PREGNANT OCCUPANT INJURY RISK USING COMPUTER SIMULATIONS WITH NCAP VEHICLE CRASH TEST DATA

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ABSTRACT

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. A previously validated MADYMO computer model of a 30-week pregnant occupant was used in this study to investigate the pregnant occupant response in a New Car Assessment Program (NCAP) frontal barrier motor vehicle crash. The effect of the restraints, all tests had a 3 point seatbelt and an airbag, and the vehicle performance in the crash are incorporated by applying the measured pelvic acceleration in the front seat passenger dummy to the pregnant occupant model. Included in the study are nine vehicle models that represent the compact, medium, and sport utility vehicle classes during the years 1996 to 2006 for a total of 26 NCAP tests with corresponding simulations. Uterine strain from the computational model, a good predictive measure of the risk of fetal injury due to placental abruption, indicates the average risk of adverse fetal outcome associated with these NCAP tests is 85 ± 13% with a minimum risk of 55% and a maximum risk of 100%. NCAP star rating correlates with the risk of adverse fetal outcome (p=0.001) with 3 stars having an average risk of 99 ± 3% (n=3), 4 stars having an average risk of 89 ± 11% (n=14), and 5 stars having an average risk of 75 ± 13% (n=9). However, even the best NCAP rating, 5 stars, is still indicative of a high risk of fetal injury. This high risk is consistent with published pregnant occupant case studies that have an equivalent change in velocity of slightly more than 56.3 kph (35 mph). Although this study is limited to computational modeling, it suggests more research in protecting the pregnant occupant is needed.

INTRODUCTION

Automobile crashes are the largest cause of death for pregnant females (Attico, 1986) and the leading cause of traumatic fetal injury mortality in the United States (US) (Weiss, 2002). Each year in the US, 160 pregnant women are killed in motor-vehicle crashes and an additional 800 to 3200 fetuses are killed when the mother survives (Klinich, 1999a, 1999b). The best way to protect the fetus is to protect the mother considering that maternal death has a near 100% fetal loss rate (Pearlman, 1990b). If the mother survives, protection of the fetus may best be accomplished by preventing placental abruption. Placental abruption, which is the premature separation of the placenta from the uterus, has been shown to account for 50% to 70% of fetal losses in motor vehicle crashes (Pearlman, 1990a). Information gathered from crash investigations shows that placental abruption can occur without other, more severe injuries, such as uterine rupture or direct fetal injury. However, when these more severe injuries do occur they are often accompanied by placental abruption (Rupp, 2001).

Since real world crash data is limited and cadaver studies are not feasible, a previously validated Mathematical Dynamic Modeler (MADYMO) computer model of a 30-week pregnant occupant has been a useful tool in researching risk of adverse fetal outcome for motor vehicle crashes involving a pregnant occupant (Moorcroft, 2003a). Adverse fetal outcome is defined as placental abruption, uterine laceration, direct fetal injury, premature delivery due to the crash, and fetal loss (Klinich, 1999b). Previous studies have utilized the pregnant occupant computational model to assess the risk of fetal loss based on occupant position, belt placement, impact direction, and advanced restraint systems (Moorcroft, 2004; Duma, 2006). Data for dynamic failure testing of maternal tissues are available for the uterus and placenta (Manoogian, 2007a, 2007b). Currently, the only alternative pregnant surrogate is a 30-week gestation 5th percentile female crash test dummy called the Maternal Anthropomorphic Measurement Apparatus version 2B (MAMA-2B) (Rupp, 2001). Validation tests have related the peak pressure of the

simulated uterus in the MAMA-2B with real world fetal loss risk data. The pregnant surrogate has been used in further analysis to determine the risk of fetal loss for different restraint conditions in a frontal impact. However, the crash test dummy is limited in its ability to model several crash scenarios in a timely and cost effective manner. For this study, the validated computational model was selected.

