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ADVANCED BENEFIT ANALYSIS OF THE ITS-AIRBAG IN VEHICLES' SIDE- IMPCTS – FE SIMULATION AND SEVERITY ANALYSIS

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ABSTRACT

The Inflatable Tubular Structure (ITS) airbag is a potentially life-saving device that has been implemented recently in some luxury vehicles. Its main objective is to provide head protection for the front seat occupants against upper side-interior car components. In a previous research conducted by the authors, a nonlinear Finite Element (FE) model for the ITS-airbag system was successfully developed and tested. In the current research, the developed ITS model is combined with a full-scale FE vehicle model and 50th percentile side-impact dummy (SID) model. The combined model is then used to conduct two series of side-impact simulations. The first series included side impacts with narrow objects, i.e. rigid poles, while the second series included side impacts with a Moving Deformable Barrier (MDB) as a wide and deformable object. The effect of the relative position between the dummy and the rigid pole was considered by conducting variety of simulation scenarios for two different rigid pole positions and three different dummy positions. The three dummy positions were also considered in the side impacts with the MDB. For both impact series, the effect of the impact velocity was considered by conducting each impact scenario at three different velocities. The ITS model performance, in all FE simulations, was fairly similar to the actual ITS performance. The simulation results indicated a significant reduction in the Head Injury Criteria (HIC) of the dummy head due to the ITS-airbag deployment. The life-threatening severity for occupants is usually measured by the Abbreviated Injury Scale (AIS) that ranges from 1 (minor) to 6 (fatal). The AIS indices are calculated for all side impact cases. The results demonstrated a significant reduction/elimination in side-impact fatalities and severe injuries due to the ITS-airbag performance. The FE simulation results are then used in conducting a comprehensive benefit analysis for the ITS-airbag systems in vehicles' side-impacts.

KEY WORDS

Finite Element Analysis, Vehicle Crashworthiness, Transportation Safety and Inflatable Tubular Structure.

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INTRODUCTION

The Inflatable Tubular Structure (ITS) airbag is a new life-saving device designed mainly to protect the occupants' head and face during side-impacts. It deploys across the front side-windows in all crashes with lateral velocity change of 24 *km/h* or more and remains deployed for at least two seconds. The ITS provides primarily protection of a front seat occupant's head and face against impacts with: A-Pillar, B-Pillar, Side Rail, Windows' Frame and Glass, Window Pillar interfaces, and other upper side interior car components. For rear seat occupants, the ITS reduces the severity of head and face impacts with the B-Pillar. In addition to the protection mentioned, the ITS also prevents occupant ejection through front windows. Therefore, the ITS provides injury and casualty reduction for any body region due to exterior contacts of fully or partially ejected occupants through the front side windows. In the last few years, the ITS systems have been introduced in some luxury passenger vehicles.

In order to justify adding an ITS-airbag to the new vehicles as a standard safety device, detailed benefits analysis must be conducted about its performance. Recently, K. Digges conducted benefits analysis for the ITS-airbag [1] in which he relied mainly on accident data from the US National Accident Sampling System - Crashworthiness Data System (NASS/CDS), years 1988-1995. None of these accident data had ITS-equipped-vehicle involved in the crash. Consequently, it was not possible to assess the safety performance of the ITS in real vehicle fleets. Therefore, assumptions have been made in Digges study [1] to mitigate or eliminate certain injuries upon the deployment of the ITS would it have been installed in the vehicle and the crash severity fulfilled the deployment conditions. The assumptions stated in Digges study were reasonable and fairly justifiable; however, they may or may not achieve in real life. The NASS/CDS data was also lacking details about many important crash parameters necessary for detailed ITS benefits analysis. These crash parameters include the impact position, the driver's position and the impact velocity. In order to conduct a comprehensive benefits analysis for the ITS systems, more crash data must be provided with more details about the impact parameters. Thus far, the number of vehicles equipped with ITS systems on the road are still very limited and the accident data, even for the very recent years, cannot provide enough data for a detailed ITS benefits analysis. Since real crash data are not available, reliable FE simulations are proposed and considered in the current study to provide such data. In a previous research conducted by the authors [2,3], a nonlinear FE model for the ITS-airbag system was successfully developed and tested. In the current paper, a series of side impacts are modeled and simulated. The ITS model developed before [2,3] is installed in a full-scale FE vehicle model. A 50th percentile side impact dummy (SID) model is also used to represent the driver. Two series of side-impacts are conducted; the first series considered impacts with rigid poles, while the second series considered impacts with a Moving Deformable Barrier (MDB).

The objective of this paper is to provide more crash data, with ITS-equipped-vehicles involved in many side-impact scenarios, through FE modeling and simulation. The simulation results are used for more thorough benefits analysis for the ITS systems.

