash Tests conducted on Indian Passenger Vehicles

Divyan Jaju, Venuram R.R, Dileep Kulkarni, Rahul Mahajan

Abstract Several studies have highlighted that female occupants are at greater odds of being seriously injured in frontal car crashes as compared to male occupants. To analyse the injury to any occupant, certain Anthropometric Test Devices (ATD's) or crash test dummies are utilized based on the crash configuration. The Hybrid III 5th percentile female dummy has been the predominant tool to assess the injuries to female occupants in Frontal Crash configurations. This study analyses and compares the dummy injury metrics of the 5th percentile crash test dummy placed in the Front Passenger seating position. It then compared the injuries recorded in 12 vehicles, to the critical body regions of head, neck and chest of the female dummy seated in the front passenger seating position in a Full Width Frontal Impact Test conducted at 50 kph. India has introduced this Full Width Frontal Impact test christened as AIS 201 (equivalent to UN R137) test. The results highlight that the Head injury recorded by the dummy exceed the EuroNCAP Lower Performance Limit (LPL) in only two cars. All other injury parameters remain below the LPL highlighting that the restraints on Indian passenger vehicles are observed to be optimised for the 5th percentile female dummy. In addition, the effect of vehicle mass on the dummy injuries was also analysed highlighting that heavier vehicles show a better head, neck and chest performance.

Keywords Hybrid III 5th percentile dummy, UN R137, AIS 201, Front Passenger, Critical Body Region

I. INTRODUCTION

Vehicle safety systems have improved over the past few decades in multiple aspects. However, even with these improvements, several studies have shown that females and males are not equally protected. A 2019 study conducted by University of Virginia found that the odds for a belted female driver to sustain severe injuries were 47% higher than those for a belt-restrained male [1]. In its 2026 study, NHTSA [2] stated that women are at 46% higher injury risk in frontal crashes than men. To improve this scenario, various regulations and worldwide NCAP's have included assessments with the 5th percentile female dummy to fine-tune the vehicle restraints to ensure an overall protection to both male and female occupants.

The Hybrid-III 5th percentile female dummy was introduced in 1988 for frontal crash evaluations. This was followed by the introduction of the SID-IIs (Small Side Impact Dummy) in 1995 for side crash evaluations. Recently, the THOR-5F has been developed as an advanced crash test dummy with improved biofidelity as compared to the Hybrid III 5th female dummy. When mapped on the basis of a Biofidelity Ranking System (BRS) score, the THOR-05F scores 1.27 while the Hybrid-III 5th percentile dummy scores 2.91 [3]. The smaller the BRS score, the more biofidelic is the dummy response. THOR-5F will be replacing the Hybrid-III 5th percentile female dummy in frontal crash evaluations in a phased transition. Similarly, the WorldSID-5F is under development as an advanced crash test dummy for side crash evaluations.

Globally, different NCAP's have preceded the crash test regulations in adoption of the 5th percentile dummy in their assessment paradigms. Female occupant injury analysis using the Hybrid III 5th female dummy was introduced in the full-width frontal impact test of US NCAP in 1998. This was followed by

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NHTSA, introducing the Hybrid III 5th female dummy assessments under the FMVSS 208 frontal crash testing requirements in 2000. EuroNCAP and Japan NCAP adopted the 5th percentile dummy in their assessment regimes in the early 2000's. This was later followed by other NCAPs, such as China NCAP in 2012, Korean NCAP in 2013, ANCAP in 2018, etc.

The United Nations Economic Commission for Europe (UNECE) adopted the 5th percentile female dummy under UN Regulation No. 137 in November 2015 and it was put into force in June 2016. In March 2025, India published its own regulation, AIS 201, which is technically aligned to UN R137. This was done with the objective of maintaining and evaluating the safety offered by Indian passenger vehicles to female occupants seated in the front passenger seating position. Additionally, the second phase of the Bharat NCAP has also included the 5th percentile female dummy evaluations under its scheme of assessments [4].

