# Evaluation of LS-DYNA® Corpuscular Particle Method for Side Impact Airbag Deployment Applications

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## ABSTRACT

*A uniform pressure method, i.e. no pressure variation on bag surface and location, in LS-DYNA has been commonly used to simulate airbag deployment and interaction of airbag with the occupants. Another newly developed LS-DYNA CPM (Corpuscular Particle Methodology) has gained recognition and acceptance recently because it considers the effect of transient gas dynamics and thermodynamics by using a particle to represent a set of air or gas molecules and then a set of particles to represent the entire air or gas molecule in the space of interest. This innovative method, however, has yet be fully utilized and applied with confidence in airbag deployments simulation without systematic tests and validations to avoid non-physical tuning factors traditionally being applied to the uniform pressure airbag finite element models.*

*In this paper, inflator closed and vented tank tests, static airbag deployment test, and linear impactor tests with various configurations and impact speeds are systemically conducted and then correlated with a CPM airbag model to determine whether the methodology can be applied for all the tests and whether any tuning factors should be applied in the process.*

*This innovative LS-DYNA particle method has been fully investigated in this systematic study by correlating it with a comprehensive set of inflator tank tests, static airbag deployment, and rigid linear impactor tests. The correlations start from inflator closed and vented tank tests to verify the provided inflator characteristics, mass flow rate and temperature curves. The inflator characteristics will then be employed into static airbag deployment simulation to determine the airbag fabric heat convection coefficient, which is adjusted in this simulation to match the test pressure profile. This is the only parameter tuned to match the test pressure. This airbag model is then used to simulate those linear impact tests. With the systematic validations and correlations to avoid using tuning factors, the airbag model results in a good match of the overall airbag internal pressure and impactor deceleration histories with the tests and the simulations for all the linear impactor tests conducted. Effects of the inflator variations are also studied to illustrate the potential bounds of deceleration and airbag chamber pressure in impacts.*

## INTRODUCTION

Control volume (CV) method in LS-DYNA has been widely adopted as the method to simulate airbag deployment for the impact conditions when the airbags have already fully inflated and are in position before the occupant comes into contact with it [1, 2]. For out-of-position (OOP) airbag simulations [3], however, the CV has been recognized as less effective in duplicating the occupant-to-airbag interaction with fidelity. To enhance the airbag deployment and occupant interaction performance, a CPU intense ALE (Arbitrary Lagrangian Eulerian) [4] method has also been developed to address the issues. In recent years, an innovative numerical corpuscular particle methodology has gained more recognition and acceptance for airbag deployment applications [2, 3, 4, 5, 6, 7]. The particle method considers the effect of transient gas dynamics and thermodynamics by using a particle to represent a set of finite air or gas molecules. Then, a set of particles is used to embody all of the air or gas molecules in the space of interest [2]. This particle method, which has slightly higher CPU usage has been documented [2] as an improvement of accuracy over the CV method. In addition, the particle method has a similar accuracy when comparing with the ALE method, but it requires significantly less CPU resource.

Side impact airbag (SIAB) and passenger side airbag (PAB) are two typical cases that occupants may come into contact with an airbag while it is inflating. In the case of side impact airbag, it can be easily understood since the airbag mounted on the seat side panel is so close to the occupant and its surrounding structure. For the PAB, a similar situation happens when the H3-05 female dummy is in full forward seating position or when a child dummy is tested according to NHTSA out-of-position procedure.

There are numerical enhancements with the new LS-DYNA releases, and we need to understand the implication of the changes and their impacts on the correlation and modeling approach. For example, while applying the particle method in airbag simulations, there was an issue of underestimating the mass flow rate through the vent holes when using previous versions of LS-DYNA. The new LS-DYNA offered an enhancement to correctly capture the leakage through the vents, and it will be studied and validated in this project. In order to apply the CPM with confidence to the finite element model, this project was formed and executed.

The project approach was, first, to have the supplier conduct the designed inflator tank test, airbag static deployment, and airbag linear impactor tests. The supplier provided CV airbag model and was converted into a CPM model. This CPM model was then used to simulate the static deployment and impact tests according to the test setup. Thoroughly selected model parameters were carefully studied and the heat convection coefficient is tuned within the documented engineering standard ranges to achieve good correlations.

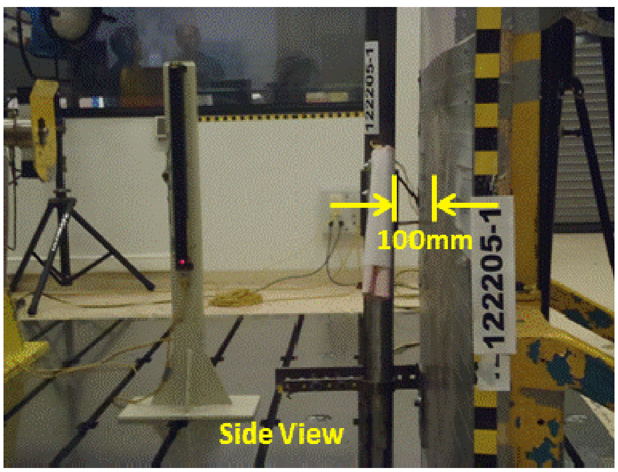
To characterize the inflator and generate the required inflator mass flow rate and temperature curves for finite element simulation [8], the inflator closed tank test was conducted by the supplier. After receiving these inflator FE curves, both closed and vented tank tests were simulated using LS-DYNA particle method to ensure fidelity of the inflator model. While calculating the mass flow rate and temperature curves from a conducted inflator closed tank test, the heat loss through conduction with the steel tank surface should be included so that the inflator mass flow rate and temperature curves can be used to reproduce and capture the characteristics seen in the test. Since these two fundamental tank tests were conducted without the complication of airbag deployment, the calculated inflator mass flow rate and temperature curves should be continued to be employed in the subsequent airbag deployment simulations.

The airbag deployment correlations are to be conducted after confirmation of the inflator model from the inflator tank test pressure correlations. We start with correlating the static deployment bag pressure history and from it we could determine what are the proper fabric heat convection coefficient, fabric leakage parameter, or the gas leakage through the seam. Then, the linear impact tests with various speeds and configuration will be correlated with the heat convection coefficient and leakage parameters derived from the static deployment test. Those parameters should be identical or very similar when applying the CV method to correlate the pressure or deceleration histories so that they all have the same physical characteristics behind all the parameters. The pressure data from the airbag tests may not be able to represent the average bag pressure in the initial deployment stage, however, the pressure data should be close to the average bag pressure after passing the initial inflating phase.

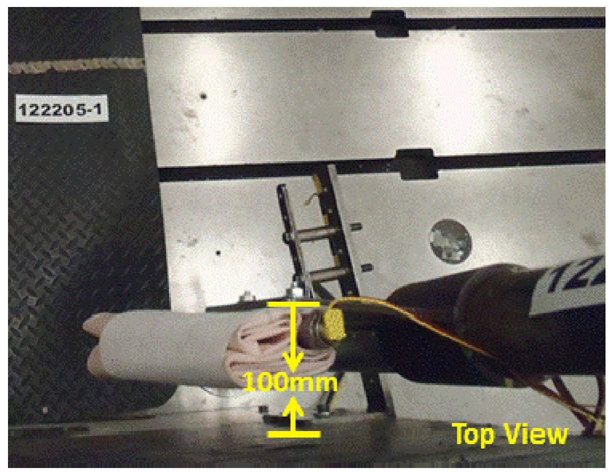
After the static deployment correlation, the linear impact tests can then be simulated and correlated and further adjustment of the leakage parameters in LS-DYNA may be necessary to have the subsequent tests well correlated. It is critical to design multiple speeds impact tests or tests with various configurations of impactor orientation relative to the airbag so that the airbag model is robust for various impact conditions.

## TEST SETUP

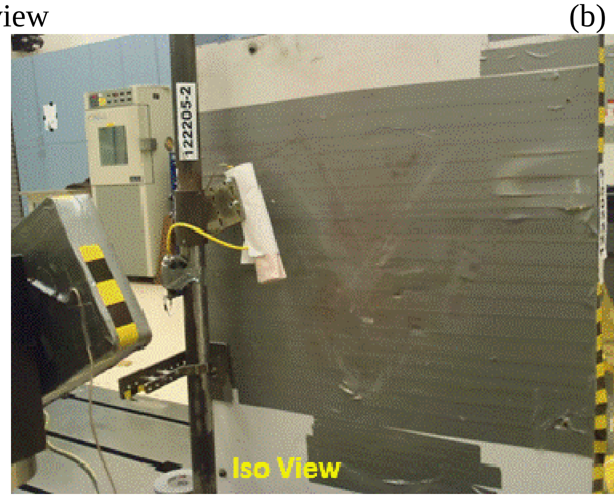
To reduce the inflator characteristic variation, the vehicle side impact airbag inflators studied in this project are secured from the same manufacturing lot. Two repeated tests are requested for the closed and vented tank tests. Numerous linear impactor tests are conducted and the linear impactor speed, mass, and orientation are allowed to be varied to test the robustness of the airbag modeling. The linear impactor test setups are shown in Figure 1 with different viewing angles. The impactor is also oriented in two directions; one of the airbag body's primary axis is parallel to the impact surface's primary axis so that the entire impactor surface will compress the airbag. The other airbag body primary axis is perpendicular to the impact surface's primary axis so that the impactor surface will compress only a portion of the airbag, as shown in Figure 2.