SIDE IMPACTS WITH RIGID POLE

To conduct the side-impacts of the first series, the developed ITS-airbag model [2,3] is installed in a complete FE vehicle model for 1991 Ford Taurus [4]. This vehicle model was developed and validated -for both frontal and side impacts- by the National Highway Traffic Safety Administration (NHTSA). The original model consists of 27,873 shell elements, 140 beam elements, and 340 solid elements. The front-end components from bumper to A-pillar were modeled with a fine mesh, while the rear half of the vehicle had a fairly coarse mesh density. In the current research the two doors in the driver side are remodeled to a finer mesh in order to account for the expected deformation in that side. This improved the model's performance in side impacts with the cost of adding extra 12,000 shell elements to the vehicle model. The ITS-airbag is installed along the roof-rail and A-pillar parts of the vehicle model. A 50th percentile Side Impact Dummy (SID) is used to represent the driver. The SID model was also developed and validated by NHTSA and consists of 9,063 solid elements and 1,910 shell elements. A cylindrical rigid pole is created from shell elements and kept stationary. To consider the effect of impact position, two different pole positions (Pole1 and Pole2) were used. The two rigid poles are created in the driver side. Pole1 is positioned near the end of the front door, while Pole2 is placed 0.3 *m* forward from Pole1 toward the A-pillar. The two pole positions -relative to the vehicle model- are shown in Fig. 1.

Three different dummy positions are also considered in order to account for the effect of the driver's position in his seat and therefore the relative distance between driver's head and the rigid pole. In the first dummy position (DP1) the dummy was placed in the center of driver seat and moved backward to lean on the seat back. The second dummy position (DP2) is a modification of (DP1) by moving the dummy 126 *mm* forward toward the steering wheel. In third dummy position (DP3), the dummy of the first position was moved 63 *mm* laterally toward the driver door. Automatic single surface contact, Type-13 in LS-DYNA [5, 6], is created between the rigid pole and the vehicle components in the crash zone. The vehicle, ITS, and SID are given three different lateral velocities of 32, 48, and 64 *km/h* toward the stationary rigid pole. These three impact velocities are selected to cover the effective velocity limit of the ITS (24 – 64 *km/h*) as indicated by Digges [1]. The complete deformed model is shown in Fig. 2 for the 48 *km/h* impact with (Pole1) and DP1, after 40 *ms* simulation time.

The first rigid pole position, together with the three dummy positions, created three side-impact scenarios. Each of these three scenarios was conducted at three different impact velocities as mentioned before. This created nine simulation cases for the side impacts with the first pole. For the second rigid pole, only the third dummy position (DP3) was chosen to represent the most likely dummy position in order to reduce the total number of simulations. This scenario was also conducted at the three designated impact velocities. This arrangement produced twelve side-impact cases. Each of these twelve cases was conducted with and without the ITS-airbag system. The Head Injury Criteria (HIC) for the dummy's head is calculated for all twelve impacts and the results are listed in Table 1. The HIC values are calculated by the formula:

$$HIC = \left[\frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a \, dt \right]^{2.5} (t_2 - t_1) \quad (1)$$

Where, *a* is the acceleration of the dummy head (*Gs*) and *t* is the time (*sec*). The time interval ($t_2 - t_1$) is 15 *ms* and should be selected in the place that will maximize the equation. The simulation results, shown in Table 1, indicate significant reductions in the HIC values for all impact scenarios. For impacts with Pole1, the HIC values for DP1 are relatively close to its corresponding HIC values for DP3. This could be attributed to the fact that both positions, DP1 and DP3, have the same axial distance from the rigid pole. In both positions, the dummy head is about 126 *mm* behind the pole, toward the B-pillar. The HIC values for the impacts of DP2 have much higher values than those of DP1 and DP3, especially when the ITS-airbag is not deployed. This is mainly due to the fact that in this position (DP2), the dummy head is almost in the same lateral position of the rigid pole. It is also shown that using the ITS-airbag in this severe position (DP2) has significantly reduced the HIC values. As shown from the results of DP3, moving the impact position from Pole1 to Pole2 (126 *mm* forward) resulted in a significant reduction in the HIC value for all impact velocities, either with the ITS system or without it. This is mainly due to the fact that for Pole1, the dummy head was very close to the rigid pole, while Pole2 is positioned 0.3 *m* further away from the dummy head. This allows the head to impact the deformable vehicle structure first before hitting the rigid pole.

Severity Reduction by the ITS (Rigid Pole Impacts)

Injuries are usually classified by life-threatening severity using the Abbreviated Injury Scale (AIS) that ranges from 1 (minor) to 6 (fatal). AIS2 injuries are moderate and AIS3 injuries are serious. The percentage probabilities of head/face injury occurrence of each AIS severity index could be calculated by the relations [1]:

$$P(AIS\ 6) = 100 \Big/ \left(1 + e^{\left(12.24 + \frac{200}{HIC} - 0.00565\ HIC\right)}\right) \quad (2)$$

$$P(AIS\ 5) = 100 \Big/ \left(1 + e^{\left(7.82 + \frac{200}{HIC} - 0.00429\ HIC\right)}\right) - P(AIS\ 6) \quad (3)$$

$$P(AIS\ 4) = 100 \Big/ \left(1 + e^{\left(4.9 + \frac{200}{HIC} - 0.00351\ HIC\right)}\right) - P(AIS\ 5) \quad (4)$$

$$P(AIS\ 3) = 100 \Big/ \left(1 + e^{\left(3.39 + \frac{200}{HIC} - 0.00372\ HIC\right)}\right) - P(AIS\ 4) \quad (5)$$