This study analysed a dataset of 12 vehicle models that have undergone the frontal full-width impact tests conducted per the AIS 201 at ARAI between 2022 and 2025. The injury metrics of the female crash test dummy recorded in these tests, i.e. the head (Peak head acceleration, Head Performance Criteria), neck (Neck Shear, Tension and Extension) and chest (Chest Compression) were compared against the Euro NCAP specified limits [5] for the 5th percentile female dummy. The lower extremity injury for female's is observed when seated in the driver's seating position. This is owing to the presence of pedals on the driver side [6]. Contrarily, lower leg injuries are much less for the occupant in the front passenger seat. Thus, the lower leg injury metrics are neglected and upper body regions are considered in this study for the female dummy placed in the front passenger seating position.

II. METHODS

Experimental Testing

All of the assessed 12 vehicles were crash-tested at the Passive Safety Laboratory of ARAI. The test procedures, along with the dummy instrumentation, configuration and dummy setup in the vehicle were carried out per the Automotive Industry Standard (AIS) 201 [7]. A hybrid-III male dummy (50th percentile) occupies the driver seat and a Hybrid-III female dummy (5th percentile) occupies the front passenger seat in this test configuration. The test vehicle is then impacted at 50 kmph onto a rigid barrier.

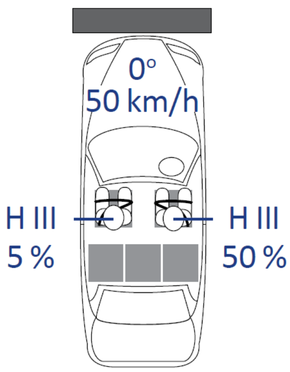

Fig. 1. Test and dummy configuration of the AIS 201 test.

The AIS 201 test requires measurement of the following parameters for the female dummy placed in the front passenger seating position:

a) Peak Head Acceleration;
b) Resultant Head acceleration;
c) Head Injury Criterion (HIC_{36});
d) Neck Shear Force;
e) Neck Tensile Force;
f) Neck Extension;
g) Thorax Compression (Chest Compression);
h) Viscous Criterion;
i) Femur Force Criterion.

For the head region, we consider three metrics - peak head acceleration, resultant head acceleration and Head Injury criterion. Peak Acceleration is the highest value recorded by the accelerometer in the dummy head while the resultant head acceleration is the value that is recorded in exceedance for cumulative duration of 3ms. HIC is the biomechanical metric developed to predict probability of severe head trauma by Mertz et al. The number following the HIC is the calculated acceleration over a maximum time window of that number of milliseconds, i.e HIC_{15} is maximum HIC calculated over a period of 15 ms. From these parameters, we considered the comparison of the critical body regions, i.e. the Head, Neck and the Chest of the dummy, in the frontal impact test. Data from these critical body regions was computed and compared for each of the crash tests.

For the Head region, Head Performance Criterion, Head Cumulative Acceleration and Resultant head Acceleration were mapped. The considered test configuration is a regulatory one and will thus be implemented across all Indian passenger vehicles. The idea of the study is to highlight the readiness of Indian passenger vehicles in ensuring female occupant protection even before it is assessed by an NCAP / Regulation.

Rationale for Injury Criteria Metrics

AIS-201 specifies measurement of Head Performance Criterion (commonly measured as HIC over 36ms time window). However, most of the NCAPs measure the head injury metric over a 15ms window, i.e. HIC_{15} with an upper limit of 700. In a study conducted on HIC levels, it was inferred that HIC_{15} upper limit of 700 corresponds to 50% probability of AIS3+ injuries to head region [8]. Another injury metric measured for head region is the Peak and Resultant Head Acceleration, which correlates risks of head injuries such as concussions, contusions and other brain injuries.

Neck injuries are measured and mapped using measurement of neck forces and extension. The plots for these injury metrics were mapped to understand the variation and distribution of neck injuries.
For chest, deflection parameter was analyzed, as high deflection caused by restraint system and deploying airbag may lead to high probability for rib fractures and puncture wounds in the chest.

Comparative Metrics

Injury parameters recorded from the female dummies undergoing the AIS 201 test were compared against the Euro NCAP adult occupant protection limits for a female dummy [5]. The limits are specified in Table I. The Higher and Lower performance limits are linked to the scores assigned in the NCAP tests, injury values beyond the HPL are assigned 4 points while those beyond the LPL are assigned 0 points. Regulatory tests have capping limits that are beyond the lower performance limits of body regions and it is mandatory for the dummy body regions to have injuries below these capping limits. This study compares the injury recorded by the female dummies in the AIS 201 test configuration and compares it with the EuroNCAP specified HPL and LPL. EuroNCAP, until 2025, conducted a similar 50 kph Full Width Rigid Barrier Frontal Impact test but with a female dummy placed in the driver, front passenger and rear passenger seating position.