(a) Side view

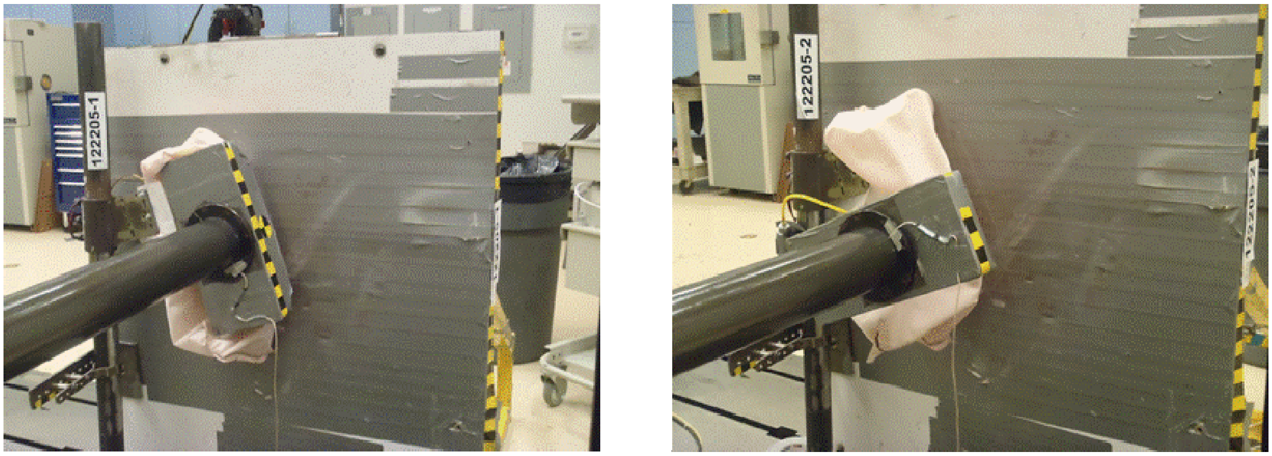



(b) Top view




(C) Iso view

Figure 1. The linear impactor test set up. The side impact airbag is tested without the plastic housing. (a) side view, (b) top view, (c) isometric view



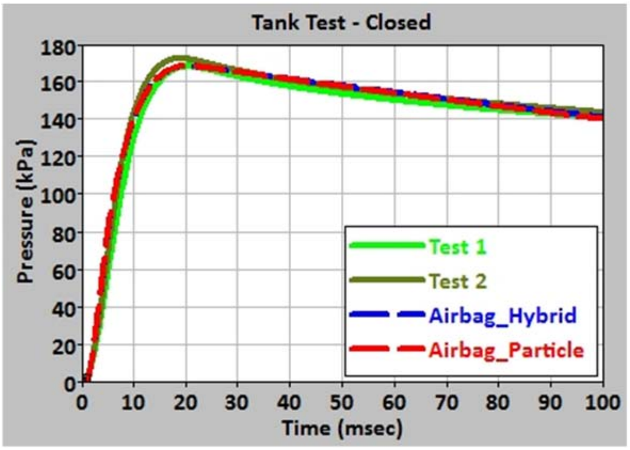

(a) Impactor parallel to airbag (b) Impactor perpendicular to airbag

Figure 2. Impactor orientation relative to deployed airbag, (a) impactor parallel to airbag, (b) impactor perpendicular to airbag

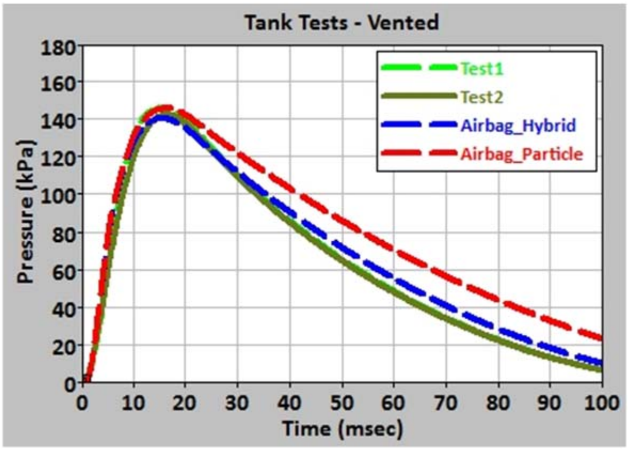
## TANK TESTS

We started with correlating the one cubic foot tank test pressure using the mass flow rate and temperature curves of the inflator provided by the supplier in the finite element model. As a standard procedure, the inflator closed tank test is conducted and the pressure is measured to generate an inflator's temperature and mass flow rate curves. The mass flow rate and temperature curves provided can match the peak pressure in a tank test well. However, the pressure after reaching the peak will not decrease gradually as shown in the test in Figure 3. To further improve the pressure correlation, the heat loss through the steel surface is also incorporated in the simulation, and good pressure correlations are achieved, as shown in Figure 3. This selected heat conduction coefficient used in the tank test is a compromise, and it will cause more reduction of the pressure in the closed tank test simulation and less reduction of the pressure in the vented tank test simulation, as shown in Figure 3. The averaged gas temperature inside the tank cannot be accurately obtained since there is a time delay in using devices for measuring the temperature unless a very expensive high speed infrared method is used, therefore the temperature of the test is not available for comparison.

In simulating the tank tests pressure, both the particle and CV methods are used to evaluate the methods in duplicating the pressure histories. When using the particle method for closed tank test, the number of particle can be relatively small (10k particles will be fine for such a purpose), and it has little influence on the pressure correlation since the particles will not leak out of the container. There are initial air molecules inside the tank, and they need to be included in the simulation to accurately represent the existing molecules. The rule of thumb in determining the number of particles in the air and gas is to obtain the ratio of the total mass of the air and gas and then formulate the mass of mole of each gas and air particle to be equal. Original kinetic molecular theory is using rigid sphere to represent each molecule. LS-DYNA is using the lumped system and each particle should hold the same amount of molecule (mole) to match the original assumption. For this side impact inflator, the initial air mass inside the one cubic foot tank is about 5 times of the inflator gas. Accordingly, the number of air particles in the tank is devised to be about 5 times of the gas particle. For the vented tank test, the number of particle for the gas is set to be 200k and the air particle is set to be 1M for this simulation. A larger number of particles will lower the peak pressure slightly in the vented tank test with a higher CPU usage .




(a) Closed tank test



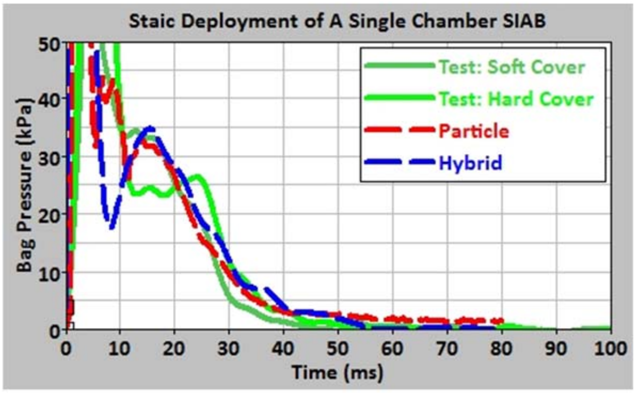

(b) Vented tank test

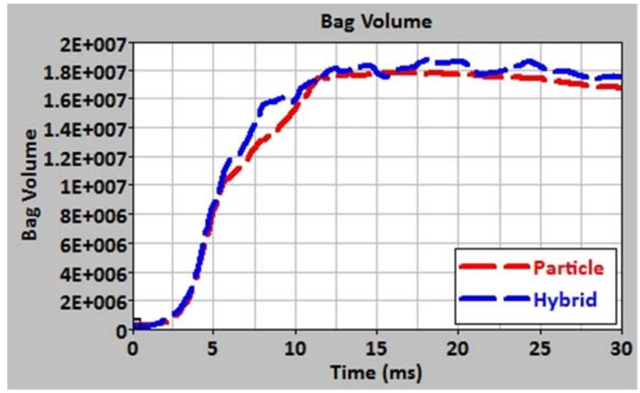
Figure 3. Tests of closed and vented tank tests and results from finite element simulations using both CV and particle methods. (a) closed tank test, (b) vented tank test.

