IMPROVEMENT OF FRONTAL CRASH SENSOR CALIBRATION THROUGH MADYMO SIMULATIONS

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ABSTRACT

This paper describes the usage of MADYMO simulations in improving frontal crash sensor calibration. MADYMO simulations were conducted in the frontal impact program to improve the sensor calibration. In developing the advanced frontal impact restraint system using dual stage inflator, sensor calibration is very important. Late firing of the first stage inflator and large time delay between first and second stage time-to-fires increased occupant injuries. In the early version of sensor calibration, the initially given TTF's were not satisfied in some test speed conditions due to late first stage TTF and large time delay. Therefore, in order to determine the correct required TTF's, MADYMO simulations were used. First, the dual stage inflator was modeled as having two stages, which are primary and secondary stages. Then, MADYMO simulations were conducted by giving time delay between first and second stages of inflator model. Through simulations, the required TTF's were determined, which produced the injury values meeting the customer targets, and it was found that the relatively large time delay could be used in the low speeds. With the new required TTF's and the relatively large time delay in low speeds, sensor calibration was repeated. The recalibration was found to satisfy the required TTF's from the MADYMO simulations. A sled test was conducted in the worst-case condition and the injury results met the regulation limits.

INTRODUCTION

In developing the advanced frontal impact airbag restraint system using dual stage inflator, sensor calibration is very important. Late firing of the first stage inflator and large time delay between first and second stage TTF's increase occupant injuries due to large momentum changes. And, in sensor calibration, some trade-off can happen between different conditions. This kind of situation happened in one program. The initial sensor calibration did not satisfy the deployment logic in some conditions. In order to improve sensor calibration which meets the deployment logic, MADYMO simulations were conducted. As the first step, two MADYMO inflator models have been made. One is the primary stage inflator model and the other is the secondary stage inflator model. Therefore, two inflator models can be fired independently in the same way as the real dual stage inflator. By doing so, any time delay between the primary and secondary stages can be given. The next step was the droptower test and simulation. Through this process, the validated airbag model has been made. Then, MADYMO simulations were conducted according to the initial sensor calibration. Injury values from MADYMO simulations were reviewed to decide the new required TTF's and the direction for sensor calibration which meets the deployment logic. Based on the MADYMO simulation results, the new required TTF's and the direction for sensor calibration have been decided and the worst-case condition has been chosen to be tested, which guarantees the injury performance in other conditions. The sled test has been conducted with the worst-case condition and the injury performance has been confirmed to meet the sensor calibration direction and the deployment logic.

MADYMO Simulations for Frontal Crash Sensor Calibration Improvement

MADYMO was used to improve the frontal crash sensor calibration which initially did not meet the required TTF's and deployment logic. In this study, only the passenger side has been considered because the passenger side injuries were more critical to sensor calibration than the driver side injuries.

Deployment Logic

For 50th %ile-unbelted condition, the deployment logic required the low output at 18 mph and the high output at 22mph. The speed range between 18 mph and 22 mph was the gray zone which means that the low or high outputs can be allowed. The high output is required in 25mph-50th-unbelted-RH 30 deg Angular condition.

Initial Sensor Calibration

Initial sensor calibration was given to be reviewed. For the high output, the fixed time delay of 5msec was applied between the primary and secondary stages. However, the initial sensor calibration did not meet the requirements in 18mph-50th %ile-unbelted, 22mph-50th %ile-unbelted and 25mph-50th-unbelted-RH 30 deg Angular conditions as shown in Table 1.

Table 1.
Initial Sensor Calibration Results

	Unbelted Stage 1				Unbelted Stage 2			
Test Condition	Required TTF (msec)	Min TTF	Normal TTF	Max TTF	Required TTF (msec)	Min TTF	Normal TTF	Max TTF
18mph-50th-unbelted-0 deg.	23	17	19	26	23+120	29	35	35
22mph-50th-unbelted-0 deg.	18	16	18	18	18+5	24	29	31
25mph-50th-unbelted-RH 30deg.	27	23	24	25	27+5	25	28	145

(Highlighted:) Did not meet the RTTF.