TABLE I

Hybrid-III 5th percentile dummy EuroNCAP Performance Limits

	Peak Head Acc (g)	**Head Resultant (g)**	**HIC 15**	**Neck Shear (kN)**	**Neck Tension (kN)**	**Neck Extension (Nm)**	**Chest Deflection (mm)**	**Seat belt Load (kN)**
Higher Performance Limit	72	-	500	1.2	1.7	36	18	-
Lower Performance Limit	80	80	700	2.0	2.6	49	42	6.0
AIS 201 Capping Limits	-	80	1000 (HIC36)	2.7	2.9	57	34	-

III. RESULTS

Twelve vehicle models were tested as per AIS 201 and airbag interaction with the 5th percentile dummy for some of these vehicles is shown in Fig. 2.

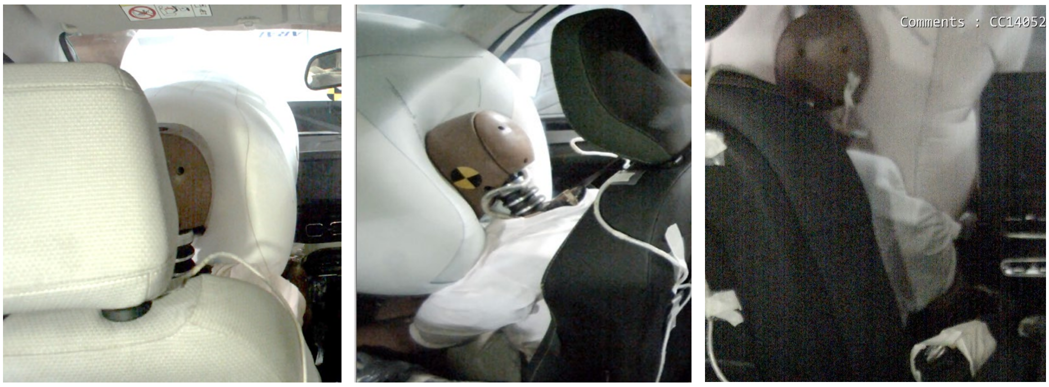

Fig. 2. Images showing impact of the female dummy in some of the vehicles tested.

The graphs of respective injury parameters for the head, neck and chest region of the female dummy were plotted with the HPL and LPL as specified in Table 1 marked for each of these parameters.

For the head region, the peak head acceleration, the resultant head acceleration and the HIC-15 were plotted as shown in the figure 3, figure 4 and figure 5 below. The plots indicate that for 10 out of the 12 vehicles, the head injury values are below the HPL threshold levels. For the other 02 vehicles, these values exceed even the Lower Performance Limits.

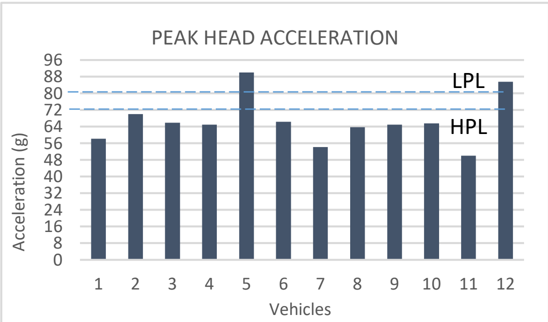

Fig.3. Peak head acceleration graph.

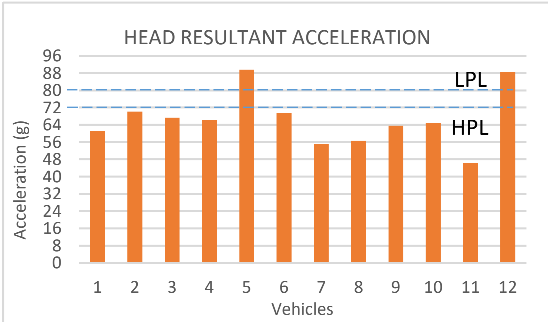

Fig.4. Head resultant acceleration graph.