## AIRBAG STATIC DEPLOYMENT

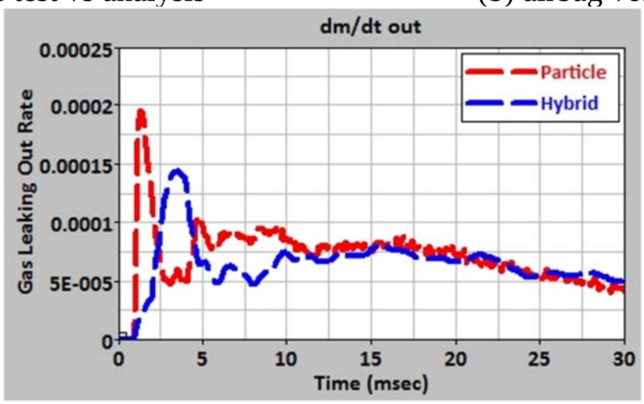
The LS-DYNA particle airbag method requires that the inflator nozzle FE meshes are enclosed by an airbag cushion throughout the analysis. Since the inflator nozzle was not meshed in the original supplier SIAB model, it needs to be created and placed inside the cushion before running analysis for gas particles to flow into the bag. The FE mesh of the inflator module is not required for CV method.

The validated inflator mass flow rate and temperature curves from the tank test are incorporated into the airbag model without using any scaling factors. Since the side impact airbag cushion is made of a coated fabric with sealed seams, which cannot leak gas, the leakage through the fabric modeled in the supplier original CV model is taken out as well. The LS-DYNA *airbag_particle model parameter of “BLOCK” on vent is set to be 10 so that the gas cannot leak out when the vent is blocked in the deployment process. The heat convention coefficient of the fabric is optimized such that the simulated static deployment pressure history matches the test. Because of the nature of the CV method, the *airbag_hybrid airbag is observed to bounce more when inflated and it can also be observed when comparing the two airbag volume histories, as shown in Figure 4. The CV method also tends to have larger volume and lower pressure in the inflating phase as well. The pressure history is shown in Figure 5 when the heat loss through the fabric was not considered. In order to match the pressure history without the heat loss, some non-physical tuning factors like additional venting or temperature scaling have been used to compensate to match the test results. The airbag model with this type of tuning can match a single validation impact test, but it is not capable of predicting other impact conditions with confidence. Without the non-physical tuning factors, the CV method can still match the static deployment pressure profile, as shown in Figure 6. Although both methods can correlate the pressure profile reasonably well, the particle method does correlate better when comparing the deployment bag shape with the CV method, as shown in Figure 7.




(a) airbag pressure test vs analysis (b) airbag volume




(c) mass flow out of airbag

Figure 4. Static deployment correlation of the single chamber side impact airbag, (a) airbag pressure of simulations and tests, (a) airbag volume in two simulations, (c) gas leaking out of airbag for the two methods.

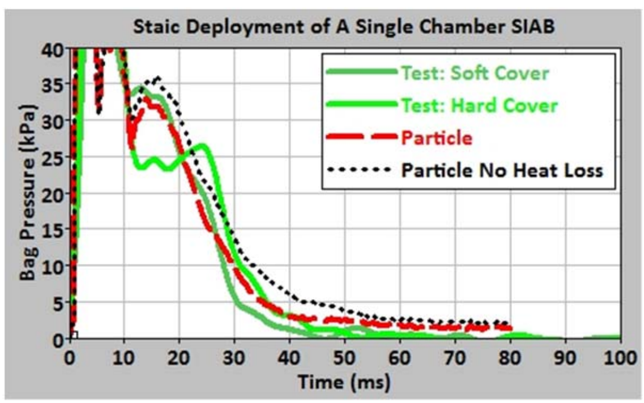



Figure 5. Static deployment of side impact airbag using particle method with and without considering the heat loss through fabric.

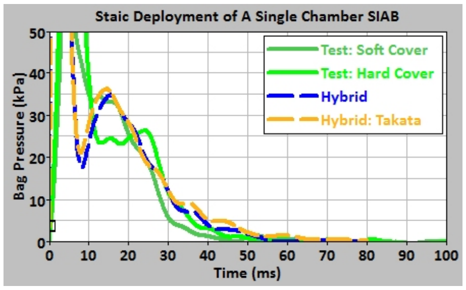
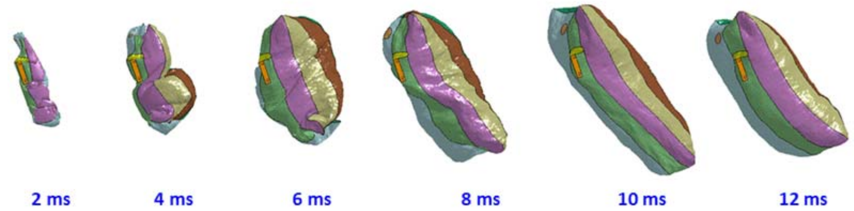
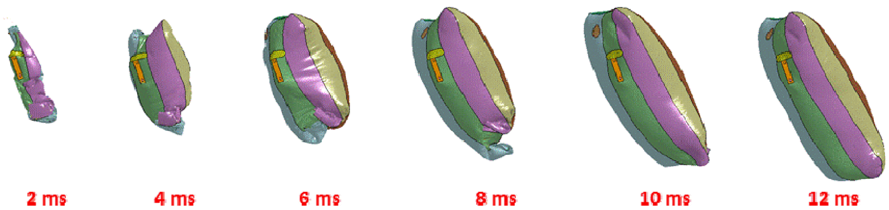


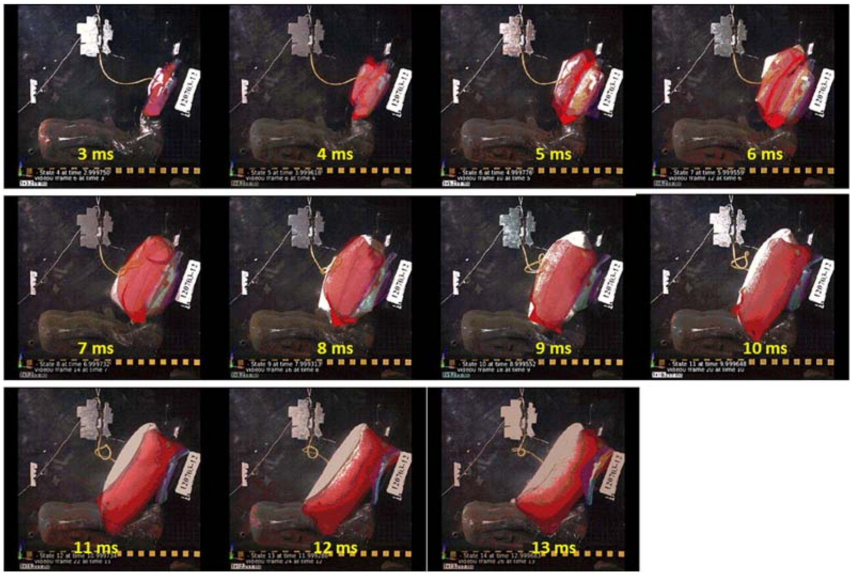

Figure 6. The static deployment airbag pressure profile using the airbag model delivered from a supplier and new airbag model after stripping off temperature scaling factor and other tuning factors.




(a) Airbag deployment first 10ms sequence by using *airbag_hybrid method




(b) Airbag deployment first 10ms sequence by using *airbag_particle method



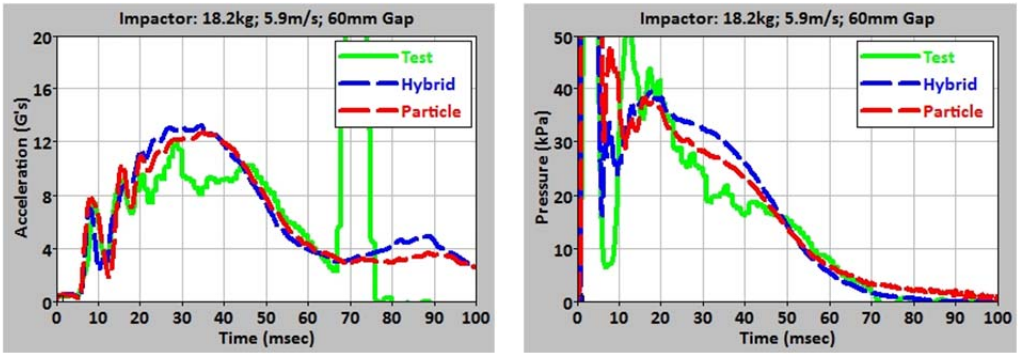

(c) Comparison of airbag deployment sequence of particle method and test

Figure 7. Static deployment shape of the single chamber SIAB. (a) deployment sequence using CV method, (b) deployment sequence using particle method, (c) comparison of sequence of particle method airbag deployment and test

## LINEAR IMPACTOR TESTS

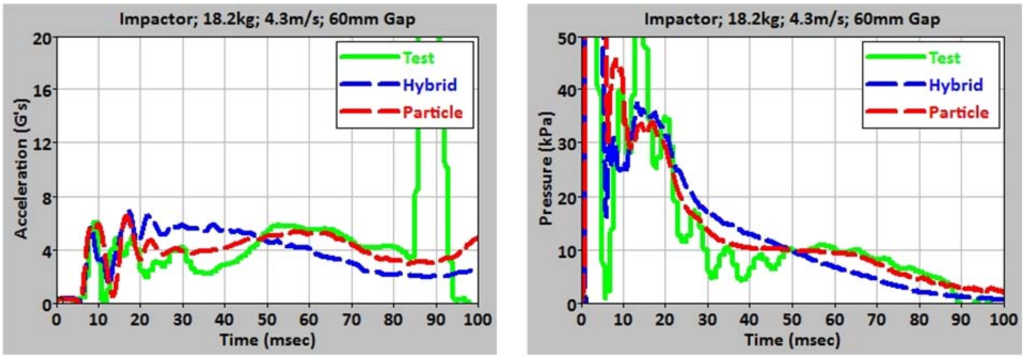
After achieving good static deployment correlation, we then proceed to simulate the first series of two tests and are able to correlate the deceleration pulses and bag pressures as shown in Figures 8 and 9. Initially, there are some reservations of the tests' validity because of the very different deceleration profiles among the two tests when their impact speeds were not significantly different. However, the model is able to match the two tests well. Figures 8 and 9 show the results of using the CV and particle methods without tuning factors, and all of the impact tests correlation are shown in Appendix A.

