# Pregnant Occupant Model with a Fetus: 'Expecting'

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**Abstract -** Detailed anthropometric data of pregnant women have been collected and used in the development of a computational model of the pregnant occupant model 'Expecting'. The model is complete with a finite element uterus and multi-body fetus, which is a novel feature in the models of this kind. The computational pregnant occupant model has been validated and used to simulate a range of impacts. The strains developed in the utero-placental interface are used as the main criteria for fetus safety. Stress distributions due to inertial loading of the fetus on the utero-placental interface play a role on the strain levels. Inclusion of fetus model is shown to significantly affect the strain levels in the utero-placental interface. This series of studies has led to the design of seatbelt features specifically for the pregnant women to enable them use the seatbelt correctly and comfortably.

**Keywords** Pregnant, occupant, fetus, crash, modeling, safety, 'Expecting'.

## NOTATION

*ATD* Anthropomorphic Test Device
*UPI* Utero-placental Interface
*FE* Finite Element

## INTRODUCTION

Car occupants are legally required to wear seatbelts in many countries both as drivers and passengers. Pregnant women are not exempt from this rule. Each year, 131.5 million babies are born in the world. Potentially, 131.5 million pregnant occupants travel as passengers or drivers in vehicles, which are not designed to take into account their anthropometric differences and vulnerability. The level of exposure of pregnant women who experience an automobile accident is on the increase. It has been shown that road traffic accidents are the leading cause of accidental fetus mortality [1].

Wearing a seatbelt is shown to be a problem for a pregnant occupant [2]. During pregnancy a woman's body undergoes a considerable change in size and shape, which can prevent her correctly wearing the safety belt during travelling in a road vehicle. Pregnant occupant anthropometry is the key to improving the positioning of the seat belt correctly around the pregnant woman's altered body shape.

The presence of a fetus, along with the unique geometry of the pregnant woman, makes them a different group of occupants [3]. In the mid 90's a pregnancy insert for the Hybrid III small female is developed to explore the effect of loading of vehicle safety systems on the approximately 28-week pregnant occupant [4]. This physical model included a urethane fetus which fitted inside a urethane casing that fitted inside a urethane uterus. A second-generation physical model of pregnancy insert is developed [5] which has more realistic anthropometry however it has neither a placenta nor fetus instead the uterus is filled with fluid. A computational model to represent a pregnant driver is developed [6], combining a FE model of uterus, without fetus, within an existing 5th percentile female occupant model available in the MADYMO package.

Another model named 'Expecting' which represents a 5th percentile female at around the 38th week of pregnancy is developed at Loughborough University [7]. The model is complete with a finite element uterus and multi-body fetus, which is a novel feature in the models of this

kind, is integrated into an existing MADYMO female model to incorporate pregnant female anthropometry. The model is validated by using rigid bar impact and belt loading tests [7] since obtaining volunteer data using pregnant women in crash tests, however low speed it may be, is not practical.

The model, 'Expecting', has been used to simulate a range of impacts of increasing severity of Δv of 15kph to 35kph.  Safety of pregnant driver when she was completely unrestrained, restrained with a three- point seat belt only, and restraint with a three-point seat belt and an airbag, have been investigated. The model has been further used in a variety of vehicle crash scenarios to demonstrate the importance of interior designs.

This paper focuses on a series of studies led by the author to highlight  the importance of including the fetus within uterus of pregnant occupant models and the contribution of 'Expecting' in investigations and design, to improve safety for the fetus.

## METHODS

The methodology covered in this section summarises the procedures of data collection for appropriate representation of pregnant women's anthropometry and the development of the pregnant woman model 'Expecting', vertical drop tests of the uterus model with and without  fetus  model, and crash simulations with the 'Expecting'  with fetus and without fetus. Furthermore, it explains the procedures followed to investigate the difference between correct and incorrect seatbelt wearing for pregnant occupants.