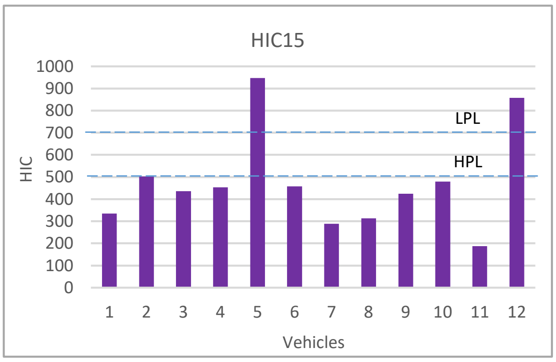

Fig.5. HIC_{15} graph.

During the interaction of the dummy head with the passenger airbag, the dummy neck is loaded for forces and flexion and extension moments. The typical representation of the same is as shown in Fig. 6.

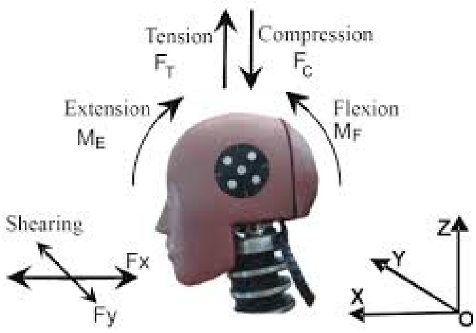

Fig. 6. Neck metrics of the female dummy in Frontal Crashes.

Comparative graphs for the measured injury values against the HPL and LPL is shown below. The vehicles that breached the Head LPL also breach the HPL for Neck Extension's HPL.

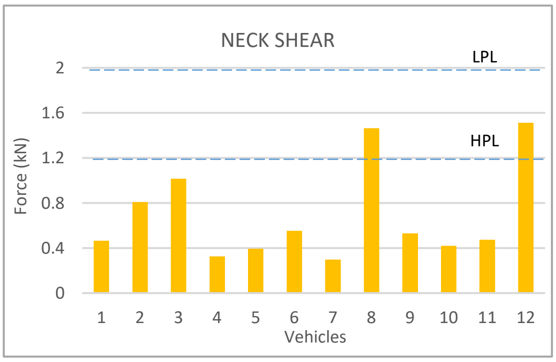

Fig.7. Neck Shear Force graph.

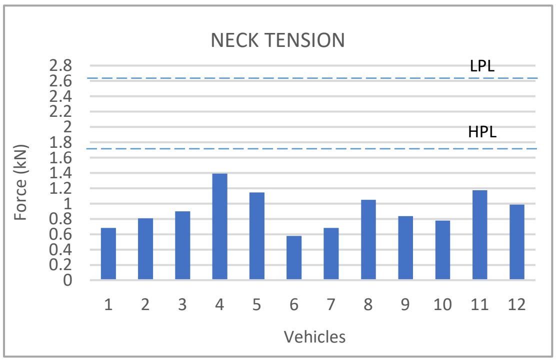

Fig.8. Neck Tension Force graph.

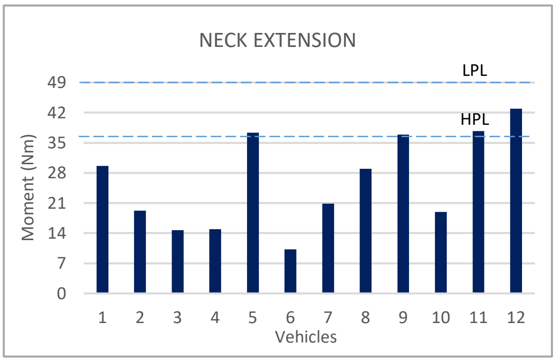

Fig.9. Neck Extension graph.

The chest injury metrics are measured in terms of deflection recorded by the dummy's chest potentiometer and the seat belt force exerted by the dummy's chest. ICE vehicle dynamics usually result in chest deflections that exceed the HPL limits for NCAP's for both male and female dummies. The same is observed in the current case.