The number of particles used in the particle method simulations can influence the accuracy of the results. The default NP (number of particle) listed in the manual is 200k, while in other publication, it was suggested to use 10k particles per liter of volume so that the mean free path or average distance between collisions is roughly 1cm. For this side impact airbag design of 18 liters, the default value in the manual seems to be a good starting point. For this model, however, 800k particles seem to improve the deceleration profile slightly, as shown in Figure 10.



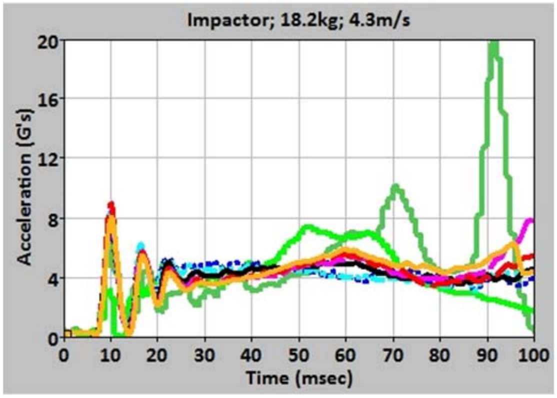

(a) Linear impactor deceleration (b) Pressure history

Figure 8. Impactor deceleration pulse and airbag pressure histories for 18.2kg impactor with 5.9m/s speed and 60mm distance from the airbag mounting plate to the reaction surface. (a) linear impactor deceleration, (b) pressure history.

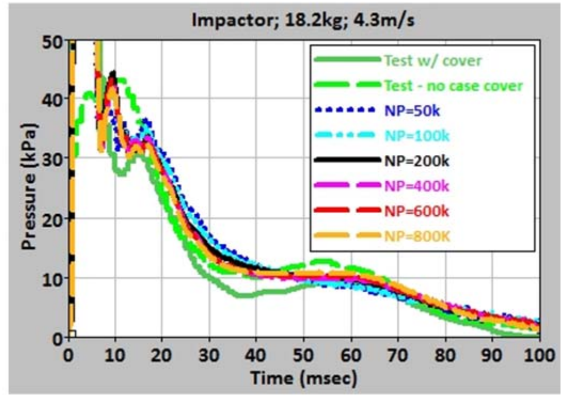



(a) Linear impactor deceleration (b) Pressure history

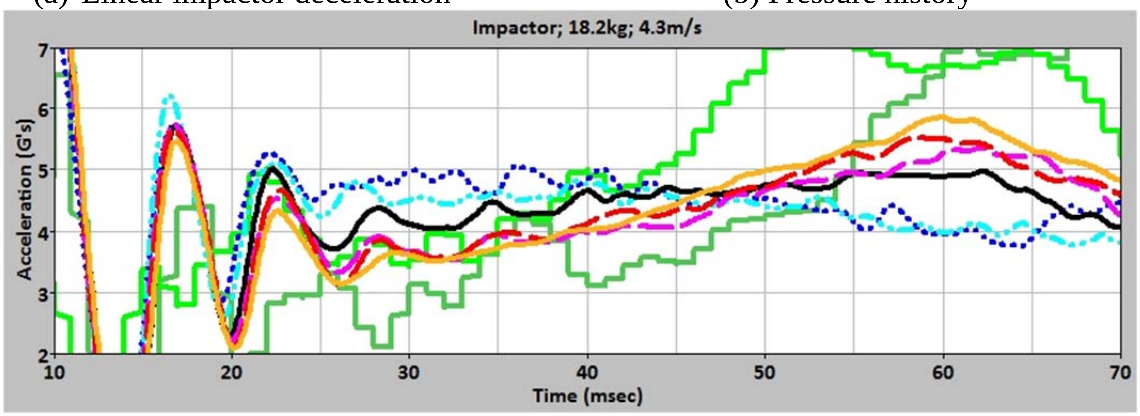
Figure 9. Impactor deceleration pulse and airbag pressure histories for 18.2kg impactor with 4.3m/s speed and 60mm distance from the airbag mounting plate to the reaction surface. (a) linear impactor deceleration, (b) pressure history.



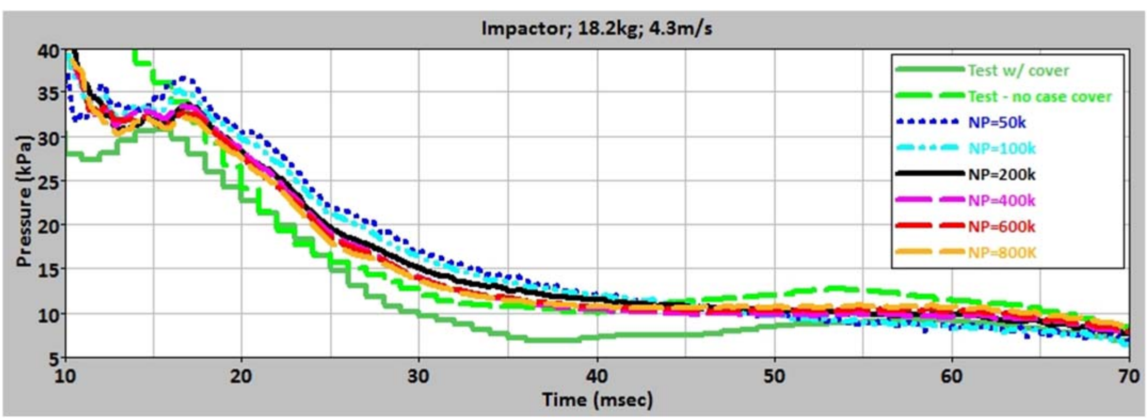

(a) Linear impactor deceleration




(b) Pressure history




(c) Close-up of the deceleration history




(d) Close-up of the pressure history

Figure 10. Impactor deceleration pulse and airbag pressure histories for 18.2kg impactor with 4.3m/s speed and 100mm distance from the airbag mounting plate to the reaction surface. (a) the deceleration history with NP (Number of Particles) ranging from 50k to 800k, (b) the associated pressure histories, (c) close-up of the deceleration history, (d) close-up of the pressure history.

## INFLATOR VARIATIONS

The manufactured inflators generally have slightly different characteristics because of slight variation in output gas from the inflator deployment process. The effect of this variation will result in closed tank pressure variation, shown in Figure 11. To mimic the inflator variation ranges captured in Figure 11, the inflator temperature curve us scaled by +/-14%, as shown in Figure 12. These lower and upper bound temperature scaling factors are then used in linear impactor simulations to capture the bounds of the linear impact tests due to the inflator variation. Results of the two simulations from inflator variation are shown in Figures 13 and 14. Appendix B plotted all the bounds from this variation.

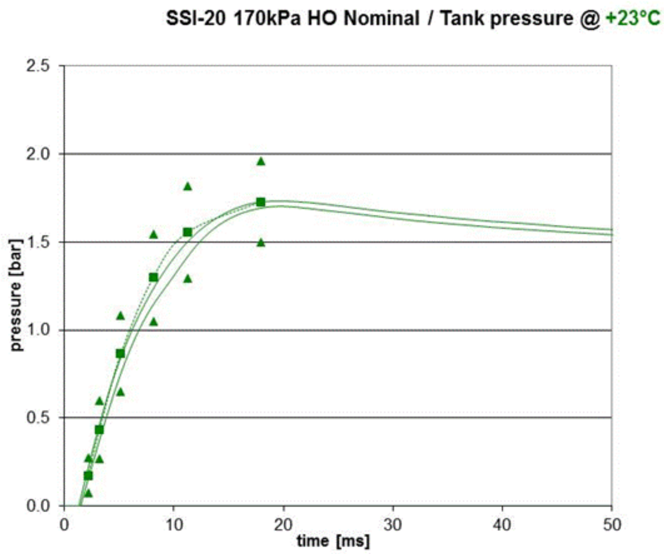



Figure 11. Pressure variation from the inflators' closed tank tests.