As seen in Table 1, the max TTF of unbelted stage 1 in 18mph-50th-unbelted-0 deg condition did not meet the RTTF. In 22mph-50th-unbelted-0 deg condition, the low output is fired because the time delay exceeded 5msec. In 25mph-50th-unbelted-RH 30 deg condition, the max TTF in unbelted stage 2 did not meet the requirement which needs the high output. It was mentioned by the sensor calibration engineer that if the time delay of 15 msec in 22mph-50th-unbelted condition is allowed for high output, all conditions can be satisfied.

Inflator Modeling

In order to do MADYMO simulations with the various time delays, inflator modeling is needed which has two stages. Inflator modeling having two separate stages starts from the tank test pressure curves. Figure 1 shows the tank test pressure curves of high and low outputs considered. The tank volume was 60 liter. For the high output tank test pressure curve, the time delay of 5 msec was used. For the low output, the time delay of 120 msec was used for disposal purpose after firing the first stage. The primary stage inflator model is obtained from the low output tank test pressure curve through MTA analysis. The secondary stage inflator model is obtained by using both the high and low output tank test pressure curves and through MTA analysis.

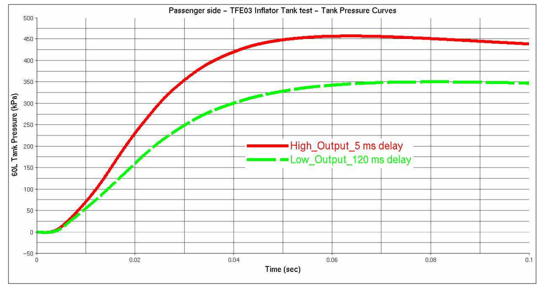

Figure 1. Tank Test Pressure Curves.

Figure 2 shows the mass flow rate curves of the primary and secondary stage inflator models obtained through MTA analysis.

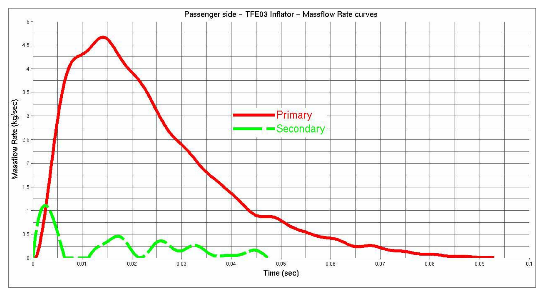

Figure 2. Mass Flow Rates For High and Low Outputs.

In order to prove that the mass flow rates are correct, the MADYMO tank simulations are conducted using the mass flow rates obtained through MTA analyses. For the MADYMO tank simulations, a 60 liter tank model was used. Figure 3 shows the comparison between tank test pressure curves and tank simulation pressure curves. From Figure 3, it is proved that the mass flow rates obtained through MTA analyses are valid.

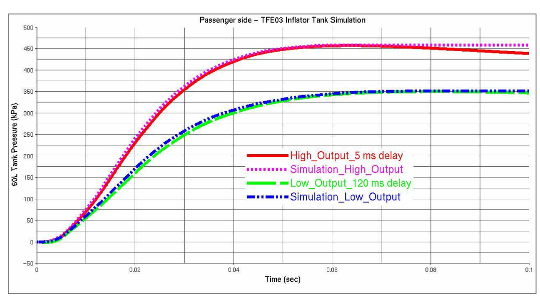

Figure 3. Comparison Between Tank Test And Tank Simulation Pressure Curves.

Droptower Tests and Simulations

To obtain the validated airbag models, droptower tests and simulations are conducted. Figure 4 shows the droptower testing picture.

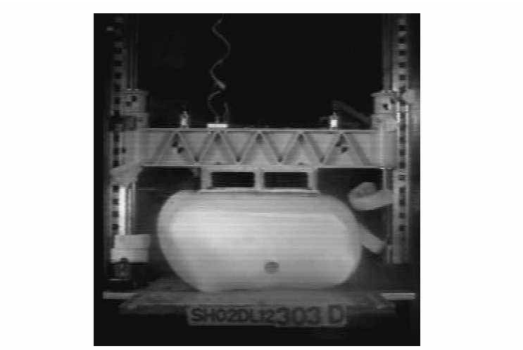

Figure 4. Passenger Airbag Droptower Testing.