$$P(AIS\ 2) = 100 / \left(1 + e^{\left(2.49 + \frac{200}{HIC} - 0.00483\ HIC\right)}\right) - P(AIS\ 3) \quad (6)$$

$$P(AIS\ 1) = 100 \Big/ \left(1 + e^{\left(1.54 + \frac{200}{HIC} - 0.0065\ HIC\right)}\right) - P(AIS\ 2) \quad (7)$$

$$P(AIS\ 0) = 100 - \sum_{1}^{6} P(AIS\ i) \quad (8)$$

Where $P(AIS\ x)$, x = 0 : 6, are the projected probabilities -in percent- of head/face injury occurrence at the given AIS severities. The probabilities of head/face injury occurrence of each AIS severity index, as indicated in equations (2) - (8) are calculated for the twelve scenarios listed in Table 1. The results are listed in Table 2 for AIS6 through AIS0. The twelve different impact scenarios indicated in Table 1 have a fair representation for the relative positions between the dummy head and the rigid pole and also for the impact velocity range. Therefore, an average value from the results of these twelve scenarios are calculated and used as a measure to the ITS effectiveness with regard to the corresponding AIS severity index. These average values are calculated in the last column of Table 2.

The average probabilities of head/face injury for each AIS severity index, calculated in Table 2, are then used to establish the severity reduction table; Table 3. In this table, a sample of 1000 drivers -engaged in general side impacts with rigid poles- is considered. The number of drivers, out of 1000, expected to suffer each AIS index, are calculated, with and without the ITS-airbag. The %reduction is also calculated in the last raw of the table. As shown in Table 3, the ITS has reduced the expected number of fatalities (AIS 6), from 750 to 472, a fatality reduction of 37%. The expected injuries with AIS5 and AIS4, which are considered very serious injuries or fatal, are also reduced dramatically by 74.7% and 48.3%, respectively. The number of injuries expected with AIS3 (serious injuries) has increased with the ITS from 51 to 83, an increase of 62.7%. However this increase is mainly due to the dramatic reductions of AIS6, AIS5 and AIS4 injuries. For the same reason, the expected injuries with AIS1 (minor) and AIS2 (moderate injuries) have increased with the ITS. The number of drivers expected to suffer no injuries at all (AIS0) has dramatically increased from 2 to 109 due to the ITS. It is clear that the ITS has significantly reduced the number of fatalities and very serious injuries by mitigating it to moderate and minor injuries.

The results in Table 3 are graphically represented in Fig. 3. As shown in the plots, starting from AIS4 and up (fatal and very serious injuries), the ITS curve went below the original curve (without ITS). In order to keep the total number of injuries for all AIS indices to be 1000, the ITS curve went over the original curve in the area of AIS3 and before, an area that represents only severe, moderate, minor, and no injuries.

SIDE-IMPACTS WITH MDB

The same combined FE model for the ITS-airbag, Ford-Taurus and SID dummy, used for the rigid pole impacts of the first series, is used again to conduct the side-impact scenarios of the second series. Instead of the cylindrical rigid pole, a moving deformable barrier (MDB) is used to represent another moving object impacting the vehicle in several side-impact scenarios. The FE model of the MDB consists of 7324 solid elements and 614 shell elements. A perspective view of the MDB model is shown in Fig. 4. The MDB is a simplified model that preserves almost the same mass and stiffness characteristics of a regular vehicle; however, it has much less elements. It is usually used to replace another vehicle model and therefore reduce the total number of elements in the entire model. To conduct the impacts of the second series, the combined model for vehicle, ITS, and dummy was given zero velocity, while the MDB was given three different impact velocities of 32, 48, and 64 *km/h* to crash the vehicle in the lateral direction from the driver side. The three different dummy positions used in the rigid pole impact series are also adopted here to cover the relative position of the driver. The deformed vehicle model, together with the ITS, SID and MDB, for 48 *km/h* impact and DP1, is shown in Fig. 5 for 40 *ms* simulation time. As seen, the ITS-airbag deployed and performed fairly well similar to the actual ITS performance.

The three dummy positions, together with the three different impact velocities generated a total of nine different side-impact scenarios. The HIC value for these nine impact scenarios are calculated and listed in Table 4, with and without the ITS-airbag. The simulation results for the impacts of this series indicated a significant reduction in the HIC values as a result of the ITS-airbag deployment, as shown in Table 4.

Comparing the results in Table 4 with its corresponding values in Table 1 indicates that the HIC values are remarkably less for the MDB impacts. This is mainly due to the wide impact zone of the MDB, while in the case of rigid pole impacts, the crash zone is narrower and the energy concentration is definitely higher. Another important reason lies in the fact that the MDB is deformable and absorbs some of the crash energy during the collision, unlike the rigid pole, which is rigid and does not absorb any crash energy at all. This means that the vehicle structure will have to absorb the entire crash energy for the rigid pole impacts, while for the MDB impacts only part of the crash energy is absorbed by the vehicle structure and the other part is absorbed by the MDB structure.