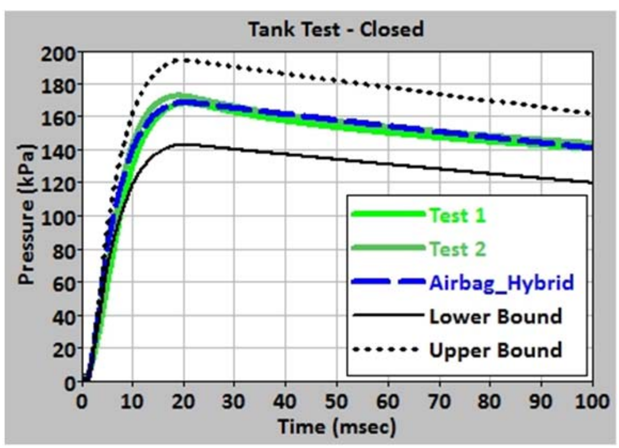
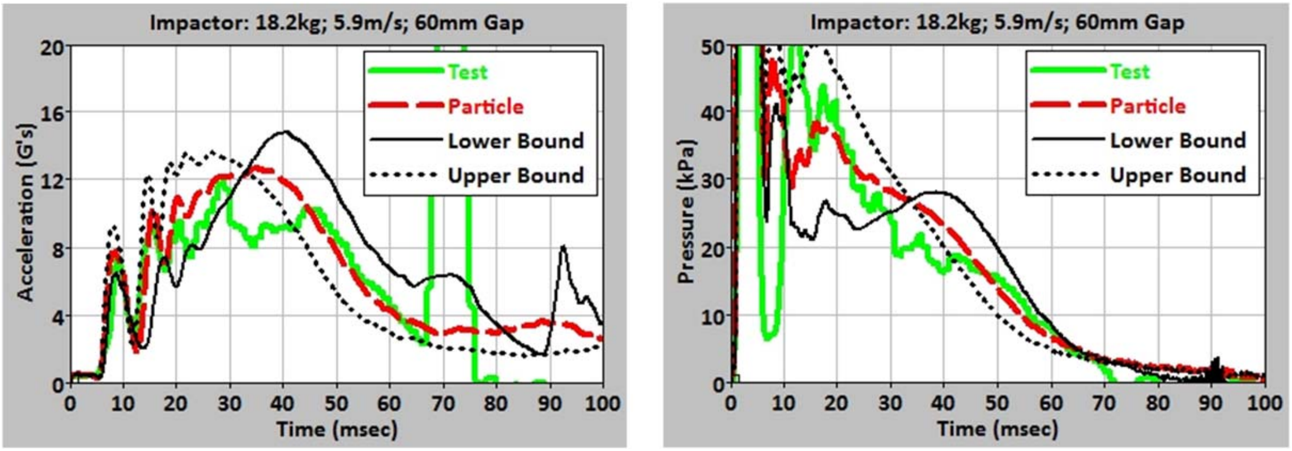
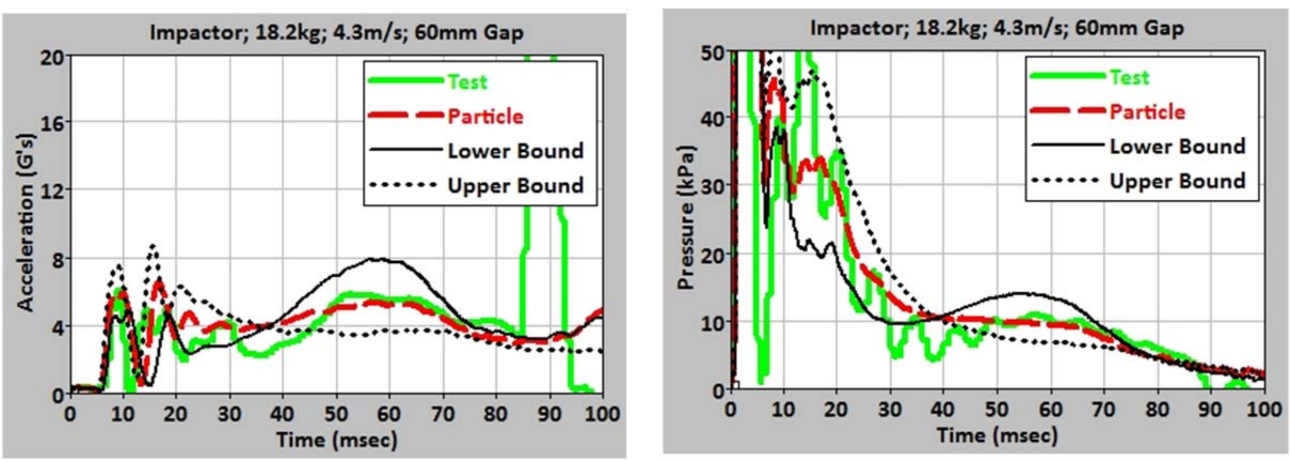



Figure 12. The upper and lower bounds of the pressure curves were replicated by adjusting the inflator temperature curve in the model by +/-14%.




(a) Linear impactor deceleration (b) Pressure history

Figure 13. Impactor deceleration pulse and airbag pressure bounds for 18.2kg impactor with 5.9m/s speed and 60mm distance from the airbag mounting plate to the reaction surface. (a) linear impactor deceleration, (b) pressure history.




(a) Linear impactor deceleration (b) Pressure history

Figure 14. Impactor deceleration pulse and airbag pressure bounds for 18.2kg impactor with 4.3m/s speed and 60mm distance from the airbag mounting plate to the reaction surface. (a) linear impactor deceleration, (b) pressure history.

## SUMMARY

This innovative LS-DYNA particle method has been fully investigated by correlating with a set of tank tests, airbag static deployment test, and the airbag rigid linear impactor tests. The correlations start from the closed and vented tank tests to verify the inflator characteristics, i.e., the mass flow rate and temperature curves. The inflator characteristics would then be employed into static airbag deployment simulation. In correlating the static deployment, the airbag fabric heat convection coefficient is adjusted to determine a proper coefficient for this airbag. Note that this is the only parameter being tuned to match the test.

This airbag model is then simulated according to test configurations of linear impact tests. The pressure curves of the model and hardware test should be correlated without altering inflator and airbag model characteristics. The airbag internal pressure information collected from the tests need to be carefully examined to ensure validity of the data since the pressure data cannot represent the overall airbag chamber pressure as the output from LS-DYNA.

Using this systematic validations and correlations approach without using tuning factors result in a good match of the overall airbag internal pressure and impactor deceleration histories between the tests and the simulations for all the linear impactor tests conductedThis allows the LS-DYNA CPMto be applied with higher levels of confidence in airbag simulations. Effects of the inflator variations are also studied to demonstrate the potential bounds of the impactor deceleration and airbag chamber pressure in repeated impacts.

## ACKNOWLEDGMENTS

Many colleagues have been generous in giving us their valuable time to discuss the project and providing us with help in airbag modeling. The authors particularly wish to thank Wenyu Lian and Amit Nair from GM for helping us in studying this project, and Jonathan Kibat for sharing his expertise in conducting the SIAB tests.

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# APPENDIX A - Correlations of Side Impact Airbag Using Uniform Pressure And Particle Methods

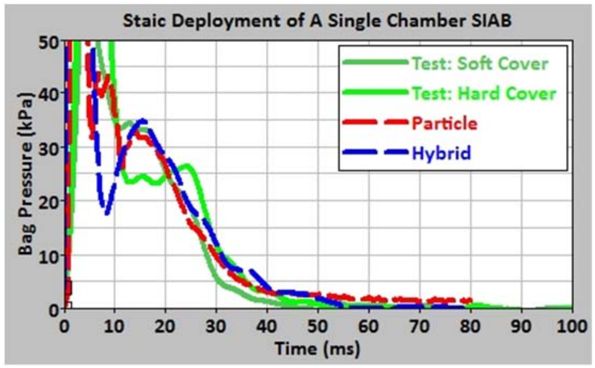
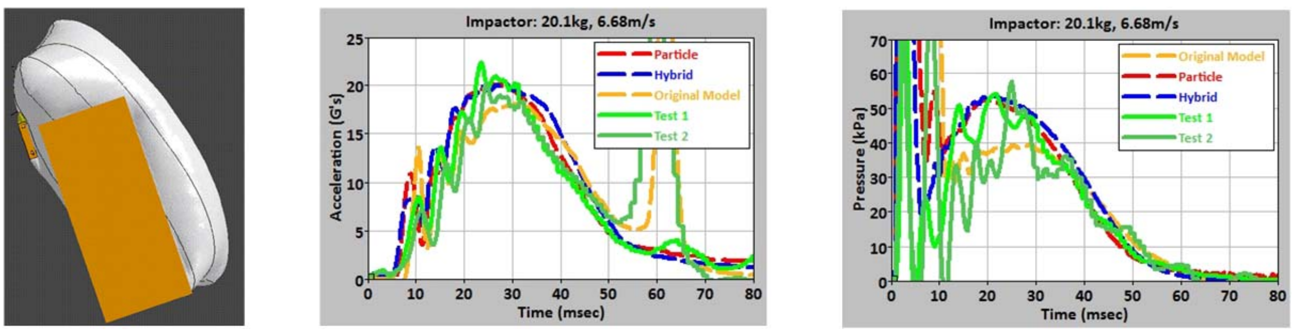
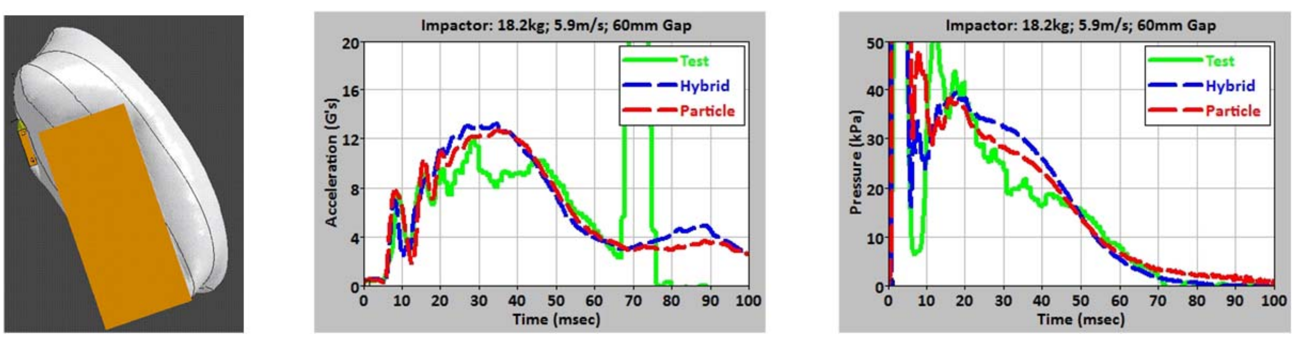