One type of vehicle safety rating is reported based on the National Highway Traffic Safety Administration (NHTSA) New Car Assessment Program (NCAP). The NCAP tests include front, side, and rollover star ratings. The large available data set from these tests proved a valuable resource of occupant response to the same impact condition for several vehicle models. In an analysis of data from the National Automobile Sampling System Crashworthiness Data System (NASS CDS), it was found that 53% of pregnant occupant motor vehicle crashes are frontal impacts (Duma, 2006). Therefore, data from NCAP frontal barrier impacts are chosen for this study. The purpose of this study is to use the pregnant occupant model to assess the risk of adverse fetal outcome in a NCAP frontal barrier motor vehicle crash.

METHODS

VT Pregnant Model

A previously validated MADYMO computer model of a 30-week pregnant occupant has been created to investigate pregnant occupant biomechanics in motor vehicle crashes. The details of model development and validation are available in Moorcroft, et al. (2003a, 2003b, 2003c), but are briefly summarized here. In order to create the model of the pregnant occupant, the finite element model of a pregnant uterus was inserted into the abdomen of a multibody human model. The finite element model anthropometry was designed to represent an occupant in her 30th week of gestation based on data from Klinich (1999a) for the second-generation pregnant dummy. The abdomen consists of the uterus, placenta, and amniotic fluid. A fetus was not included because the injury mechanism that predominantly contributes to fetal loss is placental abruption, as described by Rupp (2001). The human model is a 5th percentile female (1.52 m tall, 50 kg) and the weight of the pregnant occupant model is 61.2 kg (135 lbs). This multibody human model provides biofidelic response of an occupant in a motor vehicle crash, while reducing the computational time compared to a more complex full finite element human model.

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, 2003b). 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 forth method compared the physiological failure strain from placental tissue tests to the failure strain measured in the model. Rupp presented a summary of pregnant uterine and placental tests which suggest approximately a 60% failure strain for the UPI (Rupp, 2001). This is in agreement with the model's prediction of 80% risk of fetal loss at a 60% strain in the UPI (Moorcroft, 2003). In summary, the global, injury, and tissue level validation techniques all indicate the model is good at predicting injurious events for the pregnant occupant.

The model calculates the risk of adverse fetal outcome, or fetal loss, on the basis of statistical analyses of case report data performed by Klinich, et al. (1999b). A two variable linear regression of the entire data shows that the uterine strain from the computational model is a good predictive measure of the risk of fetal injury due to placental abruption ($R^2 = 0.85$). The regression shows that uterine strain increases linearly to tissue failure as the risk approaches 100%.

NCAP Frontal Barrier Test

NHTSA uses NCAP to rate vehicles based on their safety performance. The NCAP frontal test is a standardized test to crash a vehicle with an initial velocity of 56.3 kph (35 mph) into a fixed barrier with the full width of the front of the vehicle. This yields an equivalent change in velocity of 59.5-64.4 kph (37-40 mph) when the vehicle rebounds. During this test, the driver and front seat passenger of the vehicle are 50th percentile Hybrid III male crash test dummies. Although there are several instrumentation devices on board the vehicle and the dummies, only

head and chest acceleration measurements are used for the injury criteria which determine the NCAP star rating. The highest NCAP rating is five stars and indicates a 10% or less chance of a serious injury. The lowest NCAP star rating, one star, is associated with 46% or greater chance of serious injury. The NHTSA definition of a serious injury is one requiring immediate hospitalization and may be life threatening.

In order to use the data from the NCAP test in the pregnant occupant model, a few methodological assumptions were made. First, since the data collected is for the 50th percentile male, it was assumed that the 50th percentile male response was similar to what the 5th percentile female would experience in the motor vehicle crash. Second, it was assumed that the effect of the vehicle structure and restraints on the passenger kinematics is incorporated in the pelvic acceleration response. Moreover, only the linear acceleration of the pelvis was known, so the simulation assumes there was negligible pelvic rotation. Because there is no method to validate the interaction with the restraints and vehicle interior, the only cause of uterine strain in the simulations was due to inertial loading from pelvic acceleration. As a result, this study used the three linear acceleration components of the pelvis as inputs to the simulations. These limitations are discussed further in the discussion.