Severity Reduction by the ITS (MDB Impacts)

As performed in the first impact series, the percentage probability of head/face injury for each AIS severity index are calculated for the nine impact scenarios listed in Table 4. The results are shown in Table 5 for AIS6 through AIS0. An average value for the results of these nine impact scenarios is calculated and used as a measure to the ITS effectiveness for each AIS severity index. These average values are listed in the last column of Table 5, for all AIS indices.

The average percentage probability for all AIS indices, calculated in Tables 5, are then used to establish the severity reduction table, Table 6, for the second impact series. To explain these average injury probabilities in more comparable sense, 1000 drivers were considered to be involved in side impacts with MDB at different locations and speed. The number of injuries, out of 1000, expected to suffer each AIS index, are then calculated and listed in Table 6 using the average percentage probability for each AIS index, with and without the ITS-airbag. The percentage reduction, due to the ITS deployment, is also calculated and presented in the third raw of the table. As seen in Table 6, the number of fatalities (AIS6) has been reduced dramatically by 98.3% due to the ITS. The numbers of AIS5 and AIS4 injuries have also been reduced by 80.8% and 29.7%, respectively. Both AIS2 and AIS3 injuries have also been reduced due to the

ITS, while the AIS1 injuries (minor) have been increased by 14.6%. Also the AIS0 (no injuries) numbers have been increased by 85% due to the ITS performance. The ITS-airbag remarkably reduced the numbers of fatalities and very serious injuries for all impacts of this series.

The results of Table 6 are also graphically represented in Fig. 6. As shown, starting from AIS2 and up (moderate, serious, very serious injuries, and fatal), the ITS curve went down below the original curve (Without ITS). In order to keep the total number of injuries for all AIS indices to 1000, the ITS curve went above the original curve only in the areas of AIS1 and AIS0, areas that represent only minor and no injuries.

DETAILED ANALYSIS AND DISCUSSION

The severity reduction table for rigid pole impacts, Table 3, was mainly based on the average probabilities of head/face injury. However, the average probabilities represent a broad sense that considers the different impact velocities, different dummy positions, and different pole positions. In order to investigate the results in more depth; Table 7 is created similar to Table 3 but only for one impact scenario (Pole2, DP3). For the three impact velocities of 32, 48, and 64 *km/h*, the number of drivers, out of 1000, expected to suffer each AIS index, are calculated with and without the ITS-airbag. Fig. 7 provides graphical representations for Table 7. As shown in Fig. 7, the vertical dashed line -at the intersection of the two curves- divides the entire severity range into two zones and will be called the dividing line. The zone on the right of the dividing line is the severity zone where the ITS-airbag significantly reduces the fatalities and very severe injuries of the occupants by reducing their AIS index down. The right zone is then the zone where the impact severity improved significantly due to the ITS and therefore could be called the improvement zone. The zone on the left of the dividing line has of course less severity indices and in order to maintain the total number of occupants constant (1000 in our case study), the severities reduced from the improvement zone will be shifted to this left zone. This is why the solid line (with ITS) went above the dashed line (without ITS) in this left zone for all impact velocities. As a result of this negative effect to the left of the dividing line, the left zone could be called the negative zone. It could be also noticed that for the 32 *km/h* impact, the improvement zone started right after the AIS-1 index, meaning that all injuries with AIS2 and more are significantly reduced and shifted to the negative zone due to the ITS deployment. However for the 48 *km/h* impact the improvement zone started in the middle between AIS2 and AIS3 and for the 64 *km/h* impact the improvement zone started almost midway between AIS4 and AIS5. This clearly explains the fact that as the impact velocity goes higher -for the same impact scenario- the improvement zone shrinks and the negative zone expands. Therefore the impact velocity should be carefully considered before any assessment to the expected benefits of the ITS.

In order to investigate further how injuries with higher AIS indices were shifted to the left due to the ITS-airbag, detailed severity reduction analysis are conducted for the 48 *km/h* impact of the same scenario (Pole2, DP3) as listed in Table 7. In this analysis, the expected injuries with AIS0 after the ITS (324 in this case) are filled from the expected injuries before the ITS with AIS0, then with AIS1, then with AIS2, etc. till it is filled. The procedure should be continued for higher AIS indices until all injuries from the upper raw are transferred to the lower raw. The percentage contributions of each AIS index in the upper raw (without ITS) transferred to any less AIS index in the lower raw (with ITS) are then calculated and listed in Table 8. The non-existence of any ratio along the main diagonal of the table indicates clearly that all AIS indices were completely reduced to less indices as a result of the ITS deployment. As shown in the table, all injuries with AIS1, AIS2 and AIS3 are completely reduced to AIS0, i.e. became with no injuries at all. 91.6% of the injuries with AIS4 are reduced to AIS1 and 8.4% are reduced to AIS0 after the ITS. Injuries with AIS5 are reduced to AIS3, AIS2 and AIS1 with ratios of 13.6%, 71% and 15.4% respectively. Fatalities with AIS6 are reduced to AIS5 (3.7%), AIS4 (32.7%) and AIS3 (63.6%). The detailed analysis for this case demonstrate the great benefits expected from the ITS-airbag, however it should be remembered that this case is considered a regular side-impact case with narrow object and not a very severe case.