Figure A1. Static Deployment pressure history of using both particle and uniform pressure methods



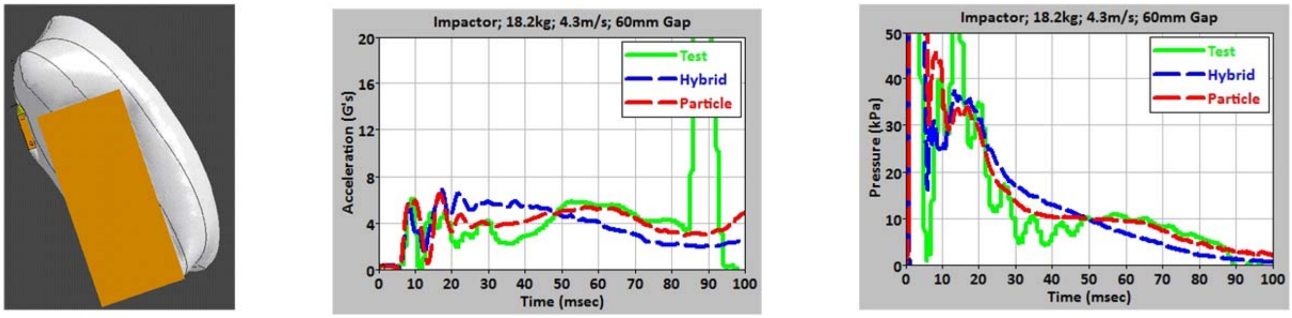

(a) Impact (b) deceleration (c) pressure

Figure A2. Impactor deceleration pulse and airbag pressure histories of using both particle and uniform pressure methods for 20.1kg impactor with 6.68m/s speed and 100mm distance from the airbag mounting plate to the reaction surface. (a) the impact configuration, (b) deceleration pulse, (c) pressure history.



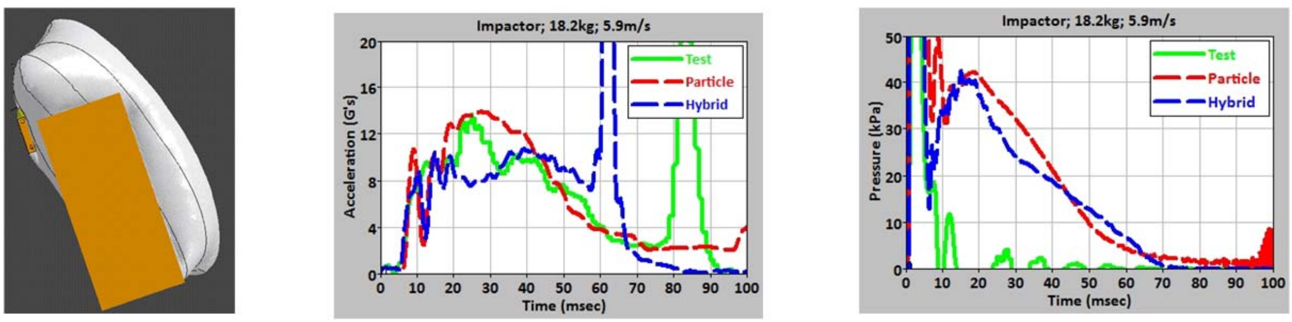

(a) Impact (b) deceleration (c) pressure

Figure A3. Impactor deceleration pulse and airbag pressure histories of using both particle and uniform pressure methods for 18.2kg impactor with 5.9m/s speed and 60mm distance from the airbag mounting plate to the reaction surface. (a) the impact configuration, (b) deceleration pulse, (c) pressure history.



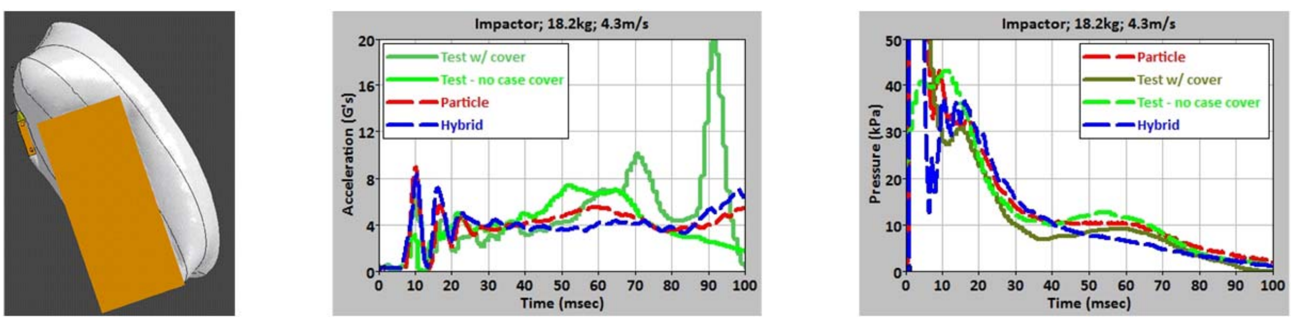

(a) Impact (b) deceleration (c) pressure

Figure A4. Impactor deceleration pulse and airbag pressure histories of using both particle and uniform pressure methods for 18.2kg impactor with 4.3m/s speed and 60mm distance from the airbag mounting plate to the reaction surface. (a) the impact configuration, (b) deceleration pulse, (c) pressure history.



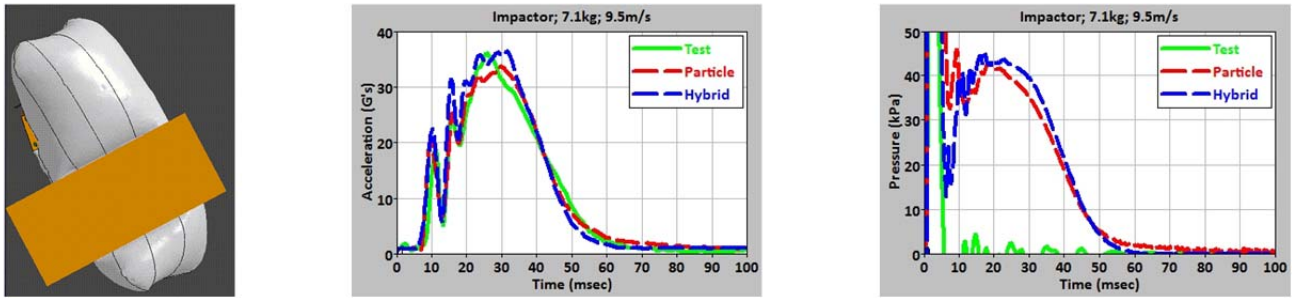

(a) Impact (b) deceleration (c) pressure

Figure A5. Impactor deceleration pulse and airbag pressure histories of using both particle and uniform pressure methods for 18.2kg impactor with 5.9m/s speed and 60mm distance from the airbag mounting plate to the reaction surface. (a) the impact configuration, (b) deceleration pulse, (c) pressure history.