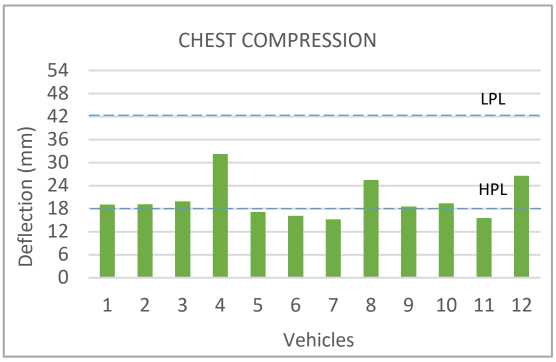

Fig.10. Chest Compression graph.

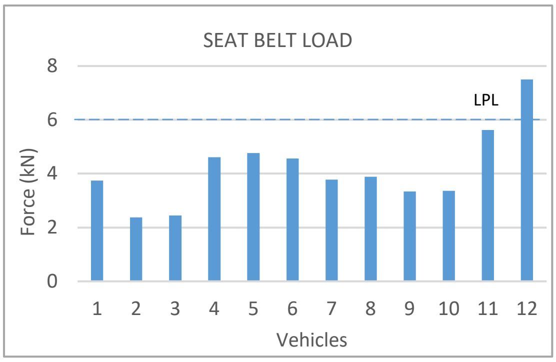

Fig.11. Seat-belt load graph.

The plot of each of the injury parameters against the vehicle kerb mass were plotted in the form of scatter charts in order to visualise the trend. Owing to the limited data size, the linear regression for the trend is not plotted. Further observations from the kerb mass variation has been discussed in section IV.

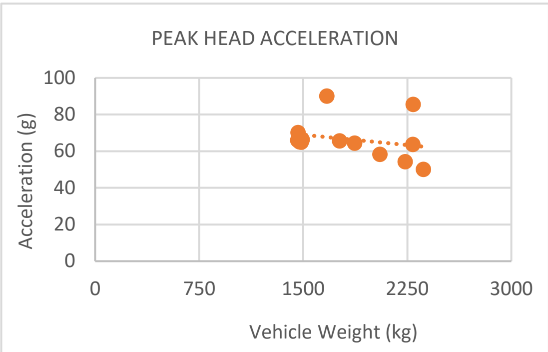

Fig.12. Peak Head Acceleration graph.

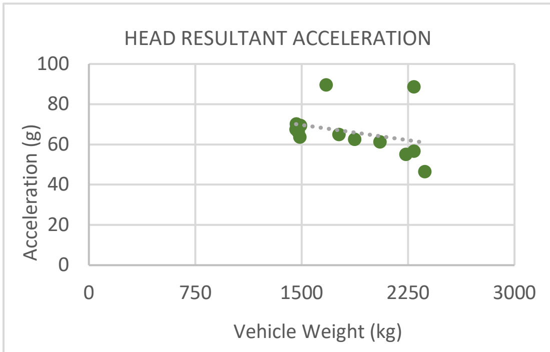

Fig.13. Head Resultant Acceleration graph.

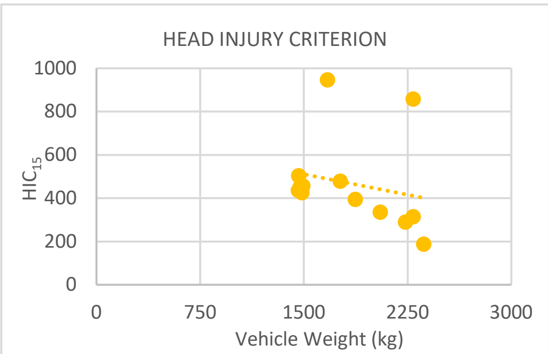

Fig.14. Head Injury Criterion (HIC_{15}) graph.

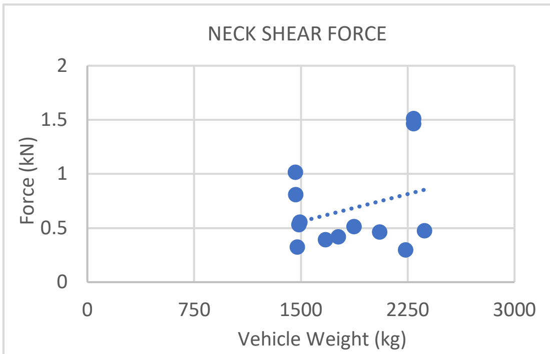

Fig.15. Neck Shear Force graph.