### Measurements of pregnant women

As the first step of a series of investigations, anthropometric measurements were recorded from pregnant women. The anthropometric measurements were selected for their applicability to the vehicle design process, and for understanding the changes in physical size and shape that occur during pregnancy.
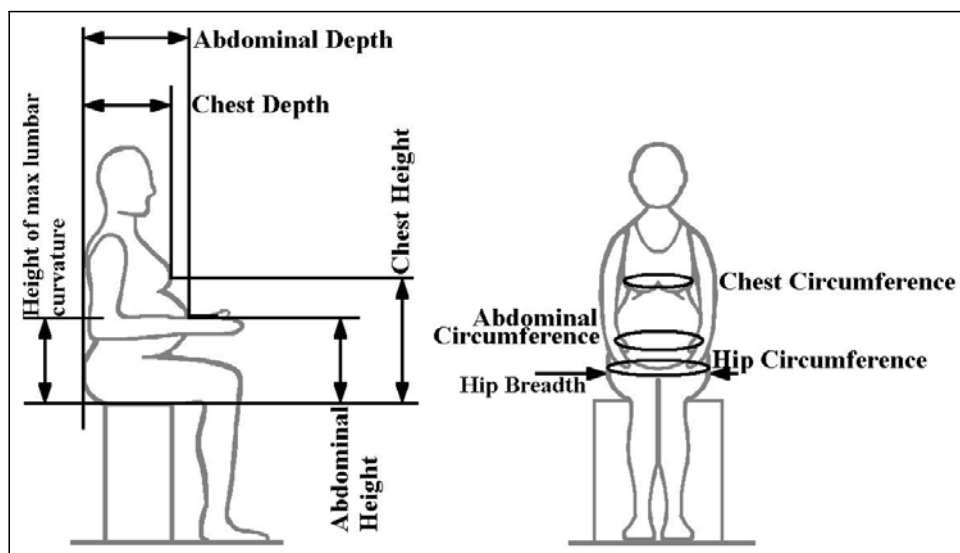


Figure 1.  An illustration of the anthropometric measurements: Trunk region (Abdomen, chest and hips). Measurements and figures adapted for pregnant women from standard measurements in DTI, Adultdata, [8].

The measurements used the standard postures and procedures, as in [8] and [9], but were adapted where necessary to suit the pregnant body. For example the waistline diminishes during pregnancy so the abdominal circumference was recorded at the point of maximum circumference, rather than at the waistline (point of minimum circumference). 49 measurements of 107 women were recorded. The full measurement details and analysis can be found in [3]. As an example trunk region measurements are illustrated in Figure 1. Pregnant women were recruited in two locations in the United Kingdom. Over 800 pregnant women also completed a questionnaire to identify problems of pregnant occupants. The questionnaire findings are not in the scope of this paper although they are used to understand the need for specific measurements and interactions [2]. Volunteers wore light clothing and removed their shoes, and the equipment used included weight scales, a stadiometer, a digital vernier caliper, a tape measure and an anthropometer.

