

## **Analysis of Pregnant Occupant Crash Exposure and the Potential Effectiveness of Four-Point Seatbelts in Far Side Crashes**

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### **ABSTRACT**

The purpose of this paper is to present the crash exposure patterns of pregnant occupants and to evaluate the effectiveness of restraint systems, including four-point seatbelts, in far side crashes. The NASS CDS database revealed that 53.0 % of pregnant occupants are exposed to frontal crashes while 13.5 % are exposed to far side impacts. Given that far side crashes were the second leading crash mode after frontal impacts, a previously validated MADYMO computer model of a 30 week pregnant occupant was utilized to investigate pregnant occupant biomechanics in far side crashes. Three impact speeds (5, 15, and 25 mph) were simulated with four restraint conditions: unbelted, lap-belt only, three-point belt, and a four-point belt. Direct abdominal contact from the shoulder strap of the three-point or four-point belt caused uterine-placental strain in contrast to the inertial loading induced strain in the lap-belt and unbelted cases. Overall, the three-point and four-point belt systems provide superior restraint effectiveness for the pregnant occupant compared to the lap-belt and no restraint cases. The four-point resulted in slightly better performance than the three-point belt by reducing the fetal injury risk and occupant excursion.

Automobile crashes are the largest single cause of death for pregnant females and the leading cause of traumatic fetal injury mortality in the United States (Attico, 1986; Weiss, 2002). Each year, 160 pregnant women are killed in motor-vehicle crashes (MVCs) and an additional 800 to 3200 fetuses are killed when the mother survives in the United States (Klinich, 1999a; Klinich, 1999b). Unfortunately, fetal injury in motor vehicle crashes is difficult to predict due to the fact that real world crash data is limited and cadaver studies are not feasible.

A pregnant anthropometric test dummy (ATD) has been developed at the University of Michigan Transportation Research Institute (Rupp, 2001). From that research it was determined that the most common cause of fetal death from motor vehicle accidents is placental abruption, which is the premature separation of the placenta from the uterus. The pregnant dummy (MAMA-2B) utilizes this injury mechanism to predict fetal outcome. However, due to the difficulties in measuring this mechanism in the pregnant dummy, such as tissue strain and pressure, a computational model of the pregnant occupant was created (Moorcroft, 2003). This computer model has been used to evaluate frontal crashes and has shown that local uterine compression is a critical factor in predicting placental abruption (Duma, 2004).

Although several studies have investigated pregnant occupant biomechanics, there is much that remains unknown. In particular, this paper investigates two objectives. First, the overall crash distribution of pregnant occupants is analyzed. Second, computer simulations are presented to examine the effectiveness of current restraint systems as well as possible future four-point restraint systems in far side impacts.

## METHODS

In order to determine the pregnant occupant crash exposure, the National Automobile Sampling System Crashworthiness Data System (NASS CDS) was searched for the 11 years between 1993 to 2003. All crashes involving pregnant occupants were collected for these years. The raw case data are presented and the weighted case data were analyzed. NASS CDS is a national sample of 4,000 to 5,000 police-reported crashes investigated each year by the National Highway Traffic Safety Administration (NHTSA) at 27 locations throughout the United States. The NASS CDS database includes a weighting factor which allows national estimates to be computed from this sample of all police-reported crashes. The weighting factor accounts for the probability of a crash occurring at one of the 27

NASS/CDS sampling locations or Primary Sampling Units (PSUs), the probability of the crash occurring in a member of the subset of police jurisdictions investigated at a given PSU, and the probability of the crash being sampled from the entire inventory of crashes that could occur in the given police jurisdiction. For this study, the weighted data were sorted based on pregnant occupant seating position and crash impact direction. Next, these variables were combined to determine the resulting crash exposure for pregnant occupants.