From the droptower tests, the acceleration, velocity and displacement of the drop mass are measured. To obtain the validated airbag models, droptower simulations are conducted using a droptower model as seen in Figure 5.

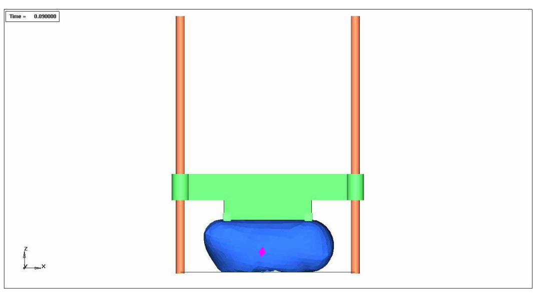

Figure 5. Passenger Airbag Droptower Simulation Model.

During droptower simulation, the acceleration, velocity and displacement of drop mass in the droptower model are correlated to the ones from the droptower test by changing the parameters in the model. The parameters adjusted were the effective area of vent hole according to bag pressure change and gas leakage amount through connection parts according to bag pressure change. Therefore, the airbag models are dependent on the bag pressure and independent of time. Figure 6 shows the correlated acceleration, velocity and displacement curves for high output. For the high output airbag model, the primary stage inflator model is fired first and then the secondary inflator model is fired with the time delay of 5 msec. For the low output airbag model, the primary stage inflator model is fired first and then the secondary inflator model is fired with the time delay of 120 msec.

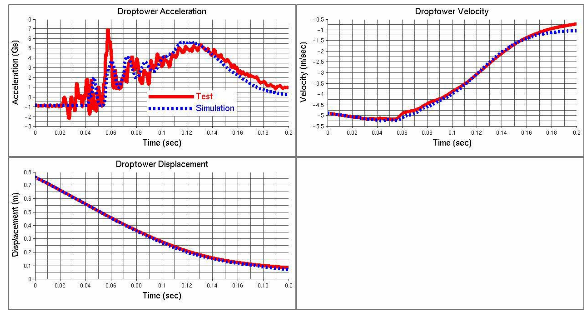

Figure 6. Droptower Correlation For High Output.

The validation levels of airbag models are checked by the validation statistics S/W which is internally developed by Key Safety Systems. The validation static number of "0" means the perfect matching of the simulation curve against the test curve. The large validation static number means poor matching between curves. If the average validation statistic number is below 0.15, the validation level is considered acceptable. In the passenger airbag models considered here, the average validation statistic number of low output airbag model was below 0.15 and the average validation statistic number of high output airbag model was also below 0.15. Both were considered acceptable. Since the airbag models from droptower simulations are independent of time and dependent on airbag pressure, the airbag models can be incorporated into MADYMO sled models without concerning TTF's.

MADYMO Sled Model Simulations

In the initial sensor calibration, there were issues in 18mph-50th-unbelted-0 deg, 22mph-50th-unbelted-0 deg and 25mph-50th-unbelted-RH 30deg Angular conditions. In 18mph-50th-unbelted condition, the max TTF of 26 msec in the unbelted stage 1 needs to be investigated through MADYMO simulation. In 22mph-50th-unbelted condition, all TTF's in unbelted stage 2 need to be investigated through MADYMO simulation. For the 25mph-50th-unbelted-RH 30 deg Angular condition, the high output is required. Therefore, MADYMO simulations are not needed and the sensor calibration needs to be improved to change the max TTF of 145 msec to within 30 msec which guarantees the high output with the fixed time delay of 5 msec. Considering the above, the MADYMO simulation matrix has been made as shown in Table 2.

