Factors Influencing Submarining in Frontal Crashes for Automated Vehicle Occupants at Varying Seatback Angles

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I. INTRODUCTION

An occupant is said to be submarined in the seat when the lap belt moves over the Anterior Superior Iliac Spines (ASIS) and loads the abdomen. Submarining increases the risk of abdominal injuries due to the lap belt loading of abdominal organs, which is one of the concerns for automated vehicles with unconventional seating. This makes it important to study the various factors affecting submarining to better understand the mechanism and design better safety systems to prevent submarining. Previous experimental [1–2] and computational studies [3–4] have investigated various factors that influence submarining, including occupant variation in body shapes and sizes, vehicle and seat parameters (knee bolster, seatback angle, seat cushion angle, etc.), and delta-V (ΔV). Most of these studies have focused on higher ΔV (56 km/h) and used limited tests or simulations to study submarining. The objective of this study was to take a holistic simulation-based approach to better understand the effect of seatback angle, ΔV, crash type, pelvis angle, and inboard and outboard lap belt angle on the submarining of driver and rear-seat passengers using a full-factorial design of experiments (DOE).

II. METHODS

The Global Human Body Models Consortium (GHBMC) simplified average male occupant model with a modular brain (M50-OS+B) was used to represent both the driver and rear-seat passenger in a simplified generic vehicle model (Fig. 1). The setup was used to simulate four frontal crash types—Left-Offset (LO), Left-Offset Oblique (LOO), Front-to-Left-Offset Oblique (FLOO), and Full-Frontal (FF)—at three impact severities (ΔV: 25, 35, and 45 km/h). Four seatback angles (13°, 23°, 45°, and 57.5° about vertical) were used for both occupants. A total of 192 simulations were carried out as part of a full-factorial design of experiments (DOE) using the Ansys LS-DYNA (Ansys, Inc. R10.2.0). This is a subset of a larger study, and more details about the simulation setup are mentioned in the previous study [5]. The pelvis angle, inboard, and outboard lap belt angle were measured at the start of the crash pulse (Fig. 2). All nodes from the lower edge of the lap belt and right and left ASIS nodes were tracked for the duration of the crash to detect submarining. If the lap belt went over and beyond one of the ASIS nodes, the simulation was marked as unilateral submarining (1), both ASIS nodes then bilateral submarining (2), and if none of the ASIS nodes, then no submarining (0). Pearson correlation coefficients were calculated to assess collinearity among the independent variables, including seatback angle, ΔV, inboard lap belt angle, outboard lap belt angle, and pelvis angle, which were independent variables. Additionally, ordinal logistic regression analysis was performed to evaluate the effect of these independent variables on the submarining as the outcome variable.

III. INITIAL FINDINGS

Only one simulation out of 192 was terminated with errors and was removed from the analysis. Given the relatively low number of positive cases of submarining within the driver set (n =5 out of 191), this study was only focused on the rear passenger. For the rear passenger, 56 simulations with no submarining, 76 with unilateral submarining, and 59 with bilateral submarining were observed. An exemplary plot of submarining detection is shown in Fig. 2. The distribution of submarining cases by ΔV and seatback angle is shown in Fig. 3. The submarining count increased with ΔV and seatback angle. The seatback angle was highly correlated with the pelvis angle ($r=0.998$, $p<0.0001$), inboard lap belt angle ($r=0.937$, $p<0.0001$), and outboard lap belt angle ($r=0.989$, $p<0.0001$). Based on Nagelkerke's R^2 values, seatback angle, ΔV, and either of the lap belt angles were able to explain 88%

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of the variance in the submarining outcome for the passenger. The highest R^2 observed in the univariate analysis was 0.71 for seatback angle. Although the R^2 value (0.91) was higher if we considered the crash type along with the other variables, it was decided to remove the crash type from the analysis as the model was not stable with wide confidence intervals, and its contribution was just 3% in explaining the submarining outcome. The results of regression analysis in terms of odds ratio and 95% Wald confidence interval are plotted in Fig. 4 and Fig. 5. As per unit increase in the seatback angle, the odds of occupant submarining were 1.7 times higher when the inboard lap belt angle was adjusted, and 2.4 times higher when outboard lap belt angle was adjusted in the analysis along with ΔV. Similarly, as ΔV increased, the odds of occupant submarining were 1.3 times higher. Both inboard (OR=0.62) and outboard (OR=0.14) lap belt angles had a protective effect on submarining.