Given that far side crashes were the second leading crash mode, and no previous research had examined this event, the second part of this study investigated pregnant occupant biomechanics in far side impacts. For this study, a previously validated MADYMO computer model of a 30 week pregnant occupant was utilized to investigate pregnant occupant biomechanics in far side crashes (Moorcroft, 2003). The model is a modified MADYMO small 5<sup>th</sup> percentile female human model which stands at 152.4 cm and weighs 50.0 kg. In the modified model a pregnant abdomen is added and the total weight is therefore increased to 61.4 kg. The abdomen consists of the uterus, placenta, and amniotic fluid. The uterus is supported by two pairs of ligaments and surrounded by fat. Four techniques were used to validate the pregnant model. First, a global biofidelity response was evaluated by using a seatbelt to compress dynamically the pregnant abdomen (Moorcroft, 2003). The force versus compression results were within the published corridors from scaled cadaver tests (Hardy, 2001). Second, a similar validation procedure was performed with a 2.54 cm diameter rigid bar (48 kg) at an impact speed of 6 m/s and these results were also consistent with previous data (Rupp, 2001; Hardy, 2001). The third technique involved validating the model against real-world crashes in order to investigate the model's ability to predict injury. Using fatal crashes involving pregnant occupants, the model showed strong correlation ( $R^2 = 0.85$ ) between peak strain at the utero-placental interface (UPI) as measured in the model compared to risk of fetal demise as reported in the real-world crashes over a range of impact velocities and restraint conditions (Klinich, 1999b). The fourth method compared the physiological failure strain from placental tissue tests to the failure strain measured in the model. Tissue tests suggested approximately a 60 % failure strain for UPI tissues which is in agreement with the model's prediction of 75 % risk of fetal loss at a 60 % strain in the UPI (Rupp, 2001). In summary, the global, injury, and tissue level validation techniques all indicate the model is good at predicting injurious events for the pregnant occupant.

A total of 12 simulations were performed using three impact speeds (5, 15, and 25 mph). The crash speeds, or change of velocity, of 5 mph, 15 mph, and 25 mph were chosen to represent mild, moderate, and very severe far-side impacts. To achieve the desired change in velocity, the occupant was accelerated with a triangular pulse for 100 ms. Maternal head and pelvis accelerations were recorded in addition to fetal injury risk as measured by peak strain at the uterine-placental interface as a predictor of placental abruption.

Four restraint conditions were simulated including unbelted, lap-belt only, three-point belt, and a four-point belt. The four-point belt is shown in Figure 1 and is modeled as a standard three-point belt with the addition of another diagonal belt. All belt properties are standard MADYMO finite element belt properties. The vehicle interior was comprised of a driver seat, passenger seat, center console, and passenger door with window (Figure 1). This interior was modeled with a combination of planes and ellipsoids. The driver's seat, modeled as two planes, was considered rigid to minimize the effect on the occupant's motion. The center console was modeled with an ellipsoid 2.5 inches wide, 6.5 inches tall, and 20 inches long. The top of the console is approximately 7.5 inches above the seat cushion-seat back intersection.

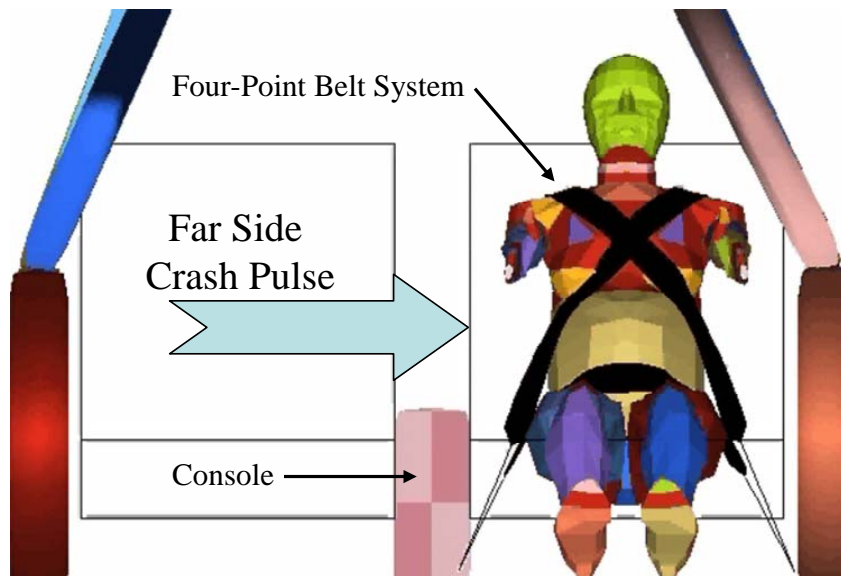


Figure 1 - Front view of the far-side impact pulse on the pregnant occupant with a four-point belt system.