Simulations

The MADYMO simulations in this study modeled a total of twenty-six NCAP tests from the years 1996 to 2006. Three vehicle models were selected from each of the three vehicle classes: passenger car compact (PC/C), passenger car medium (PC/Me), and sport utility vehicle (SUV). All of the tests chosen had a three point seatbelt and at least a front airbag for the passenger. Previous research shows the pregnant occupant is the driver in 75% of pregnant occupant related motor vehicle crashes (Duma, 2006). However, the pregnant occupant in the driver seat also has more interaction with the vehicle interior in a motor vehicle crash (Moorcroft, 2004). Because the goal of this study is only modeling the inertial loading and not the contact loading to the abdomen, the simplified case of the pregnant occupant passenger was chosen. Data were collected from the front seat passenger pelvis accelerometer in each of the NCAP tests evaluated.

The MADYMO pregnant occupant model was locked in a standard sitting position as measured by Klinich et al. for the small female group at 30-weeks gestation (Klinich, 1999a). By locking the occupant's joints, she moved as a rigid body in inertial space. Internally the uterus, placenta, and amniotic fluid were allowed to translate and rotate in the abdomen (Figure 1). Since no vehicle interior or restraints were added to the model, only the inertial response of the uterus is measured without external contact forces or compression due to thoracic movement. The pelvic linear acceleration data extracted from the NCAP tests was filtered to CFC600 per SAE J211. Applying the x, y, and z components of the pelvic acceleration pulse to the model for 0.125 seconds provided a simulation of the inertial effect pelvic acceleration would have on a pregnant abdomen. As a result, the uterus strained and rotated from the inertial loading. Since the assumed injury mechanism is placental abruption, the simulations output uterine strain at the fundus of the uterus for the duration of the impact. The peak von mises uterine strain corresponds to a risk of fetal demise using the linear relationship from the previous validation of this model. It is anticipated that this loading presents a best case scenario for the pregnant occupant in an NCAP style crash given no abdominal intrusion from the steering wheel or belt.

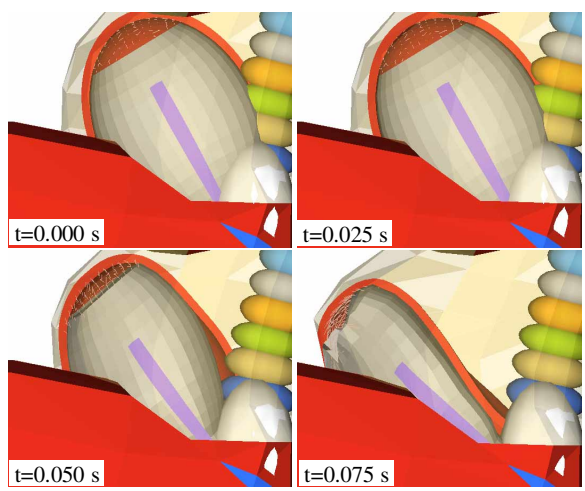

Figure 1: The simulation emulates the response of the uterus from pelvic acceleration due to a motor vehicle crash.

RESULTS

The results for this study include the risk of fetal loss for 26 different NCAP frontal barrier tests (Table 1). The average risk associated with these tests is 85 ± 13% with a minimum risk of 55% and a maximum risk of 100%. This information provides insight into how the vehicle type and pelvis acceleration determine the inertial loading of a 30-week pregnant uterus in a motor vehicle crash.

Table 1: A total of 26 simulations included nine vehicles in three vehicle size groups.

Vehicle Type	Model Year	NCAP Star Rating	Peak Pelvis X Acceleration (g)	Risk of Adverse Fetal Outcome (%)
PC/C 1	1996	5	49.4	87
	1999	4	48.5	74
	2006	5	44.0	55
PC/C 2	1998	4	55.6	82
	2003	5	42.4	77
	2005	5	46.3	97
PC/C 3	2000	4	73.0	100
	2002	4	92.8	100
PC/Me 1	1998	4	53.1	77
	2000	4	51.5	72
	2003	5	46.5	65
PC/Me 2	1996	4	42.2	88
	2000	5	59.6	75
	2004	5	39.3	72
PC/Me 3	1997	4	53.1	93
	2000	5	51.9	67
	2004	4	79.7	78
SUV 1	1998	3	74.2	100
	2001	4	84.3	100
	2004	5	59.7	80
SUV 2	1998	4	66.8	99
	2002	3	80.1	100
	2005	4	69.6	100
SUV 3	1996	3	66.4	95
	2001	4	67.5	100
	2004	4	58.1	83