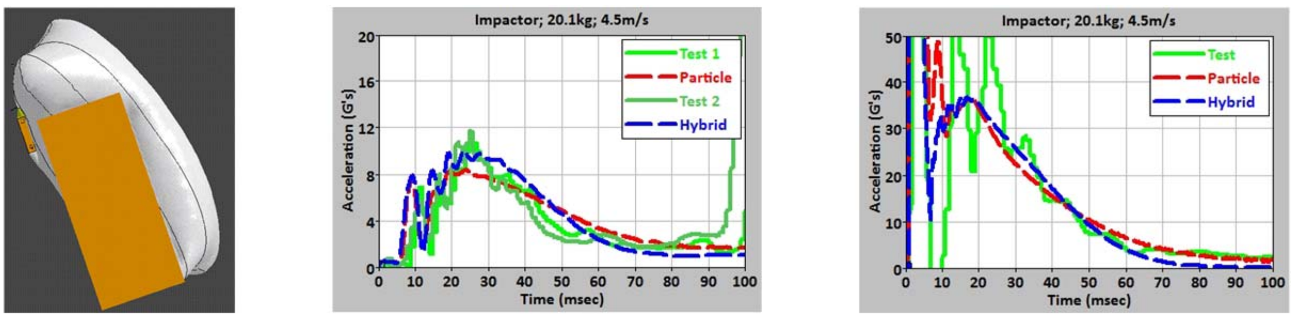

(a) Impact (b) deceleration (c) pressure

Figure A6. Impactor deceleration pulse and airbag pressure histories of using both particle and uniform pressure methods for 18.2kg impactor with 4.3m/s speed and 100mm distance from the airbag mounting plate to the reaction surface. (a) the impact configuration, (b) deceleration pulse, (c) pressure history.



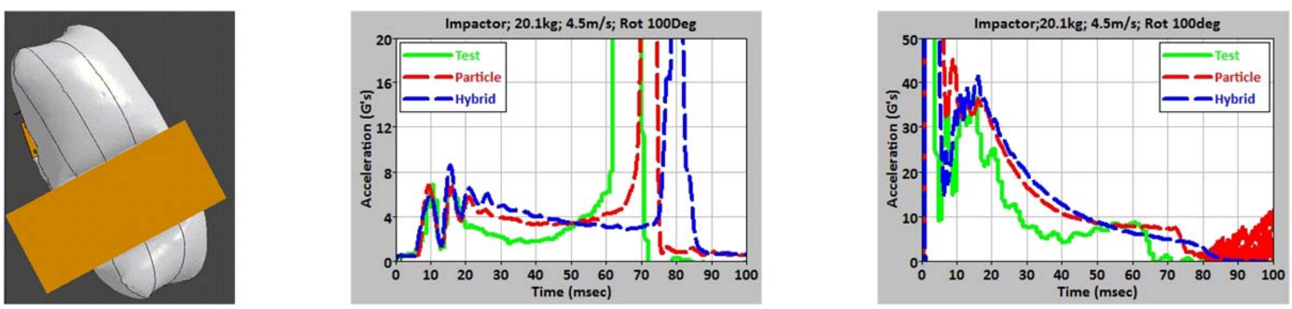

(a) Impact (b) deceleration (c) pressure

Figure A7. Impactor deceleration pulse and airbag pressure histories of using both particle and uniform pressure methods for 7.1kg impactor with 9.5m/s speed and 100mm distance from the airbag mounting plate to the reaction surface. (a) the impact configuration, (b) deceleration pulse, (c) pressure history.




(a) Impact (b) deceleration (c) pressure

Figure A8. Impactor deceleration pulse and airbag pressure histories of using both particle and uniform pressure methods for 20.1kg impactor with 4.5m/s speed and 100mm distance from the airbag mounting plate to the reaction surface. (a) the impact configuration, (b) deceleration pulse, (c) pressure history.




(a) Impact (b) deceleration (c) pressure

Figure A9. Impactor deceleration pulse and airbag pressure histories of using both particle and uniform pressure methods for 20.1kg impactor with 4.5m/s speed and 100mm distance from the airbag mounting plate to the reaction surface. (a) the impact configuration, (b) deceleration pulse, (c) pressure history.

# APPENDIX B - Correlations With Lower And Upper Bounds of Side Impact Airbag

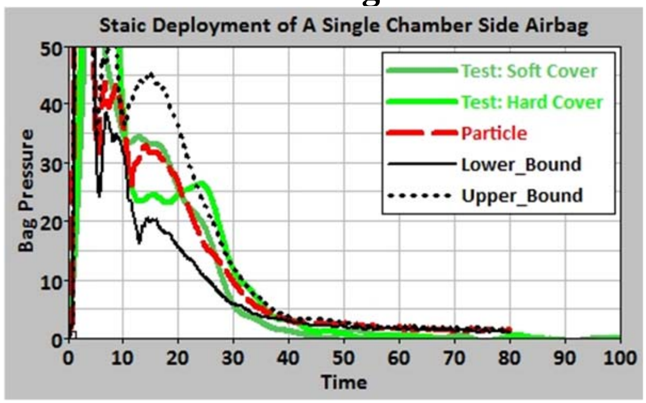
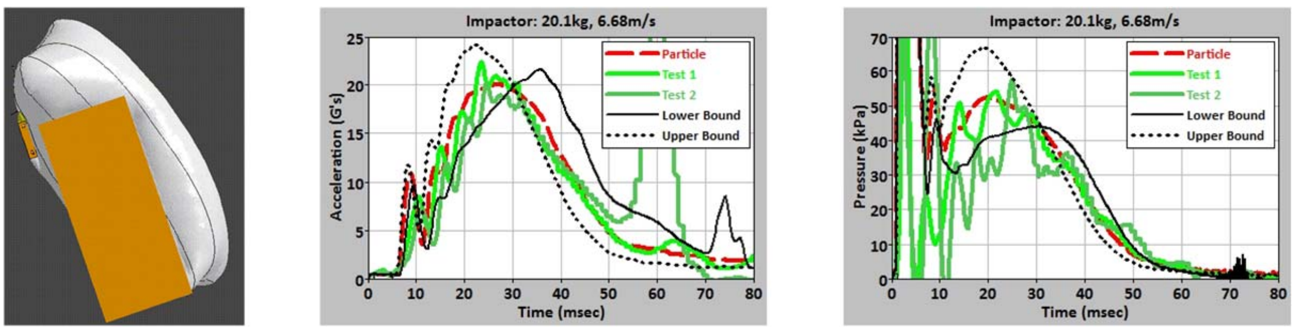
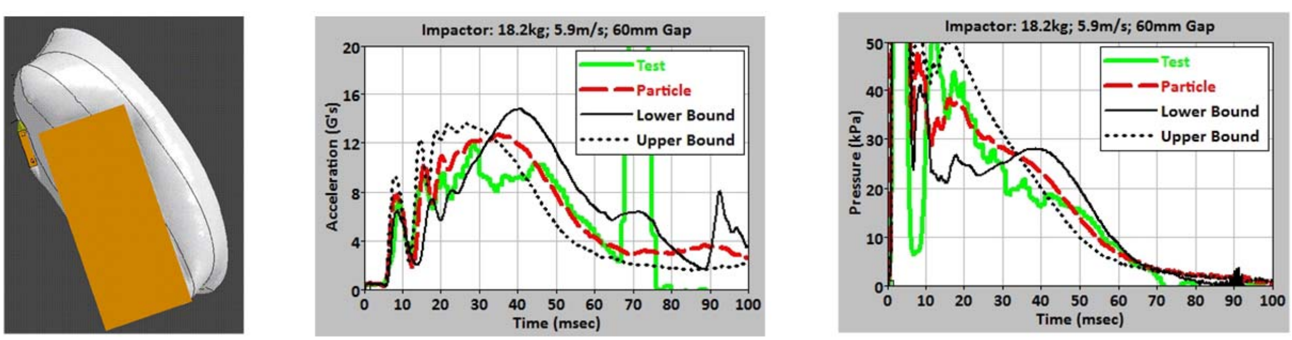



Figure B1. Static Deployment pressure history of using both particle and uniform pressure methods



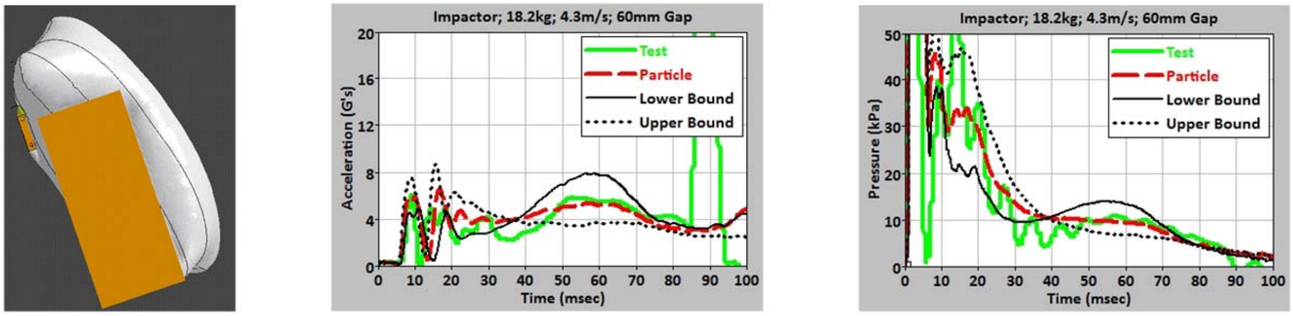

(a) Impact (b) deceleration (c) pressure

Figure B2. Impactor deceleration pulse and airbag pressure histories of using both particle and uniform pressure methods for 20.1kg impactor with 6.68m/s speed and 100mm distance from the airbag mounting plate to the reaction surface. (a) the impact configuration, (b) deceleration pulse, (c) pressure history.