**The Pregnant Occupant Model: 'Expecting'**

'Expecting', the computational pregnant occupant model, embodies the complexity of pregnant women's anatomy and anthropometric details based on 49 measurement sets of data from 107 pregnant women volunteers [3]. A detailed multi-body representation of a fetus within a finite element uterus model is also integrated into the model. The model is placed within a typical vehicle interior model, consisting of a seat, vehicle floor, pedals, bolsters and steering wheel as shown in Figure 2(a), in the multi-body/finite-element software package MADYMO [10]. The finite element uterus model is built in accordance with the fetus dimensions and configuration controlling the dimensions of the uterus to provide a snug fit around the fetus to represent the 38 weeks of pregnancy as shown in Figure 2(b). The multi- body fetus model is composed of 15 rigid bodies representing the various anatomical regions of the fetus interconnected by kinematic joints. A finite element layer of fat encloses the outer surface of the uterus. A total fetal mass is 3.3kg and the resulting total mass of the uterus with the placenta and the fetus is nearly 4.60 kg. Further details of the multibody fetus model development can be found in [11]. Further details of the pregnant occupant model development and validation can be found in [7]. Simulations representing various crash scenarios are conducted with the 'Expecting'.
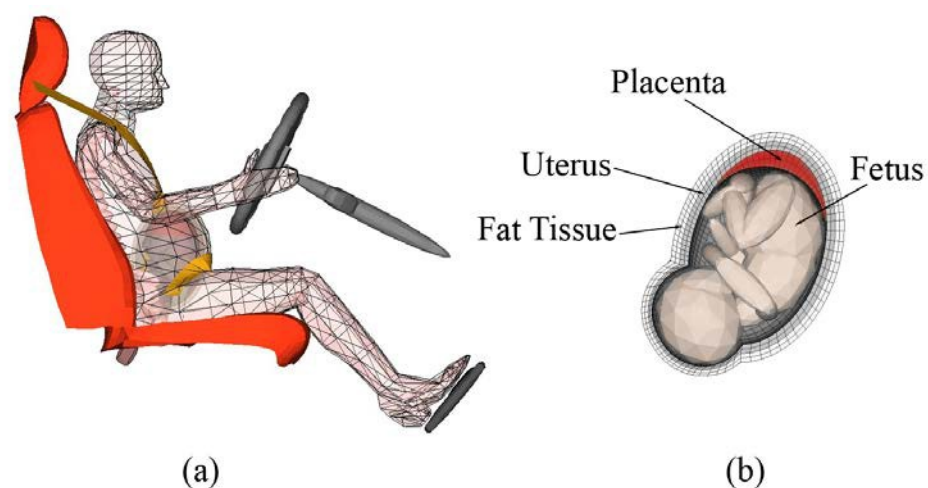


Figure 2. The pregnant occupant model 'Expecting' (a); uterus, placenta and fetus in 'Expecting' (b).

**Vertical drop tests and crash tests with and without the fetus**

Previous computational pregnant occupant models were designed without a fetus. A study of vertical drops of a simplified fetus and uterus model onto a rigid flat surface at different angles reported that the effect of impact on the uterus is independent of the fetus [12]. The uterus model of 'Expecting' and an identical uterus model without the fetus are used to repeat the drop tests conducted in earlier studies in the study above to investigate the effect of the fetus on the strains on utero-placental interface (UPI).

In addition, a version of the 'Expecting' model without a fetus is developed in which the entire uterus is filled with the amniotic fluid. 'Expecting', the pregnant occupant model and its without-fetus version are used in a number of frontal crash test simulations to investigate the contribution of the inclusion of a fetus on the strains generated at the UPI (Figure 3). Details of the vertical drop tests and crash tests with and without the fetus can be found in [13]. Maximum von Mises equivalent strain levels in uterus at the UPI are determined for with-fetus and without-fetus models to assess the possibility of placental abruption.
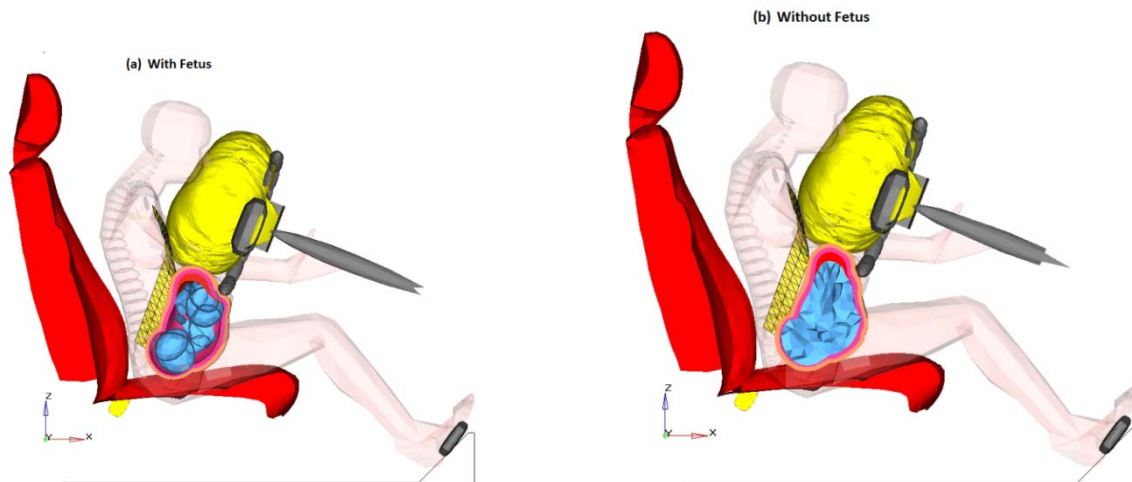