Vehicle Type

When the risk of adverse fetal outcome is considered for each vehicle type, the medium size passenger car group had the lowest risk associated to it with an average of 76 ± 9%. The sport utility vehicle group had the highest average risk of 95±8%. The passenger compact car group was in between these two with an average risk of 84 ± 16%. The former group had the largest standard deviation with the minimum risk being 55% and the maximum risk being 100%. The only statistically significant difference was between the medium passenger car and the sport utility vehicle groups (Figure 2). Within each vehicle group, the risk was evaluated for a vehicle model as the model year progressed. In the 17 comparisons made between the same model car and an increase in model year, the risk of injury did not always decrease over time (Figure 3). The peak uterine strain increased in five of these cases with the associated risk either increasing or remaining the same at 100% (Figure 4). The remaining 12 cases showed a decrease in uterine strain and risk with an increase in model year. Because some vehicles had poor performance in recent years, there is not a significant trend associated with an increase in model year.

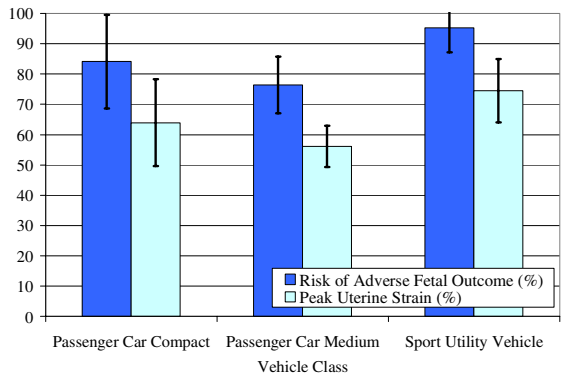

Figure 2: The medium passenger car class had a significantly lower risk associated with it than the sport utility vehicle class (p<0.001).

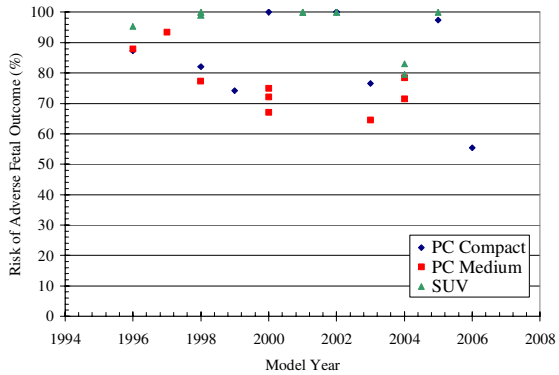

Figure 3: The risk of fetal loss versus vehicle model year indicates a decrease in risk for the medium passenger car class.

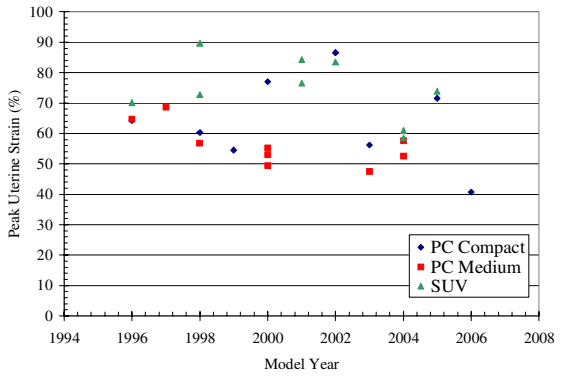

Figure 4: Peak uterine strain decreases in 12 of the 15 vehicle model year comparisons in this study.