In order to investigate the performance of the ITS-airbag in a more severe side-impact case with narrow object, the impact case for Pole1 and DP2 is also analyzed here in detail. This case is considered very severe because the dummy head in this position is very close to the impact point with Pole1 as mentioned before. Table 9 is created, similar to Table 7, for the three impact velocities. The numbers inside the tables indicate the number of expected injuries (out of 1000) for each severity index before and after the ITS-airbag. Fig. 8 provides graphical representation for Table 9. As shown in Fig. 8.a, the improvement zone for the 32 *km/h* impact started right after AIS5 and is relatively small, however the ITS still very beneficial for this impact velocity since it was able to reduce all fatalities with AIS6 and shift it to less AIS indices. This fact could also be observed from the numbers in the first two rows of Table 9. Before the ITS, all 1000 drivers were suffering fatality with AIS6. This number is reduced to zero after the ITS and the peak of the injury curve is shifted to AIS2. For the 48 *km/h* impact, the numbers in Table 9 indicate that the ITS only reduced 7 fatalities to less AIS indices while 993 fatalities remained the same after the ITS. This fact is interpreted in Fig. 8.b by the very small improvement zone as the dividing line starts right before AIS6. It is obvious that the ITS benefits is very limited for this impact velocity. For the 64 *km/h* impact, no improvement at all obtained from the ITS deployment as one can see from the numbers in Table 9. The improvement zone for this impact velocity is zero as shown in Fig. 8.c. The analysis of this very severe impact case explains the importance of the relative distance between the driver's head and the impact point on the rigid pole. It could be inferred from the numbers listed in Table 9 and Fig. 8 that no benefits should be expected from the ITS-airbag in such a severe impact (Pole1 and DP2) for impact velocities of 40 *km/h* or higher.

These two selected cases demonstrated the remarkable changes that could be encountered in the ITS benefits due to differences in the rigid pole impact position, the distance between driver's head and impact point, and impact velocities.

For more analysis of the second impact series (with MDB), Table 10 is created similar to Table3, but only for DP3, and all impact velocities. The number of drivers, out of 1000, expected to suffer each AIS severity index, are calculated with and without the ITS-airbag and presented in the table. Fig. 9 provides graphical representations to Table 10. As shown in Fig. 9.a, for the 32 *km/h* impact, the improvement zone started very early, even before the AIS1 index and the solid line representing the ITS performance converged very fast to zero at AIS3. For the 48 *km/h* impact, the improvement zone started one-third the way from AIS1 to AIS2 and the ITS performance line converged reasonably fast to approach zero at AIS5 as shown in Fig. 9.b. For the 64 *km/h* impact, the improvement zone started midway between AIS3 and AIS4 and the ITS performance curve converged fast to approach zero at AIS6. It could be clearly noticed that as the impact velocity increases the improvement zone shrinks and the negative zone expands as noticed before in the rigid pole impacts. From the three plots of Fig. 9, it is expected to obtain the most beneficial performance for the ITS with the 64 *km/h* impact. This is mainly due to the fact that the main concentration of injuries before the ITS is around AIS5 while after the ITS the main concentration is shifted back to be around AIS2. Further analyses are conducted on Table 10 (64 *km/h* impact) to investigate how injuries with higher AIS indices were reduced to smaller AIS indices due to the ITS-airbag. The results are presented in Table 11, which is created similar to Table 8 before. The numbers in Table 11 demonstrate clearly the great benefits obtained from the ITS-airbag, where 64% of the fatalities are reduced to AIS3, 32% of the fatalities are reduced to AIS4 and only 4% are reduced to AIS5. All injuries with AIS5 (very severe injuries) before the ITS are reduced to AIS2 (76%), and AIS3 (24%). Injuries with AIS4 and AIS3 are also reduced two and three indices less. While injuries with AIS2 and AIS1 are completely eliminated and reduced to AIS0.

ADVANCED ITS BENEFITS ANALYSIS

From the detailed analysis conducted in this research, a more advanced benefits analysis for the ITS-airbag system could be presented in the following guidelines:

1- All injuries resulted from impacts with wide objects like MDB, other vehicle, or deformable guardrails are estimated to be either eliminated or reduced to a moderate injury (AIS2) or minor injury (AIS1) as a result of the ITS deployment.

2- All injuries resulted from impacts with narrow rigid objects like rigid poles are estimated to be either eliminated or reduced to moderate or minor injuries (AIS2 and AIS1) as a result of the ITS deployment, only if the impact is not severe (i.e., axial distance between the rigid pole and the driver's head is over 125 *mm* and the impact velocity is 40 *km/h* or less).

3- For impact cases with rigid poles, if the impact is severe due to an axial distance between the head and rigid pole of 125 *mm* or less and impact velocity of 40 *km/h* or more, the estimated ITS benefits should be reduced by 50%. It should be also expected here that most injuries of such severe impacts will be reduced to AIS3 and AIS4 after the ITS.

4- The assumed upper and lower limits of ITS protection as 64 and 24 *km/h* respectively seems to be reasonable assumption for impacts with wide objects, while for impacts with narrow and rigid objects the upper limit should be 40 *km/h* if the pole is very close to the driver's head (axial distance of 125 *mm* or less). The upper limit could be considered 64 *km/h* only if the distance between the rigid pole and the driver's head is 375 *mm* or more.