Two contact properties were used for the center console, one for contact with the lower legs and one for contact with the pelvis and remainder of the occupant model. The pelvis contact was modeled as stiff to represent the actual car console, while the leg contact was modeled as soft due to numeric instabilities in the human model from

leg to leg contact that resulted in extreme local motion that caused the simulation to terminate. The passenger side of the vehicle was predominately modeled with planes for simplicity, with a few notable exceptions. The seat back was modeled as an ellipsoid because of the possibility of the head hitting the edge of the seatback and the window was modeled as an ellipsoid to allow for the observed angle. All contacts utilized the stiff console force-deflection property. The seat friction coefficient was set to 0.4 in order to match dummy kinematics in side impact collisions. It was found that this value better simulated overall dummy kinematics particularly at the lower side impact speeds compared to the traditional 0.2 friction value.

## RESULTS

The NASS CDS search yielded a total of 220,672 weighted cases (876 raw cases) involving pregnant occupants. For crash direction, 53.0 % were frontal, 16.4 % were left side, 10.3 % were right side, 8.3 % were rear, and 11.0 % were rollover (Figure 2). For seat position, 75.2 % were drivers, 21.7 % were passengers, and 2.7 % were in the rear seat. When accounting for seating position and crash direction, frontal was first with 53.0 %, far side was second with 13.5 %, near side was third with 13.2 %, with rear impacts fourth at 8.3 % each (Figure 3).

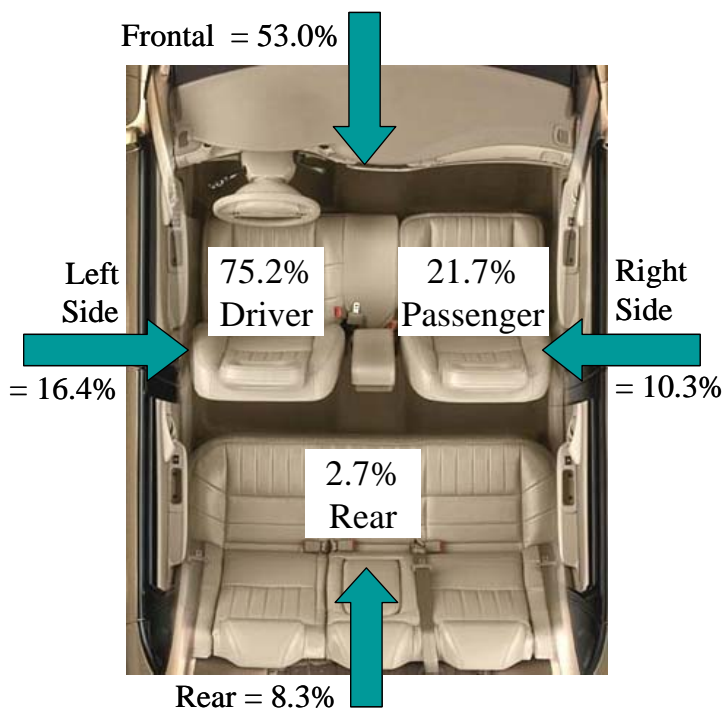


Figure 2 - Occupant seating position and impact direction distributions for pregnant occupants.