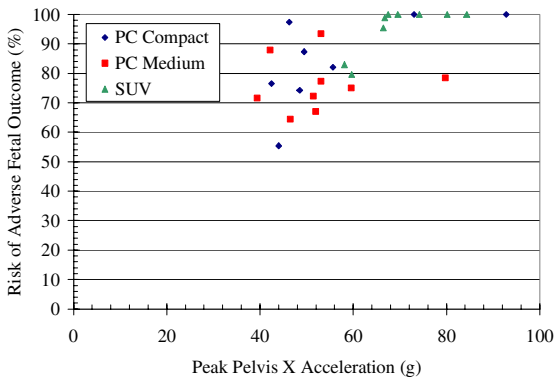

Figure 5: Overall, the SUV class had higher peak accelerations which correspond to higher risks of fetal demise.

Peak Pelvic Acceleration

The risk of placental abruption and peak pelvic acceleration in the x direction had a statistically significant relationship ($p<0.001$). The peak pelvic x acceleration is used rather than the resultant pelvic acceleration because in the frontal crash this value is dominant. Due to inertial loading only, 7 out of 8 vehicles with a peak pelvic acceleration above 67 g had a 100% risk of fetal loss (Figure 5). The relationship between peak pelvic acceleration and peak uterine strain is also shown, although a strain of above 74% corresponds to a 100% risk of fetal demise (Figure 6). Since all of these vehicles experience approximately the same change in velocity, the acceleration curves differ mainly in their peak acceleration and duration. This difference is seen best between the acceleration pulses that resulted in the least and greatest uterine strain (Figure 7). The acceleration curve with a peak pelvis x acceleration of 74.2 g maintains above a 5 g load for 0.0493 seconds and corresponds to the highest value of peak uterine strain, 90%. However, the acceleration curve with the lowest resulting peak uterine strain of 41% holds an acceleration above 5 g for 0.0889 seconds with a peak of 44.0 g. The longer duration, lower peak g acceleration curve results in a lower peak uterine strain and an analogous reduction in risk of fetal loss for the pregnant occupant.

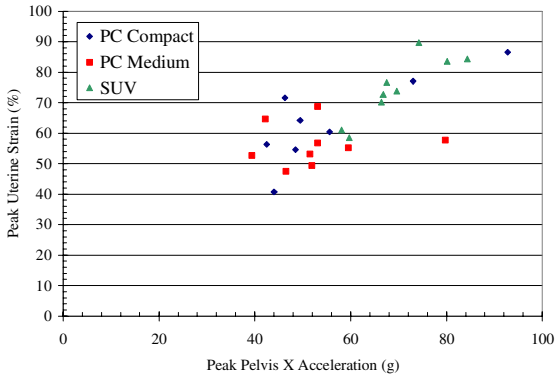

Figure 6: The linear relationship between peak pelvis x acceleration and peak uterine strain is significant but not strongly correlated due to differences in the acceleration profiles.

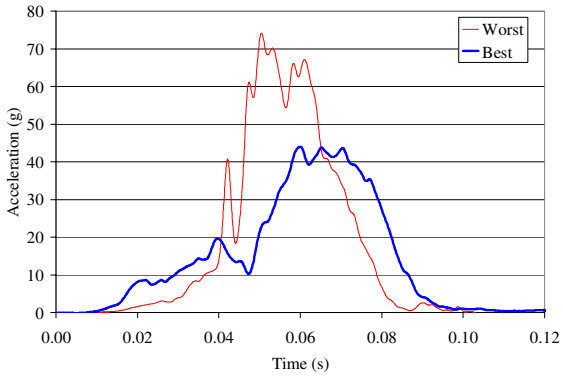

Figure 7: The acceleration pulses that resulted in the least and greatest uterine strain are plotted for comparison.

Although there was an increase in risk with an increase in pelvic acceleration, it was not strongly correlated. Some vehicles had similar peak pelvis x acceleration values and very different associated peak uterine strains. A closer evaluation of the acceleration profiles and their matching strain outputs addresses the weak correlation. When the pelvic acceleration and uterine strain profiles are plotted together, a time delay between the input and the response is present for the inertial loading. Due to the delay, a rapid change in pelvic acceleration does not have time to load the uterus. For example, an acceleration curve which has a peak duration of less than 5 milliseconds does not have a parallel large peak in the uterine strain (Figure 8). On the other hand, a curve with a steady increasing acceleration causes a similar steady increase in uterine strain (Figure 9). Therefore, two acceleration profiles with similar peak values can have different fetal injury risks associated with them.