5- The assumptions and procedures used in the benefits analysis of Digges[1] had more generalizations for all AIS that may not be consistent for all types of impacts.

REFERENCES

[1] Digges, K., "Benefits Analysis of the Inflatable Tubular Structure (ITS)," NCAC library, Ashburn, VA, August 1997.

[2] Omar, T., Bedewi, N., and Rehm, W., "Advanced Crashworthiness and Transportation safety Analysis – ITS Finite Element Modeling and Simulation," *Proceedings of the 10th International Conference on Applied Mechanics and Mechanical Engineering*, AMME-10, Cairo, Egypt, May 14-16, 2002.

[3] Omar, T.A., Bedewi, N.E., Al-Fraiji, A., and Rehm, W., "Finite Element Modeling and Simulation of Inflatable Tubular Structure Airbag," *Proceedings of the ASME Winter Annual Meeting*, *Transportation Safety Session*, New York, NY, November 11-16, 2001.

[4] U.S. Department of Transportation and National Highway Traffic Safety Administration, "Development of a Passenger Vehicle Finite Element Model," Final Report, 1993.

[5] Hallquist, J. O., "LS-DYNA3D User's Manual," Livermore Software Technology Corporation, 1997.

[6] Hallquist, J. O., "LS-DYNA3D Theoretical Manual," Livermore Software Technology Corporation, 1997.

Table 1 – HIC Values for the First Series (Side-impacts into Rigid Poles)

Pole	**Pole-1**									**Pole-2**		
Dummy Position	**DP1**			**DP2**			**DP3**			**DP3**		
Velocity km/*h*	**32**	**48**	**64**	**32**	**48**	**64**	**32**	**48**	**64**	**32**	**48**	**64**
w/o-ITS	2340	8848	27450	6860	60420	98750	2200	7580	23490	821	1682	2421
w-ITS	726	2670	7740	730	3065	10360	455	2420	7046	287	423	950

Table 2 – Percentage Probabilities of Head/Face Injury (Rigid Pole)

Pole		**Pole1**									**Pole2**			**Average**
Dummy Position		**DP1**			**DP2**			**DP3**			**DP3**			
Velocity (*km/h*)		**32**	**48**	**64**	**32**	**48**	**64**	**32**	**48**	**64**	**32**	**48**	**64**	
AIS1	**w/o-ITS**	0.0	0	0	0	0	0	0.0	0	0	19.8	0.4	0.0	**1.7**
	w-ITS	27.1	0.0	0	26.8	0	0	40.2	0	0	26.6	39.1	12.0	**14.6**
AIS2	**w/o-ITS**	0.7	0	0	0	0	0	0.9	0	0	41.5	5.6	0.4	**4.1**
	w-ITS	40.1	0.6	0	40.3	0.0	0	21.9	0.7	0	9.5	19.3	38.5	**14.2**
AIS3	**w/o-ITS**	4.1	0	0	0	0	0	5.2	0	0	24.5	23.2	2.5	**4.1**
	w-ITS	20.9	3.5	0	21.1	0.3	0	8.2	0.5	0	3.7	7.2	33.9	**5.1**
AIS4	**w/o-ITS**	8.9	0	0	0	0	0	11.7	0	0	8.4	38.1	4.8	**6.0**
	w-ITS	6.1	7.4	0	6.1	0.2	0	2.1	0.6	0	0.9	1.9	12.6	**3.1**
AIS5	**w/o-ITS**	23.7	0	0	0	0	0	29.7	0	0	1.0	27.2	12.8	**7.9**
	w-ITS	0.7	20	0	0.7	0.2	0	0.2	0.8	0	0.1	0.2	1.8	**2.0**
AIS6	**w/o-ITS**	62.7	100	100	100	100	100	52.5	100	100	0.1	5.5	79.5	**75.0**
	w-ITS	0.0	67	100	0.0	99	100	0	98	100	0	0	0.1	**47.2**
AIS0	**w/o-ITS**	0	0	0	0	0	0	0	0	0	4.8	0	0	**0.3**
	w-ITS	5.2	0	0	5.1	0	0	27.3	0	0	59.2	32.4	1.2	**10.9**

Table 3 – Severity Reduction for the Rigid Pole Impacts

AIS INDEX		0	1	2	3	4	5	6
Expected Injuries	w/o-ITS	2	17	41	51	60	79	750
	w-ITS	109	143	142	83	31	20	472
%Reduction		-5350%	-741%	-246%	-62%	48.3%	74.7%	37%

Table 4 – HIC Values for the Second Impact Series (Side-impact with MDB)

Dummy Position	DP1			DP2			DP3		
Velocity (*km/h*)	32	48	64	32	48	64	32	48	64
Without ITS	269	695	2389	140	776	1748	174	912	1976
With ITS	116	285	1052	41	338	1452	59	317	790

Table 5 – Percentage Probabilities of Head/Face Injury (MDB)