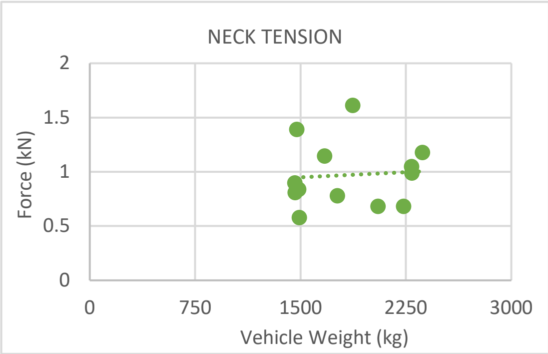

Fig.16. Neck Tension graph.

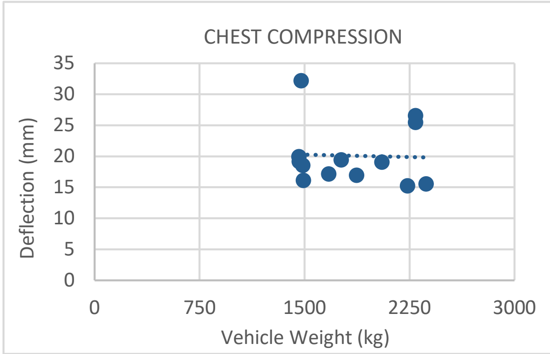

Fig.17. Chest Compression graph.

IV. DISCUSSION

For the head injury metrics, an injury value exceeding the HPL was observed for two vehicles only. The metric exceeded the EuroNCAP LPL. However, the regulatory limit of HIC_{36} was met by both of these vehicles. With the exception of these two, all other vehicles performed better than the EuroNCAP HPL. The mean value of HIC_{15} for these vehicles is 468. The standard deviation of the head injury metric from their mean values is 10.931 for the Peak Head Acceleration, 11.978 for the Resultant Head A3ms and 212.77 for HIC_{15}. The increase in vehicle weight is attributed to the improvement in the vehicle category (i.e. overall dimensions) being assessed. Thus, for larger vehicles (vehicles with higher weight), more space is available for restraining the movement of the front passenger and therefore this can be achieved more effectively. A decreasing trend in the HIC_{15} and Head Acceleration with the increasing vehicle weight is observed from figures 10, 11 and 12. This is attributed to the factor that heavier vehicles tend to have slower deceleration, and thus explaining the lower HIC values and Acceleration. It can be noted that this data corresponded to the real-world conditions. Hence, as the vehicle weight increases, the Head injury metrics, Peak Head Acceleration, Resultant Head Acceleration and HIC_{15}, all follow a decreasing trend.

For the neck injury metric, neck shear exceeds the EuroNCAP HPL for two vehicles but is lower than the LPL. For one of the vehicles, even though it was higher in weight and dimensions, the airbag performance was observed to be not fine-tuned for the 5th percentile dummy as the dummy recorded a HIC_{15} and Head Acceleration beyond the EuroNCAP HPL. For the other vehicle, the minor increase in shear force recorded was above the HPL by 0.03 kN and therefore can be treated as a test specific variation. The mean value of the shear forces is 0.69 kN and the standard deviation is 0.4095.

The neck tension for the dummy remained below HPL for all of the vehicles. The mean value of the tension forces is 0.92 kN and the standard deviation from the mean values is 0.2991. The neck extension remained near or below the HPL for the dummies highlighting the fine tuning achieved for the neck performance due to airbag interactions. The mean value for the neck extension is 26 Nm with a standard deviation of 10.926.

For the chest injury metric, the chest deflection exceeds the HPL of 18 mm for about eight vehicles as seen in Fig. 10. Out of these, the chest deflection marginally crosses the 18 mm limit (i.e. between 18 mm and 19 mm) for five vehicles. For the remaining three vehicles, the chest deflection value is in the range of 25-32 mm. For two of the vehicles, the higher chest deflection is the result of airbag loading which was also verified from its neck injury traces. For the remaining vehicle, similar to the head and neck injury metric, the chest deflection also exceeds the HPL highlighting scope for fine tuning of its restraints. The mean value of the chest deflection is 20.36 mm and the standard deviation is 5.113.