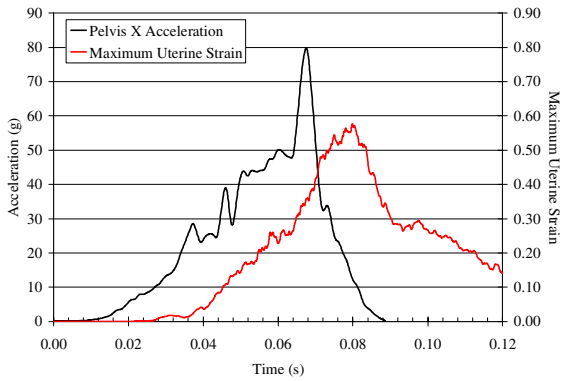

Figure 8: The large peak in the pelvis x acceleration does not have an equivalent large peak in the uterine strain measure.

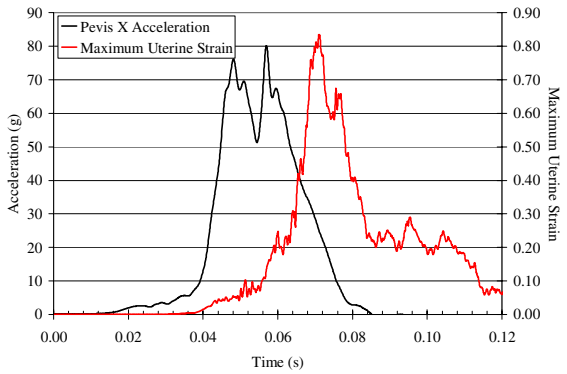

Figure 9: The steady increase in pelvis x acceleration has a corresponding increase in the peak uterine strain.

NCAP Score

The NCAP star rating for each vehicle indicates the risk of injury for the occupant based on head and chest criteria. The NCAP data used in this study was the pelvic acceleration. It was found that with an increase in the frontal NCAP star rating there was a decrease in peak pelvic acceleration for the x direction. The five star rating corresponds to a 48.8±7.2 g peak pelvic acceleration for the tests evaluated in this study. This value increased to 73.6±6.9 g for a low rating of three stars. Additionally, it was found that the star rating had a statistically significant relationship to the risk of fetal loss ($p=0.001$). The NCAP tests with 3 stars have an average risk of 99 ± 3% (n=3), 4 stars have an average risk of 89 ± 11% (n=14), and 5 stars have an average risk of 75 ± 13% (n=9) (Figure 10). These three groups are statistically different from each other and show that risk of adverse fetal outcome from placental abruption increases to almost 100% in a vehicle that passes the NCAP frontal barrier test with 3 stars. While the best NCAP rating of 5 stars indicates less than 10% risk of injury to the front passenger, it corresponds to a 75% risk of injury to the fetus.

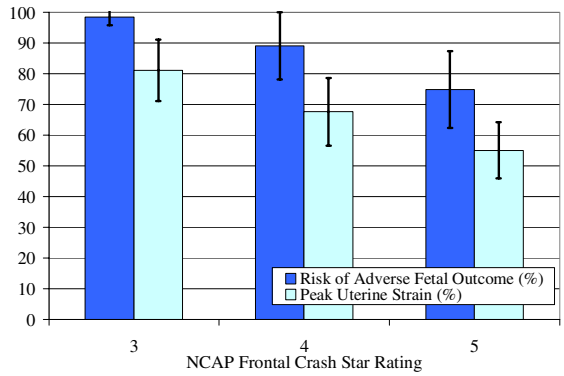

Figure 10: The best NCAP rating of 5 stars is indicative of a 75% risk of fetal loss in a 56.3 kph frontal barrier crash.