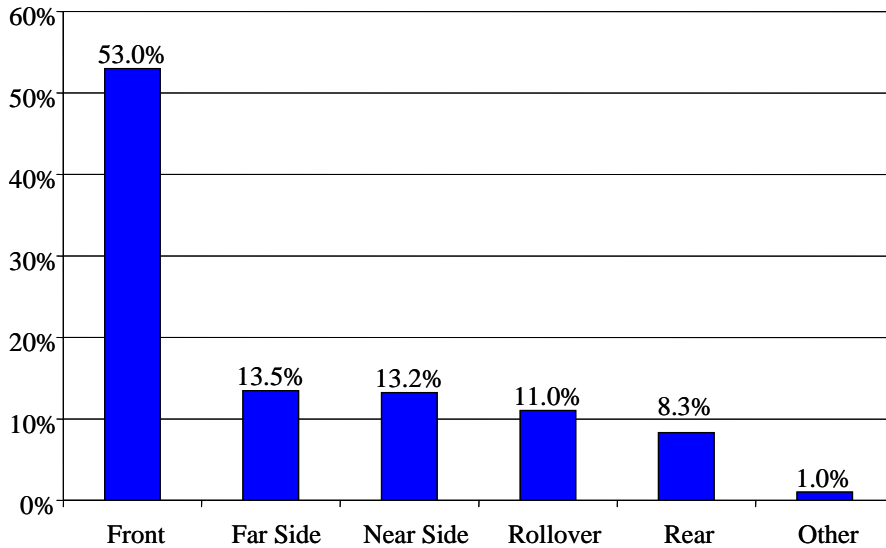


Figure 3 - Pregnant occupant crash exposure accounting for seating position and impact direction.

Direct contact with the center console created the largest pelvic accelerations for all simulations (Figure 4). This interaction between the occupant and the interior causes the pelvis to absorb most of the energy to slow the occupant down. This occurred at 15 mph and 25 mph impact speeds. Although the peak pelvic acceleration was reduced with the presence of a restraint, it only varied slightly between the lap-belt only and lap-belt with a shoulder harness cases. Pelvic accelerations were as high as 60 g and 55 g for the lap-belt only and four-point belt simulations respectively. For a slow speed impact of 5 mph, all cases had low pelvic accelerations because there was no contact with the console.

During the low speed crash all restraint configurations produce low Head injury criteria (HIC) values (Figure 5). With an increase in the crash severity, the three-point and four-point restraints have a greater affect in limiting the occupant excursion. For both the unbelted and lap-belt only cases, the mother's head strikes the opposite side door during a 25 mph crash. Thus, the result is a HIC value of 4000 which greatly exceeds the HIC injury threshold for skull fracture. The occupant's head also strikes the opposite side of the interior for the unbelted 15 mph crash resulting in a HIC value that is above the injury threshold. The restricted range of motion allowed by the restraints with a shoulder harness prevents contact with vehicle interior by the occupant's head which greatly reduces the HIC value.

The risk of serious fetal injury was calculated from the peak uterine strain so those results have the same trends. As with the other injury criteria, the low impact velocity cases had low values with negligible

risk (Figure 6 and Figure 7). For 15 mph and 25 mph speed simulations, risk of fetal injury was between 33.5 % and 61.0 %. All of the computer simulations of pregnant occupants in far side impacts at 5 mph resulted in very low risk of maternal or fetal injury. The fetal injury risk was determined by using a linear correlation (Moorcroft, 2003a) between the peak strain found at the UPI in the model and the fetal injury risk curves developed by Klinich (1999b) from real world cases.

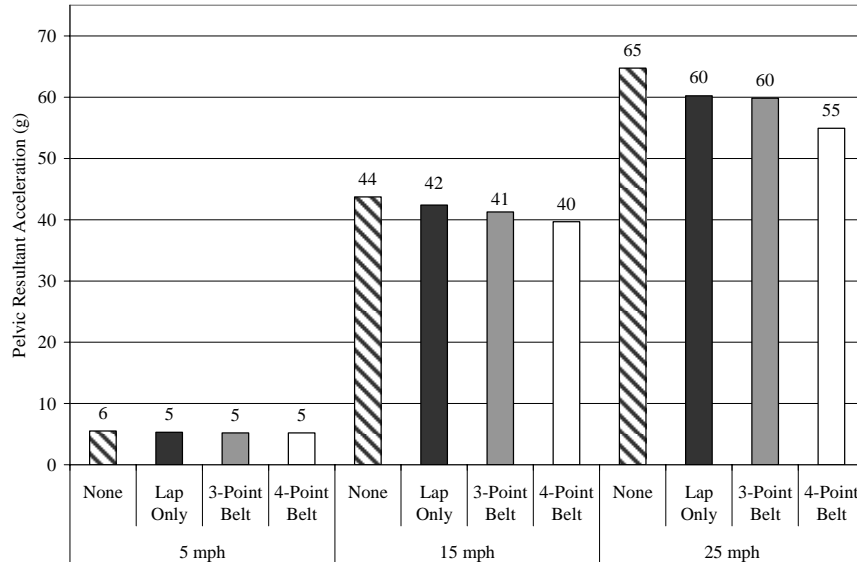


Figure 4 - Peak pelvic accelerations for all simulations.