Dummy Position		DP1			DP2			DP3			Average
Velocity (*km/h*)		32	48	64	32	48	64	32	48	64	
AIS1	w/o-ITS	24.3	29.6	0.0	7.6	23.1	0.3	11.7	14.0	0.1	**12.3**
	w-ITS	5	26.4	7.7	0.2	32.6	1.2	0.7	30.3	22.1	**14.0**
AIS2	w/o-ITS	8.5	39.0	0.4	2.4	41.3	4.5	3.7	39.9	2.0	**15.7**
	w-ITS	1.6	9.4	33.4	0.1	12.9	12.1	0.3	11.4	41.4	**13.6**
AIS3	w/o-ITS	3.3	19.1	2.8	1.1	23.8	19.8	1.6	31.8	10.6	**12.6**
	w-ITS	0.7	3.6	38.4	0.0	4.8	35.2	0.1	4.3	24.6	**12.4**
AIS4	w/o-ITS	0.8	5.4	5.5	0.3	7.2	36.2	0.4	11.2	23.8	**10.1**
	w-ITS	0.2	0.9	16.9	0.0	1.3	36.4	0.0	1.1	7.6	**7.2**
AIS5	w/o-ITS	0.1	0.6	14.9	0.0	0.9	31.6	0.0	1.5	40.0	**9.9**
	w-ITS	0.0	0.1	2.8	0.0	0.1	13.6	0.0	0.1	0.9	**1.9**
AIS6	w/o-ITS	0.0	0.0	76.4	0.0	0.0	7.7	0.0	0.1	23.6	**12.0**
	w-ITS	0.0	0.0	0.2	0.0	0.0	1.5	0.0	0.0	0.0	**0.2**
AIS0	w/o-ITS	63.1	6.4	0.0	88.7	3.8	0.0	82.6	1.5	0.0	**27.3**
	w-ITS	92.5	59.6	0.6	99.8	48.4	0.1	98.9	52.8	3.4	**50.7**

Table 6 – Severity Reduction for the MDB Impacts

AIS INDEX		0	1	2	3	4	5	6
Expected Injuries	w/o-ITS	274	123	157	126	101	99	120
	w-ITS	507	141	136	124	71	19	2
% Reduction		-85%	-14.6%	13.4%	1.6%	29.7%	80.8%	98.3%

Table 7 – Expected Number of Injuries (Pole2, DP3)

Velocity (*Km/h*)	AIS INDEX	0	1	2	3	4	5	6
32	Without ITS	48	198	415	245	84	10	0
	With ITS	592	266	95	37	9	1	0
48	Without ITS	0	4	56	232	381	272	55
	With ITS	324	391	193	72	18	2	0
64	Without ITS	0	0	4	25	48	128	795
	With ITS	12	120	385	338	126	18	1

Table 8 – Severity Reduction for Pole2, DP3 and 48 *km/h* Impact

		With ITS						
		AIS 6	AIS 5	AIS 4	AIS 3	AIS 2	AIS 1	AIS 0
Without ITS	AIS 6		3.7%	32.7%	63.6%			
	AIS 5				13.6%	71%	15.4%	
	AIS 4						91.6%	8.4%
	AIS 3							100%
	AIS 2							100%
	AIS 1							100%

Table 9 – Expected Number of Injuries (Pole1, DP2)

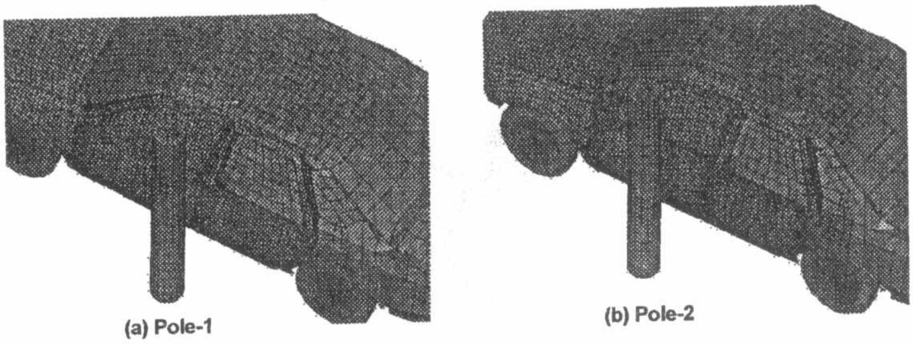
Velocity (*Km/h*)	AIS INDEX	0	1	2	3	4	5	6
32	Without ITS	0	0	0	0	0	0	1000
	With ITS	51	268	402	211	61	7	0
48	Without ITS	0	0	0	0	0	0	1000
	With ITS	0	0	0	3	2	2	993
64	Without ITS	0	0	0	0	0	0	1000
	With ITS	0	0	0	0	0	0	1000

Table 10 – Expected Number of Injuries (MDB, DP3)

Velocity (*Km/h*)	AIS INDEX	0	1	2	3	4	5	6
32	Without ITS	826	117	37	16	4	0	0
	With ITS	990	7	2	1	0	0	0
48	Without ITS	15	140	399	318	112	15	1
	With ITS	528	303	114	43	11	1	0
64	Without ITS	0	1	20	105	238	400	236
	With ITS	36	222	411	246	76	9	0