Table 2.
MADYMO Simulation Matrix

	1st TTF (msec)	2nd TTF (msec)
18mph-50th-unbelted	26	146
22mph-50th-unbelted	16	24
22mph-50th-unbelted	18	28
22mph-50th-unbelted	18	29
22mph-50th-unbelted	18	31
22mph-50th-unbelted	18	33

Madymo simulation was conducted for the 18mph-50th-unbelted-26msec-146msec condition. The injury bar chart is shown in Figure 7. As seen in Figure 7, all injuries were below 80% of the FMVSS 208 FRM limits.

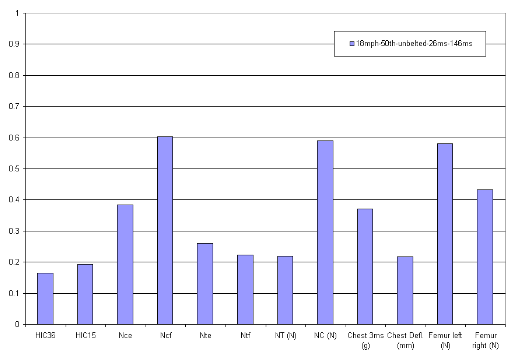

Figure 7. Injury Plot for 18mph-50th-unbelted-26ms-146ms

For the Madymo simulations of 22mph-50th-unbelted conditions, two more cases were added to Table 2 to investigate the wide range of time delay. Two added items to Table 2 were the "22mph-50th-unbelted-18ms-36ms" and "22mph-50th-unbelted-18ms-38ms" conditions. Therefore, seven conditions were simulated for the "22mph-50th-unbelted" condition. For Madymo simulations, the validated Madymo sled model of "22mph-50th-unbelted-15ms-135ms" was used. Table 3 shows the injury differences between the validated Madymo model simulation, sled test and barrier test in the "22mph-50th-unbelted-15ms-135ms" condition. From Table 3, it is noticed that the N_{cf} and neck compression were the concerns in 22mph-50th-unbelted condition. In the N_{cf} and neck compression, the validated Madymo model over-predicted against the sled test results and the sled test results over-predicted against the barrier test results.

Table 3.
Comparison Between Validated Madymo Simulation, Sled And Barrier Test Results In 22mph-50th-unbelted-15ms-135ms Condition

	Madymo	Sled	Barrier
HIC36	451	403	264
HIC15	451	403	241
Nce	0.754	0.609	0.494
Ncf	1.041	0.877	0.775
Nte	0.293	0.457	0.279
Ntf	0.367	0.269	0.392
NT (N)	423	819	1517
NC (N)	4646	3751	3044
Chest 3ms (g)	29.3	38	32.3
Chest Defl. (mm)	17.4	7.5	6.5
Femur left (N)	5456	4340	5062
Femur right (N)	4979	4369	3728

Exceeded FRM limits.
Exceeded 80% of FRM limits.

The reason why the sled test results over-predicted against the barrier test results is that the Lexan windshield is used in the sled test and there is pitching motion in the barrier test. The Lexan windshield is much stiffer than the glass windshield of the vehicle. Also, the vehicle pitching motion in the barrier test minimizes the head contact with the windshield. Considering these facts, MADYMO simulations were conducted using the validated MADYMO model to investigate the maximum allowable time delay in 22mph-50th-unbelted condition. As pointed out before, seven conditions were simulated. In determining the maximum time delay, the N_{cf}, neck compression and HIC_{15} were the critical injuries which were considered here and may be produced from head contact with the windshield. Table 4 shows the Madymo sled model simulation results. As seen in Table 4, HIC_{15}, N_{cf} and neck tension were the responses which need to be investigated. Figure 8 shows the variation in HIC_{15}, N_{cf} and neck compression according to TTF's variation. Considering Figure 8, Madymo simulation with "18ms-33ms" produces HIC_{15}, N_{cf} and neck tension which are below 100% of the FMVSS 208 FRM limits. However, considering over-prediction in Table 3, the TTF condition of "18ms-36ms" is considered to produce HIC_{15}, N_{cf} and neck tension which are below 100% of the FMVSS 208 FRM limits, in sled and barrier tests. Therefore, the TTF condition of "18ms-36ms" was chosen for the sled test to confirm the injuries.