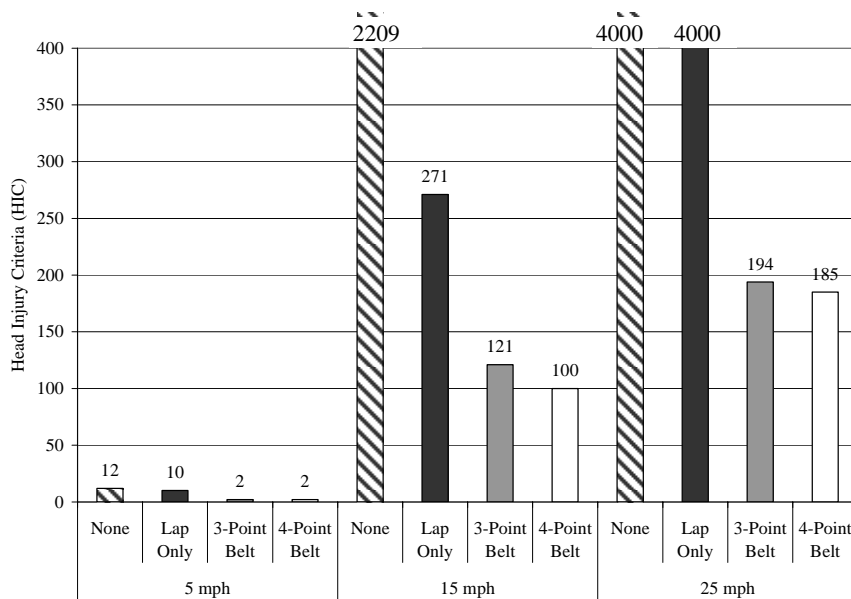


Figure 5 – Peak maternal HIC values for all simulations.

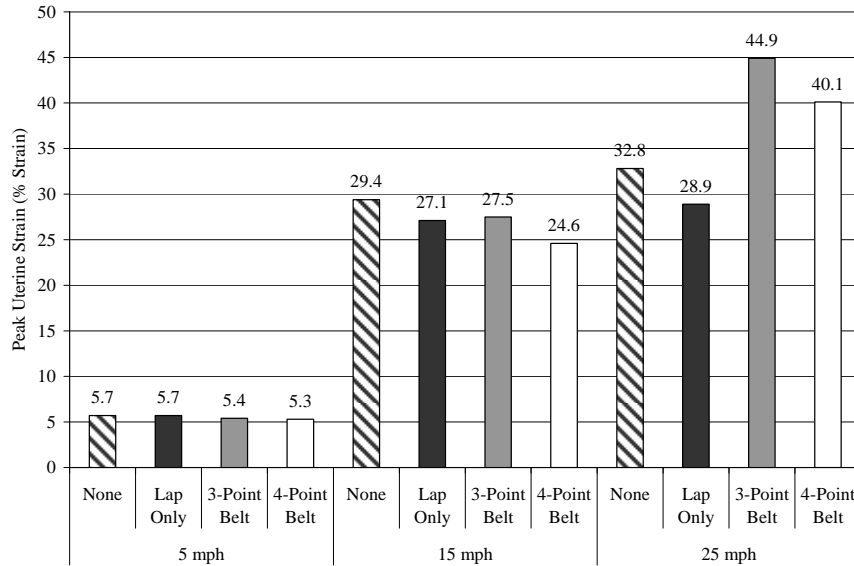


Figure 6 Peak UPI strain values for all simulations.