Figure 3. Typical frontal impact responses of the model with and without fetus for 30 kph at 105ms of the impact.

**Crash tests for correct and incorrect use of the seatbelt during pregnancy**

Hybrid III 5th percentile female ATD with the MAMA2B pregnancy conversion, the only commercially available device capable of representing the pregnant female was used for a series of Hyper-G sled tests to assess the effectiveness of correctly and incorrectly worn seatbelts.

A sinusoidal pulse with a delta-v of 50km/h was used, similar to the regulatory requirements for seat belts [15]. Two types of test were completed; a seat only style test (just the car seat and seat belt system with no pre-tensioners fired), and a buck style test (vehicle buck mounted on the sled with airbag and seat belt double pre-tensioners deployed). The driver's seat was used in all tests. The tests had the lap portion of the seat belt positioned correctly (across the hips and underneath the abdomen) and incorrectly (across the middle of the abdomen).

## RESULTS AND DISCUSSIONS

The analysis of the data collected from pregnant women revealed that the key regions of physical change during pregnancy are the chest, abdominal, and hip regions. The size of the chest, abdomen and hips of a pregnant woman can be so enlarged during pregnancy that these measurements exceed the equivalent measurements of the large 95th percentile male by a considerable amount. The abdomen region for males, non-pregnant women and pregnant women are shown in Figure 4. Details of the differences for other regions can be found in [3] and prove that pregnant women form a new population that was not considered in modelling before. Hence it is important to use the measurements of pregnant women in models that represent them.
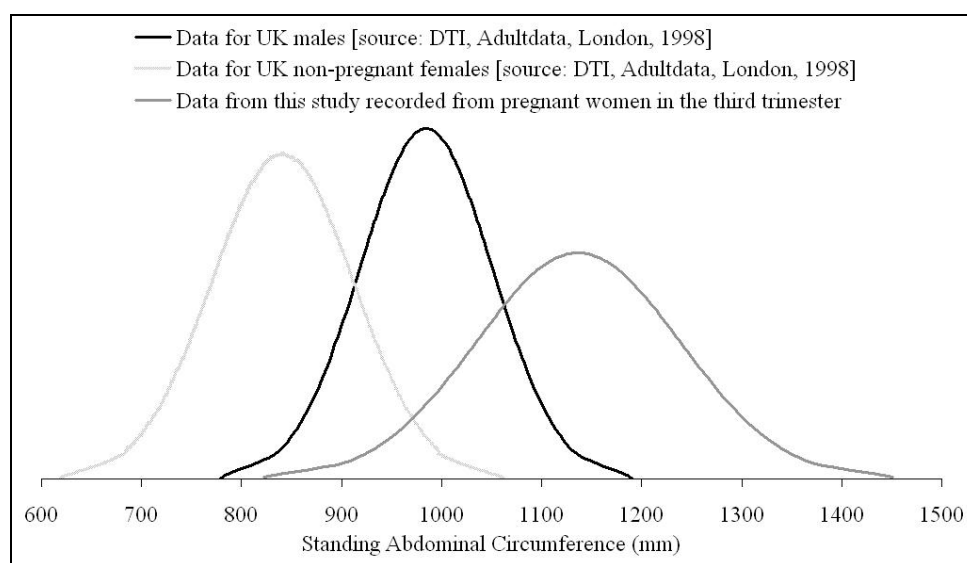


Figure 4. Standing abdominal circumference: A comparison of pregnant women in the third trimester against data for UK males and non-pregnant females.