For the seat-belt loading of the dummy, the vehicle for which the injury metrics exceeded the Euro NCAP HPL has a dummy seat-belt load greater than the specified limit of 6 kN. For all other vehicles, the seat-belt loading is less than 6 kN, with a mean value of 4.2 kN and a standard deviation of 1.409.

Increasing vehicle weight relates to increased vehicle dimensions. This improves the available crush space for the occupants and supports the possibility to better design the restraints on the vehicles. This in turn helps to reduce occupant injuries. A study by Brumbelow.L indicated that the females are preferring to drive a smaller vehicle, as compared to male, putting them in imminent danger [9]. Thus, increase in vehicle weight supports reduction in occupant injuries and the same can be observed for each of the injury parameter where there is reduction in the injury value as the vehicle kerb weight increases. An interesting observation is that in the case of Neck shear force, it is observed to follow a rising trend, with increase in vehicle weight, even as the other neck metrics and Head Acceleration values are decreasing. This is because of two heavy vehicles recording high shear forces as seen in figure 15 and will be investigated for the probable cause.

It can thus be inferred that most of the passenger vehicle models assessed in this study have their restraint systems designed to meet the HPL set down for 5th percentile dummies in NCAPs. This study also focussed on the injuries recorded by the female dummy placed on the front passenger seating position as defined in AIS 201. Indian accident statistics also highlight female occupant presence occurring most frequently in the front passenger and rear passenger seating positions, as compared to the driver seating position. NHTSA [2] has highlighted female occupants have a 62% higher risk of lower extremity injuries in frontal crashes compared to male occupants. For females sitting in the driver's seat, frontal crashes also pose a higher injury risk due to intruding pedals and closer proximity to the steering wheel.

Therefore, as an extension to this study and with an aim of further improving safety for the female occupant, injuries recorded by the 5th percentile female dummy seated in the driver's seat in a frontal crash test should also be mapped. Additionally, citing the improved BRS score of the THOR-05F dummy as compared to the Hybrid-III 5th percentile female dummy, the THOR dummy can be considered as an alternate to the Hybrid-III dummy to study the effects of the restraints of the same vehicle on the THOR dummy. In a study conducted by Mathew L. Brumbelow, he concluded that female drivers initially show upto 75% higher fatality odds, but this difference reduces to near unity after controlling for vehicle mass, type and age [9]. Considering this, and with availability of tools like the HBM's, further studies can include assessments of 50th percentile female dummy in virtual environments.

The limitation of this study is the data size of the assessed vehicles, as not all vehicle models in India have undergone the Full Width Frontal Impact test with a female dummy. Plotting linear regression of the trend lines for the available dataset of comparison of vehicle weights with injury parameters indicated a R^2 value lower than 0.1. A much larger dataset could help to establish a stronger mathematical function for identifying dummy performance against the crash load case and could be considered for future studies. This study shows that, India is on a clear path to demand compliance requirements to enhance protection for female occupants through future regulatory and NCAP mechanisms.

V. CONCLUSION

The comparative analysis of the tested vehicles highlights that many passenger vehicle manufacturers present in India have already aligned their restraint system aligned to female occupant protection showing their voluntary commitment to advanced safety requirement. The injury parameters measured for assessing injuries to the head, neck and chest region of the female dummies highlights that out of the 12 vehicles assessed in the study (from different passenger vehicle manufacturers in India), non-optimisation of restraints for 5th percentile dummy was observed on only one of the assessed vehicles while minor optimization for two vehicles would be all that was necessary to achieve better overall performance.

VI. ABBREVIATIONS

AIS	:	Automotive Industry Standard
NCAP	:	New Car Assessment Program
ANCAP	:	Australasian New Car Assessment Program
BNCAP	:	Bharat New Car Assessment Program
BRS	:	Biofidelity Ranking System
FMVSS	:	Federal Motor Vehicle Safety Standards
HBM	:	Human Body Models
HIC	:	Head Injury Criterion
HPL	:	Higher Performance Limit
LPL	:	Lower Performance Limit
NHTSA	:	National Highway Traffic Safety Administration
UNECE	:	United Nations Economic Commission for Europe

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