Table 4. MADYMO Simulation Results With Different Time Delays In 22mph-50th-unbelted Condition

Speed	22mph	22mph	22mph	22mph	22mph	22mph	22mph
Dummy	50th	50th	50th	50th	50th	50th	50th
Belt	unbelted	unbelted	unbelted	unbelted	unbelted	unbelted	unbelted
Primary	16 ms	18 ms	18 ms	18 ms	18 ms	18 ms	18 ms
Secondary	24 ms	28 ms	29 ms	31 ms	33 ms	36 ms	38 ms
HIC36	178	259	267	272	405	389	654
HIC15	125	213	221	216	405	389	654
Nce	0.244	0.547	0.496	0.568	0.62	0.689	0.908
Ncf	0.249	0.85	0.695	0.84	0.886	0.893	1.284
Nte	0.178	0.168	0.188	0.172	0.352	0.22	0.309
Ntf	0.273	0.333	0.336	0.327	0.331	0.362	0.452
Neck Tension (N)	346	93	381	193	336	637	484
Neck Comp. (N)	990	3369	3056	3497	3820	4244	5593
Chest 3ms (g)	32	29.7	30.9	31.2	32.6	31.2	33.5
Chest Def. (mm)	17	18.5	18.4	18.5	19.3	19.1	19.7
Femur left (N)	5519	5418	5471	5453	5484	5486	5511
Femur right (N)	4944	5020	5030	5019	5014	5043	5033

(yellow) Exceeded 80% of FMVSS 208 FRM limits.
(red) Exceeded 100% of FMVSS 208 FRM limits.

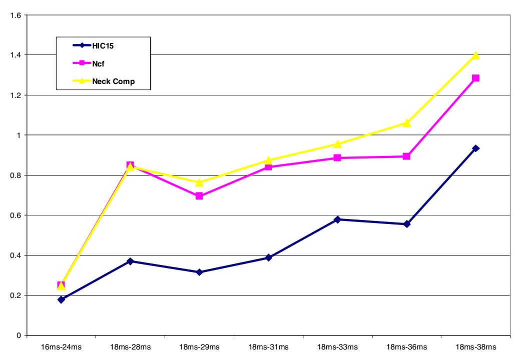

Figure 8. Comparison In HIC_{15}, N_{cf} And Neck Compression.

Confirmation Sled Testing

The confirmation sled testing has been conducted with the "22mph-50th-unbelted-18ms-36ms" condition to identify the injuries. Table 5 shows the sled test and Madymo simulation results. It is seen from Table 5 that Madymo simulation under-predicted N_{cf} by 13% and over-predicted neck compression by 9% against the sled test. When considering Table 3, the TTF condition of "18ms-36ms" may be OK to meet the FMVSS 208 FRM in the barrier test. However, the TTF condition of "18ms-33ms" was chosen for safety which shall guarantee all injuries in the barrier test below 80% of the FMVSS 208 FRM limits. Therefore, the worst case in 22mph-50th-unbelted condition which the sensor calibration should satisfy was the "18ms-33ms" which gives the time delay of 15 msec in the speeds below or equal to 22mph. Initially the fixed time delay of 5msec had to be met by the sensor calibration.

Table 5. Madymo Simulation Vs. Sled Test Results In 22mph-50th-unbelted-18ms-36ms

	Madymo	Sled
HIC36	389	279
HIC15	389	279
Nce	0.689	0.626
Ncf	0.893	1.009
Nte	0.22	0.19
Ntf	0.362	0.408
Neck Tension (N)	637	311
Neck Comp. (N)	4244	3864
Chest 3ms (g)	31.2	38.4
Chest Def. (mm)	19.1	20.8
Femur left (N)	5486	4225
Femur right (N)	5043	3470

(red) Exceeded 100% of FMVSS208 FRM limits.
(yellow) Exceeded 80% of FMVSS208 FRM limits.