'Expecting' incorporates the anthropometric details of pregnant women. Regarding the inclusion of the fetus, in general vertical drop tests of the uterus with fetus caused higher strain levels than without fetus model at angles of 0°, 30°, 90°. More importantly, at 180° drop, where the placenta is at the leading end of the uterus in the impact simulations, the highest strains on the uterus are observed at the UPI. In this case, significantly high (almost four times as much) strains in the model with fetus are observed. Crash simulations confirmed the importance of including the fetus. Full drop test and crash test results can be found in [13]. As an example, the airbag only case, where the seat belt is not worn during the impact of 15- 35 kph the strains at the UPI are shown in Figure 5, and proves how critical it can be in cases of 20 and 25 kph impacts. This demonstrates that when the fetus is included in the model, the placental abruption risk emerges at a crash speed of 20 kph, whereas the without fetus model shows that the placental abruption risk begins at a higher crash speed of 30 kph. Without the seatbelt, it is clear that the contribution of the fetus on the maximum strains at the UPI is much more pronounced and the placental abruption risk is found to be higher. The mass of the fetus plays a significant role in the behaviour of 'Expecting', the pregnant occupant model. These results clearly demonstrate that the fetus changes the entire dynamic response to impact.
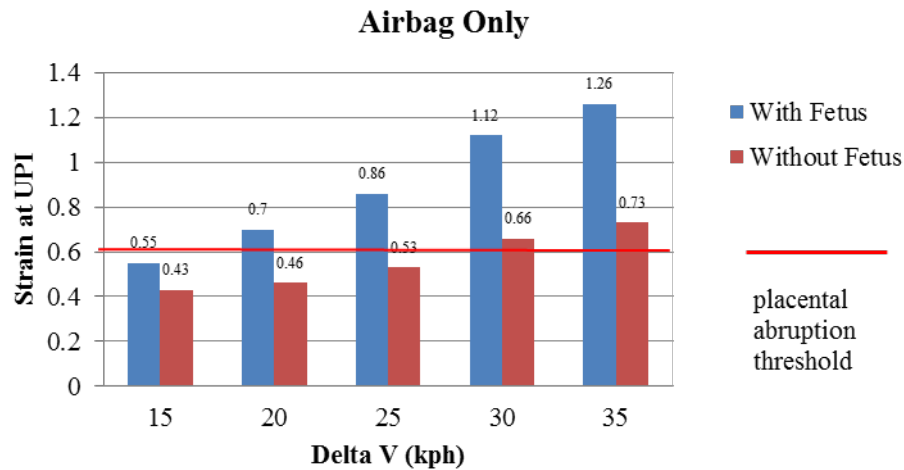
**Airbag Only**

Figure 5. Strain levels at the UPI of the pregnant occupant model with and without fetus
for airbag only case

Simulations of various crash scenarios with 'Expecting' have suggested that the fetus fatality risk
can increase with speed [7]. Results have also suggested that driving with full restrains, where both
the seatbelt is worn and airbag is active, can provide the safest conditions for the pregnant occupant.

On the other hand, the crash tests using the pregnant occupant ATD, MAMA2B , have highlighted
the importance of wearing the seatbelt 'correctly'. The correct position for the seat belt in pregnancy
is with the shoulder section passing across the shoulder, between the breasts, and around the
abdomen, and the lap section passing across the hips and underneath the abdomen. This seat belt
position is recommended by many authorities, including the UK Department for Transport [16], the
American College of Obstetrics and Gynaecology [17] and the National Highway Traffic Safety
Administration [18].