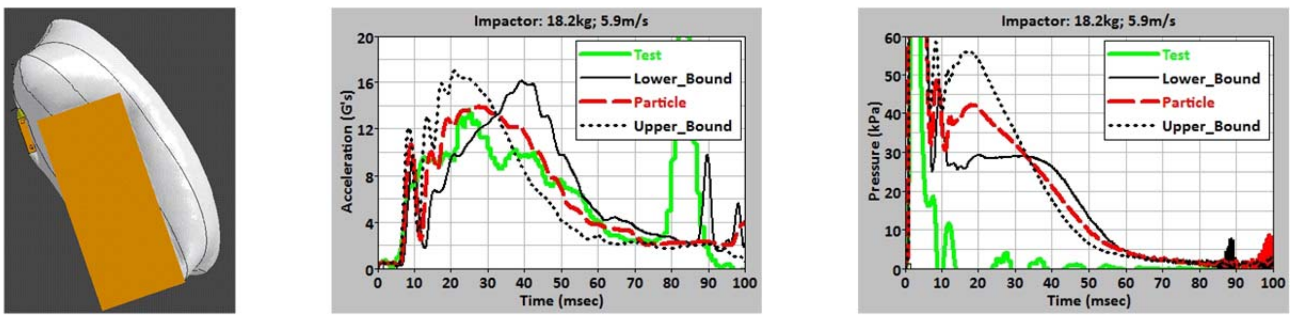

(a) Impact (b) deceleration (c) pressure

Figure B3. Impactor deceleration pulse and airbag pressure histories of using both particle and uniform pressure methods for 18.2kg impactor with 5.9m/s speed and 60mm distance from the airbag mounting plate to the reaction surface. (a) the impact configuration, (b) deceleration pulse, (c) pressure history.



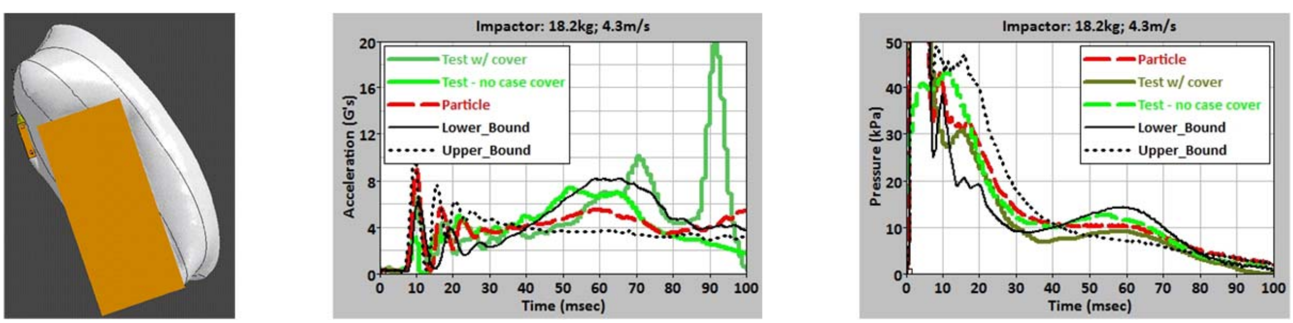

(a) Impact (b) deceleration (c) pressure

Figure B4. Impactor deceleration pulse and airbag pressure histories of using both particle and uniform pressure methods for 18.2kg impactor with 4.3m/s speed and 60mm distance from the airbag mounting plate to the reaction surface. (a) the impact configuration, (b) deceleration pulse, (c) pressure history.



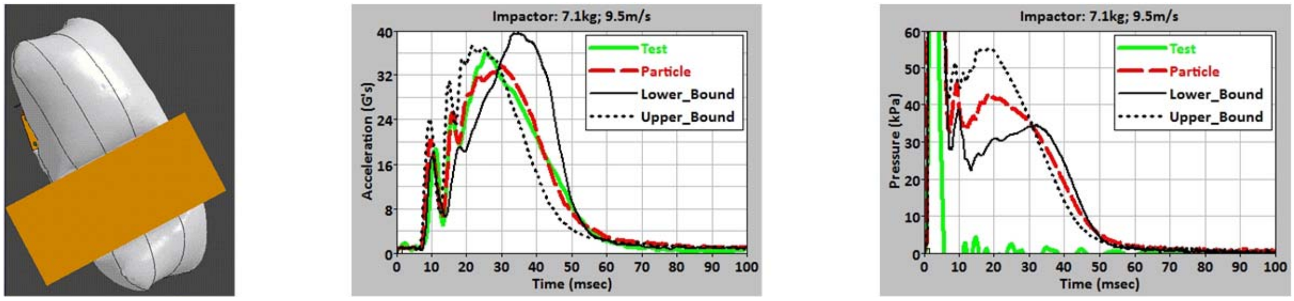

(a) Impact (b) deceleration (c) pressure

Figure B5. Impactor deceleration pulse and airbag pressure histories of using both particle and uniform pressure methods for 18.2kg impactor with 5.9m/s speed and 60mm distance from the airbag mounting plate to the reaction surface. (a) the impact configuration, (b) deceleration pulse, (c) pressure history.



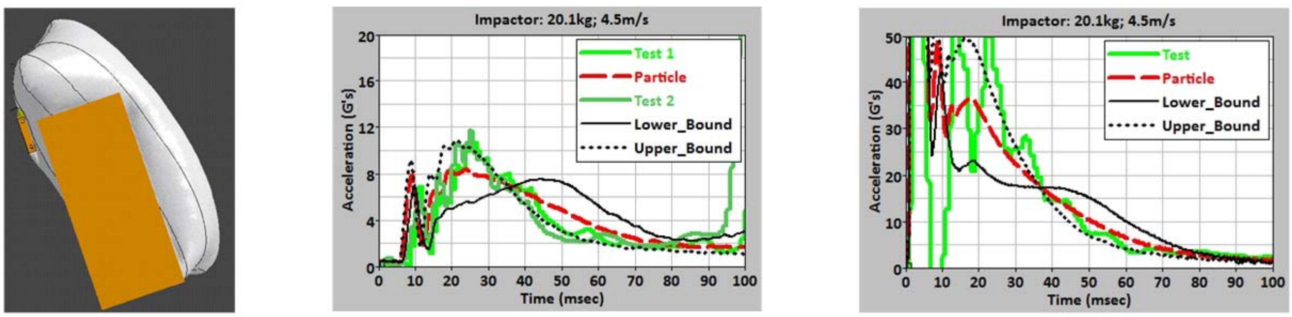

(a) Impact (b) deceleration (c) pressure

Figure B6. Impactor deceleration pulse and airbag pressure histories of using both particle and uniform pressure methods for 18.2kg impactor with 4.3m/s speed and 100mm distance from the airbag mounting plate to the reaction surface. (a) the impact configuration, (b) deceleration pulse, (c) pressure history.



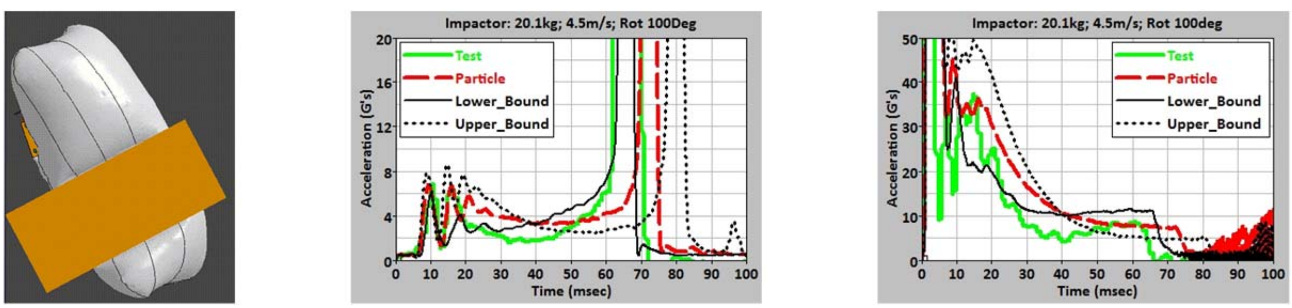

(a) Impact (b) deceleration (c) pressure

Figure B7. Impactor deceleration pulse and airbag pressure histories of using both particle and uniform pressure methods for 7.1kg impactor with 9.5m/s speed and 100mm distance from the airbag mounting plate to the reaction surface. (a) the impact configuration, (b) deceleration pulse, (c) pressure history.




(a) Impact (b) deceleration (c) pressure

Figure B8. Impactor deceleration pulse and airbag pressure histories of using both particle and uniform pressure methods for 20.1kg impactor with 4.5m/s speed and 100mm distance from the airbag mounting plate to the reaction surface. (a) the impact configuration, (b) deceleration pulse, (c) pressure history.




(a) Impact (b) deceleration (c) pressure

Figure B9. Impactor deceleration pulse and airbag pressure histories of using both particle and uniform pressure methods for 20.1kg impactor with 4.5m/s speed and 100mm distance from the airbag mounting plate to the reaction surface. (a) the impact configuration, (b) deceleration pulse, (c) pressure history.