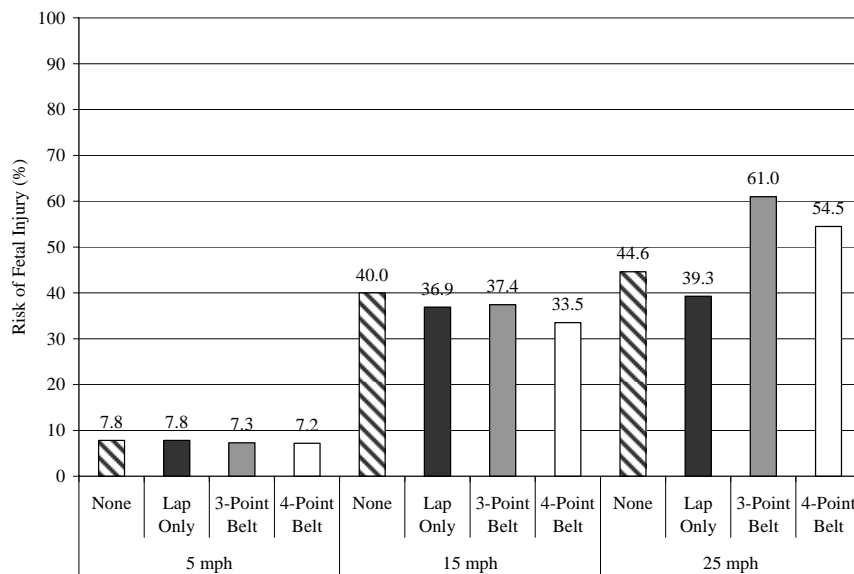


Figure 7 - Risk of serious fetal injury.

The loading mechanism for the strain was dependent on the restraint configuration. With the shoulder belts in the three-point and four-point systems, the abdomen was loaded directly (Figure 8). The four-point belt distributed the load to the abdomen and had a reduced peak strain when compared to the three-point belt. However when there was no shoulder belt present the strain was induced by inertial loading. For all the simulations the center console was not a possible injury mechanism for the fetus due to direct abdominal contact. The occupant passed over the console in the unrestrained cases and rotated above it for the restrained cases. The center console does increase the pelvic accelerations as the occupant slides and contacts it.

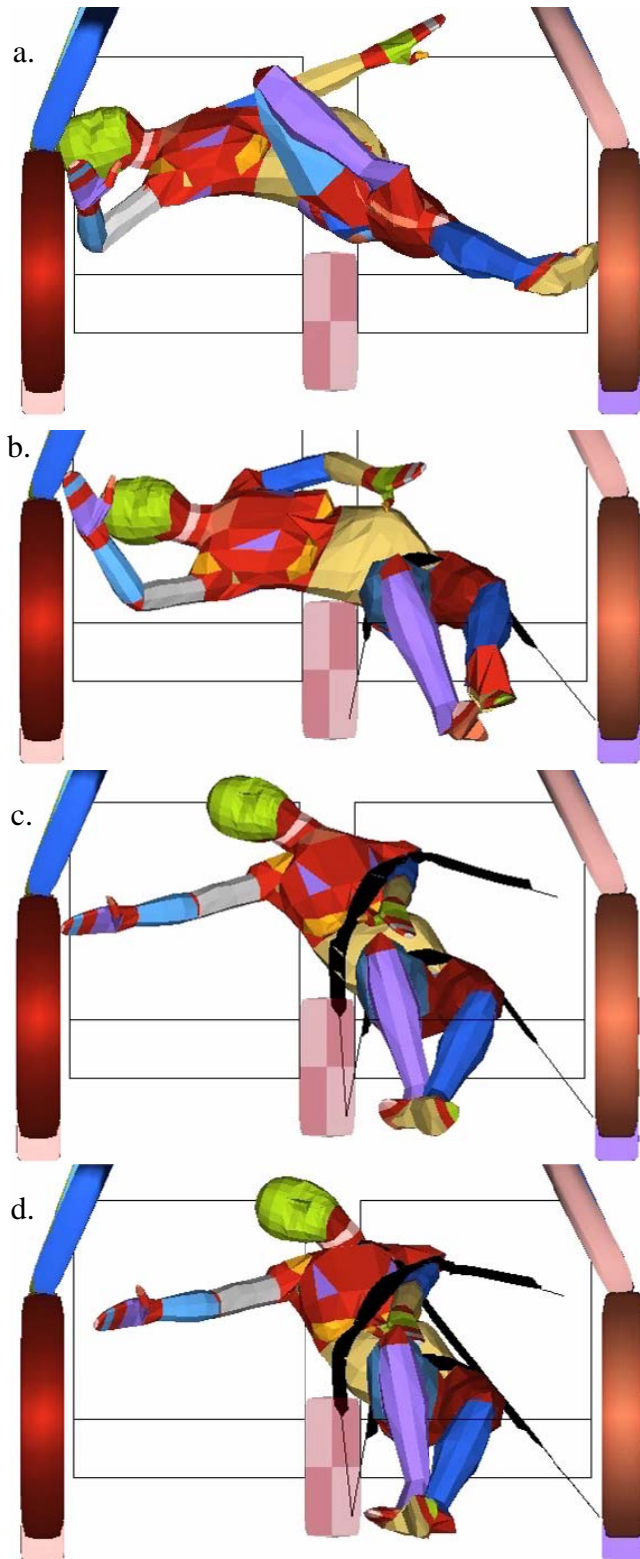


Figure 8 - The maximum excursion decreases with an increase in occupant restraint protection: a) no restraint, b) lap-belt only, c) three-point belt, d) four-point belt.