DISCUSSION

Real world pregnant occupant motor vehicle crash data and pregnant crash dummy data confirms the results from this study. In an analysis of case data for pregnant occupants, the estimated risk of fetal loss for a crash severity of 56.3 kph (35 mph) is 93% when the occupant has the proper restraint (Klinich, 1999b) (Figure 11). This risk is the minimum value associated with an NCAP test since the actual change in velocity with the rebound is generally 59.5-64.4 kph (37-40 mph). A crash severity of 64.4 kph (40 mph) is associated with 97% risk of fetal loss. Previous research using the pregnant crash test dummy MAMA-2B evaluated the uterine pressure during a sled impact with a 52.6 kph (32.7 mph) change in velocity. The result of this impact with the dummy as the passenger and wearing a 3 point belt was a risk of adverse fetal outcome equal to 87.5%. The average risk calculated in the current study for the inertial loading condition during a front impact is 85 ± 13%. All three of these methods of evaluating the pregnant occupant with the proper restraint indicate a high risk of fetal loss for a crash severity equivalent to that of an NCAP test.

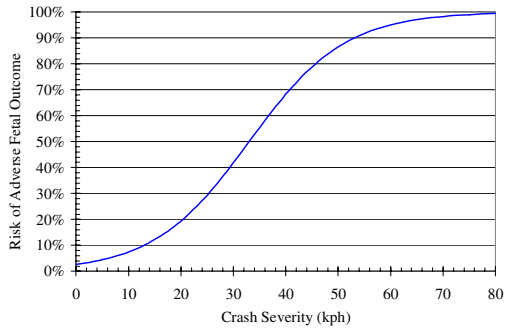

Figure 11: Risk of adverse fetal outcome as a function of crash severity for the properly restrained pregnant occupant indicates a 92% risk with a 56.3 kph impact (Klinich, 1999b).

Limitations of this study arise from the information available from a frontal NCAP barrier test. A pregnant surrogate is not used in the NCAP frontal barrier test so it is assumed that the kinematic response of the 50th percentile male is similar to that of a 30-week gestation 5th percentile female. Anthropometric differences would cause variations in the loading by the restraint system and ultimately the kinematics of the dummy. Since this cannot be accounted for, it is assumed that the pelvis of the small female has the same acceleration profile as that of the large male. As a result of a smaller mass and equivalent acceleration, a lesser force would be required by the restraints to stop the pelvis.

The data is not adequate to recreate the full body kinematics such as torso rotation and contact loading from the restraints or vehicle interior that contribute to uterine strain. Therefore, the model predicts the fetal outcome for an ideal loading scenario of a pregnant occupant in a 56.3 kph (35 mph) frontal impact. The assumption of a 3-point seatbelt positioned correctly minimizes the risk because placing the seatbelt too high on the abdomen can increase the risk of fetal loss by contributing unfavorably to uterine compression (Moorcroft, 2004). Additionally, using the shoulder belt and airbag decreases the risk of injury (Klinich, 1999b). These simulations do not consider contact loads from the seatbelt and vehicle interior to the abdomen since they could not be validated. Contact loads can increase the risk of fetal complications because of abdominal compression. Early research on the pregnant occupant indicated that bending of the torso also increased uterine pressure (King, 1971). These effects are not modeled since the body is locked in a seated position.

Moreover, this model does not predict the additional complications for the fetus due to maternal injury. A 3 star NCAP rating for the front passenger indicates a 21% to 35% risk of serious injury to the mother. Serious injury to the mother further increases risk of adverse outcome to the fetus. Because the model simulations are evaluating an ideal scenario, the associated risk is expected to be greater in a real world crash for a 56.3 kph (35 mph) impact. Overall, the attachment of the placenta is very delicate, and the data from this study and previous studies indicate that prevention of placental abruption with such a severe impact may not be plausible.

CONCLUSIONS

Using a validated pregnant occupant computer model, this study assessed the risk of fetal loss for the pregnant front seat passenger in 26 different NCAP frontal barrier tests. Nine vehicles were selected that ranged 10 model years and three vehicle weight classes. The results from this study show that in an ideal loading condition the average risk of adverse fetal outcome is 85% due to inertial loading only. Moreover, all vehicle models for all years showed a greater than 50% risk of fetal loss. When compared to previous research, the results from this study are confirmed. Although this study is limited to computational modeling, it suggests even with the best case restraint system scenario the risk of fetal death is highly probable in severe crashes like those that the NCAP standard emulates.

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