Renewed Sensor Calibration

As mentioned before, the fixed time delay of 5msec caused the issues in 22mph and 25mph-RH 30 deg angular conditions and the late TTF caused issue in 18mph. After Madymo simulations and confirmation sled test, the maximum time delay of 15 msec could be given in 22mph-50th-unbelted condition. Also the 1st stage TTF of 26ms could be confirmed in 18mph-50th-unbelted condition. Therefore, the RTTF of 18mph became 26ms and the time delay of 15ms could be allowed in the speeds below or equal to 22mph. However, the fixed time delay of 5ms was kept in the speeds above or equal to 22mph. With these new conditions, the sensor calibration was repeated. Table 6 shows the new calibration results in 18mph-50th-unbelted, 22mph-50th-unbelted and 25mph-50th-unbelted-RH 30 deg angular conditions.

Table 6. 2nd Sensor Calibration

	Unbelted Stage 1				Unbelted Stage 2			
Test Condition	Required TTF (msec)	Min TTF	Normal TTF	Max TTF	Required TTF (msec)	Min TTF	Normal TTF	Max TTF
18mph-50th-unbelted-0 deg.	26	19	25	26	26+120	139	145	146
22mph-50th-unbelted-0 deg.	18	18	20	20	18+15	22	24	29
25mph-50th-unbelted-RH 30deg.	27	16	16	18	27+5	18	18	20

(yellow) Did not meet the RTTF.

In Table 6, it is noticed that the normal TTF and maximum TTF of 1st stage in 22mph did not meet the RTTF. Therefore, MADYMO sled simulations were conducted to confirm the injury values in 22mph-50th-unbelted-20ms-24ms and 22mph-50th-unbelted-20ms-29ms conditions.

2nd Madymo Sled Model Simulations

As mentioned above, Madymo sled model simulations were conducted in the above two conditions. The injury results are shown in Table 7. As seen in Table 7, all injuries were below 80% of the FMVSS 208 FRM limits. Therefore, the RTTF of 1st stage in 22mph can be changed from 18 msec to 20 msec. In that case, the yellow colored cells in Table 6 can be removed. With the 2nd sensor calibration , there were no issues in other speed conditions. Therefore, the 2nd sensor calibration could be finalized, producing acceptable injury values in all speed conditions.

Table 7.
2nd Madymo Simulation Results In 22mph-50th-unbelted Conditions

Speed	22mph	22mph
Dummy	50th	50th
Belt	unbelted	unbelted
Primary	20 ms	20 ms
Secondary	24 ms	29 ms
HIC36	267	273
HIC15	222	270
Nce	0.341	0.647
Ncf	0.537	0.79
Nte	0.159	0.236
Ntf	0.278	0.316
Neck Tension (N)	414	28
Neck Comp. (N)	2103	1599
Chest 3ms (g)	29.8	31.82
Chest Def. (mm)	17.9	19.2
Femur left (N)	5431	5455
Femur right (N)	5006	4591

CONCLUSIONS

In this work, dual stage inflator modeling was very important to give time delays between the 1st and 2nd stages of inflator. Even if the validated Madymo sled model is used, the Madymo sled model simulation results should be carefully analyzed with sled and barrier test results to judge over-predicted or under-predicted injury numbers. Through Madymo sled model simulations, the RTTF of 1st stage could be changed from 23 msec into 26 msec in 18mph-50th-unbelted condition. In the 22mph-50th-unbelted condition, Madymo sled model simulations allowed the time delay of 18 msec between 1st and 2nd stages and the sled test result confirmed it. However, the time delay of 15 msec was chosen for safety. With the maximum time delay of 15 msec allowed in the speeds below or equal to 22mph, the 2nd sensor calibration was successful in all conditions except the 1st stage RTTF confliction in 22mph. Through the Madymo sled model simulations, the original RTTF of 18 msec could be changed to 20 msec without any injury issues. Therefore, Madymo sled model simulations could guide the sensor calibration successfully in all conditions.

REFERENCES

[1] TNO Automotive, “PART III MADYMO Tank Test Analysis”, MADYMO v5.4 Utilities Manual