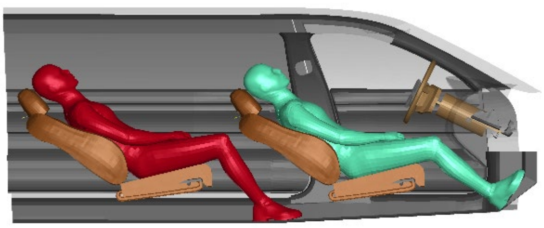

Fig. 1. Simulation setup with passenger and driver seatback angle of 57.5°.

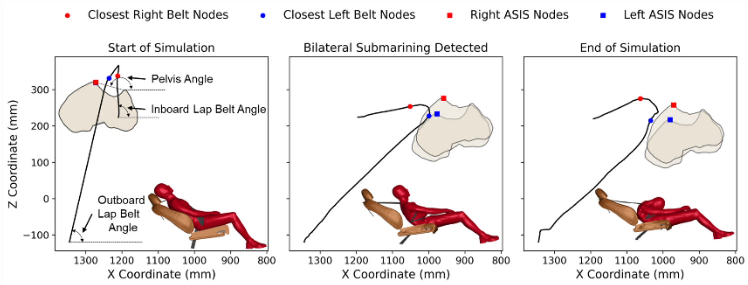

Fig. 2. Bilateral submarining detection for the passenger with seatback angle 57.5° in full-frontal crash at 45 km/h ΔV.

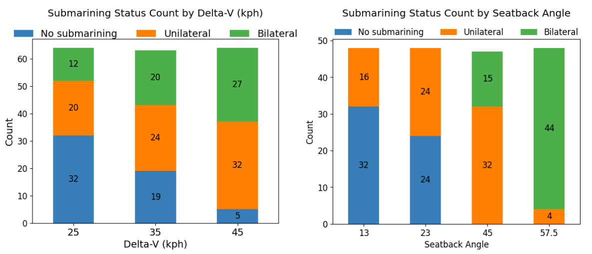

Fig. 3. Submarining status count by ΔV and seatback angle. No submarining cases are in blue, unilateral cases are in orange, and bilateral cases are in green.

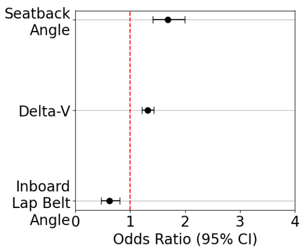

Fig. 4. Odds ratios (OR) with 95% Wald Confidence Limits for seatback angle, ΔV, and inboard lap belt angle.

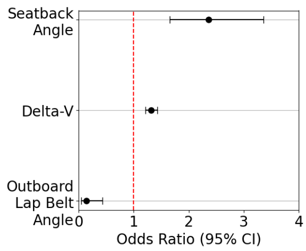

Fig. 5. Odds ratios (OR) with 95% Wald Confidence Limits for seatback angle, ΔV, and outboard lap belt angle.

IV. DISCUSSION

There were 135 submarining cases observed for the passenger compared to just 5 cases for the driver due to the absence of a knee bolster or any other structure that would restrict the passenger's forward motion. Similar observations have been made in the past by other researchers regarding the presence of knee bolsters [3]. All the results presented in this study apply to rear-seat passengers as the driver data was excluded from the analysis due to lower submarining cases. Out of all the variables analysed for the rear passenger, seatback angle explains a greater proportion of the variance in submarining (Nagelkerke's R^2=0.71), followed by outboard lap belt angle (R^2=0.67), inboard lap belt angle (R^2=0.56), and ΔV (R^2=0.13). It was also observed that the inboard and outboard lap belt angles had a protective effect against submarining, suggesting a higher belt angle will help reduce the likelihood of submarining, a finding also reported by other researchers [4–6]. A key limitation of this study is the use of a single model representing an average male occupant and a single seat model. Future research incorporating a range of anthropometries and seat models will be important for understanding the impact of these parameters on submarining risk across the population. To the author's knowledge, this was the first study to examine the effects of various parameters on both driver and rear-seat passenger simultaneously using a DOE that varied ΔV (25-45 km/h) and frontal crash types (LO, LOO, FLOO, and FF).

V. ACKNOWLEDGEMENTS AND DISCLOSURE STATEMENT

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VI. REFERENCES

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