The traces for abdominal pressure (KPa) comparing the lap belt correctly positioned across the hips
according to the guidelines against the lap belt incorrectly positioned across the abdomen are shown
in Figure 6. Full experiment results can be found in [19]. It is clear that the lap belt positioned across
the abdomen gives a much higher pressure indicating higher risks, than with it positioned across the
hips. The peak pressure for the incorrectly positioned lap belt over the abdomen was one quarter to
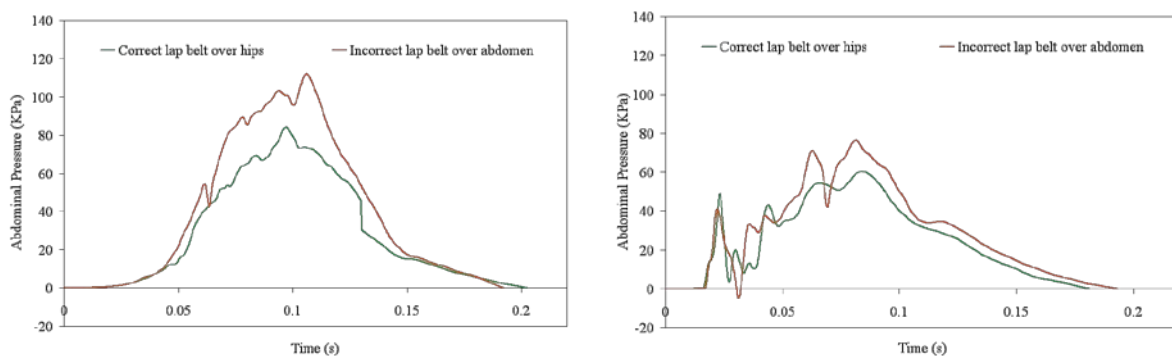one third greater in comparison to the correctly positioned lap belt over the hips.



Figure 6 Abdominal pressure (KPa) traces for seat and buck tests: Comparison of correct lap belt
position across the hips versus incorrect lap belt position across the abdomen.

The visual material from the simulations with 'Expecting' supports that in the investigated cases, the maximum strains in uterus at the placental location seem to be mainly due to steering wheel loading for the full-frontal impacts, whereas maximum strains in overall uterus occur mainly due to lap belt loading. As lap belt section of the seat belt tends to ride up towards the abdomen during driving [2], it is vital to wear it as correctly as possible in accordance with the guidelines.

Anthropometric data from pregnant women, the computational pregnant women model 'Expecting', simulation of the accidents and the need to wear the seatbelts correctly led the authors to design a commercially viable device to solve the problem. The devise is applied to the conventional, industry standard three-point seat belt and it does not interfere with its functionality.

Static and dynamic user tests of the device were conducted with pregnant women at Loughborough University with excellent results. During the user tests, pregnant women assessed the device's comfort and ease of use as well as its functionality. Sled tests at Thatcham Crash Test Laboratory has also taken place and confirmed that the device keeps the three-point seatbelt always where it should be.

## CONCLUSIONS

The work described in this paper is a part of a comprehensive research program at Loughborough University to improve fetus safety using a computational pregnant occupant model. First the features of the pregnant women were identified. Then a computational pregnant occupant model with a finite element uterus model and a fetus were developed. The model also incorporates the geometric features of a $5^{th}$ percentile female at around the $38^{th}$ week of gestation. Vertical drop tests of the uterus and crash tests of the model 'Expecting' have been conducted. In conclusion, the findings of the research suggest that the fetus should be included in the uterus in pregnant woman models to take into account its effect in more realistically simulated dynamic behaviour of pregnant occupants.

Simulations with 'Expecting' and sled tests with the commercially available physical model MAMA2B show that the correctly worn seatbelt is essential for the safety of pregnant occupant and fetus, and further systems that enable the correct use without interfering with the existing restraint systems are beneficial.

## ACKNOWLEDGEMENTS

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