The neck loads were increased slightly in the four-point belt cases compared to the three-point belt cases. Although there was more direct contact in the four-point simulations, the inertially induced loads in the other cases resulted in similar neck loads. In the side impact simulations at 25 mph, the peak neck lateral shear force measured 673 N for the three-point cases versus 950 N for the four-point case at the upper neck load cell. The peak lateral bending moments at the upper neck load cell location were also slightly increase from 53 Nm for the three-point belt simulation at 25 mph to 87 Nm for the four-point belt simulation. All neck loads at the 5 mph and 15 mph simulations were substantially lower.

## DISCUSSION

In order to restrain the pregnant occupant in any crash, forces must be applied to her in order to stop her momentum. Ideally, these forces are applied over the greatest duration in order to reduce their magnitude, and they are applied to the strong bones of the body. It was shown that the three-point belt and the four-point belt were superior in protecting the pregnant occupant by reducing the movement towards the far side door and therefore eliminating the head strike potential. However, this resulted in some force being applied through the abdomen and therefore it increased the risk of fetal injury. This is an acceptable trade-off given the most important factor in saving the fetus' life is keeping the mother alive. The reason that the four-point belt is better than the three-point belt with respect to abdominal loading is that some of the overall load is applied through the mother's neck and therefore less is applied to the abdomen in order to restraint her for the same given crash speed. The belt contact loads through the neck were below published injury thresholds.

It is important to note several limitations of this study. The pregnant model approximates the pregnant female, and although it has been validated, there are still limitations. As with all computational models, this model is limited by the accuracy of input and simplifications made. The tissue data, from which the failure strain is derived, is sparse and simplifications are made to use that data as a material model. Additionally, the boundary conditions and geometry can and should be improved in future generations of the model. Furthermore, the model only looks at injury at the UPI. In cases with very large deflections, direct injury to the fetus may occur at injury rates different then those for placental abruption. It is recommended that the methods in this paper be applied to future generations of the

pregnant occupant model to provide a continually improving understanding of pregnant occupant injury risk prediction.

Additional limitations of this study include the fact that only one type of four-point belt system was investigated. It is possible that other styles of four-point belts would have different and possibly better results. Another limitation is that vehicle crush and intrusion was not modeled in these simulations. By moving the far side door closer to the pregnant occupant, the intrusion into the passenger compartment becomes more important and the possibility of a head strike is increased.

Finally it is important to note that these results agree with previous simulations for frontal impacts. Overall, the results indicate for all frontal and side impacts that it is safest for the pregnant occupant to ride in the passenger seat while wearing a three-point belt, or four-point belt if possible, and utilizing the frontal airbag when appropriate (Moorcroft, 2004).

## CONCLUSIONS

Overall, the crash exposure of pregnant occupants is nearly identical to the average driving population. Although the fetal injury risk is slightly increased in the three-point and four-point simulations, this negative trend is outweighed by the considerable benefit observed in the substantial reduction in maternal HIC when using the three or four-point belts. It has been demonstrated that the a critical factor in protecting the fetus is keeping the mother alive. While both the three-point and four-point belt systems provided good protection in far side simulated crashes, the four-point belt did a superior job of restraining the pregnant occupant and reducing overall translation. Given the magnitude and severity of pregnant occupant injuries, this study illustrates the need for manufacturers to consider four-point belt systems for this population.

## ACKNOWLEDGEMENTS

The authors thank Kathy Klinich at the University of Michigan Transportation Research Institute for her assistance in the development of the pregnant model. The funding for this research has been provided by the Virginia Tech – Wake Forest Center for Injury Biomechanics Foundation. Also, the authors thank Altair Engineering Inc. for the use of HyperWorks as the pre and post processor, and TNO for the use of MADYMO.

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