Table 11 – Severity Reduction for MDB, DP3 and 64 *km/h* Impact

		With ITS						
		AIS 6	AIS 5	AIS 4	AIS 3	AIS 2	AIS 1	AIS 0
Without ITS	AIS 6		4%	32%	64%			
	AIS 5				24%	76%		
	AIS 4					45%	55%	
	AIS 3						86%	14%
	AIS 2							100%
	AIS 1							100%



(a) Pole-1

(b) Pole-2

Fig. 1 – Two Different Pole Positions

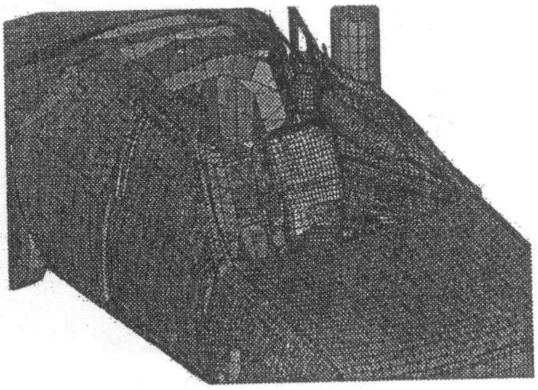


Fig. 2 – Side Impact with Rigid Pole (Pole1, DP1, 48 *km/h* and 40 *ms*)

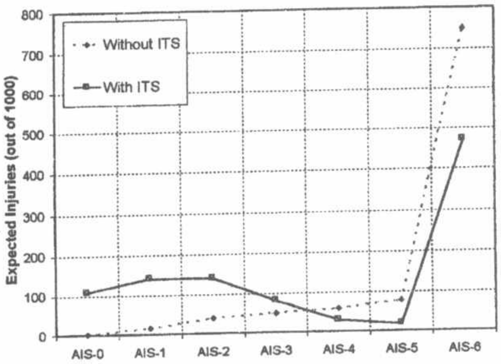


Fig. 3 – Severity Reduction for the Rigid Pole Impacts

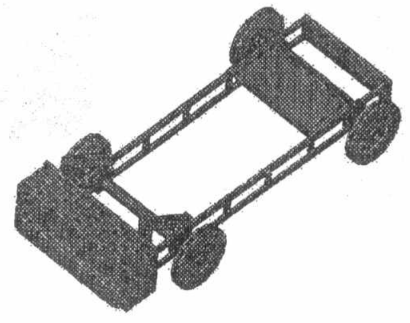


Fig. 4 – FE Model for the MDB

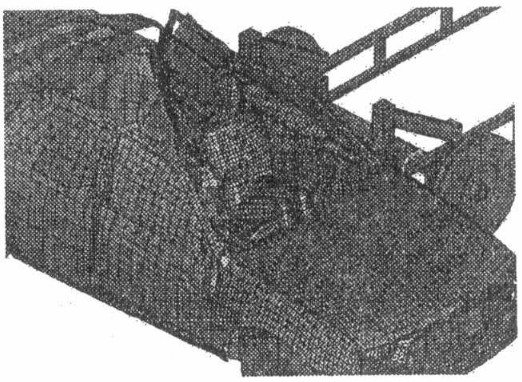


Fig. 5 – Side Impact with MDB (DP1, 48 *km/h* and 40 *ms*)

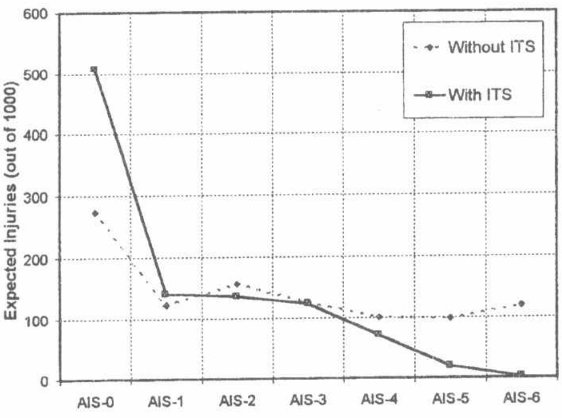
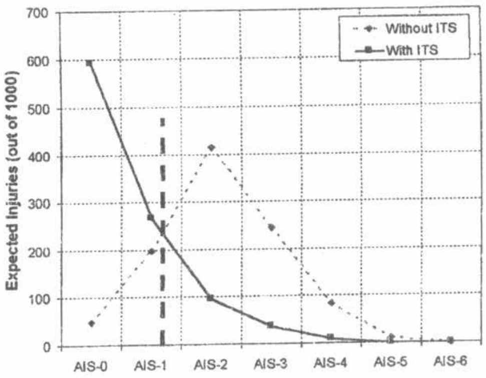
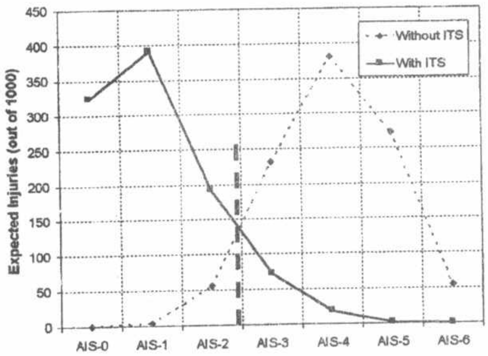


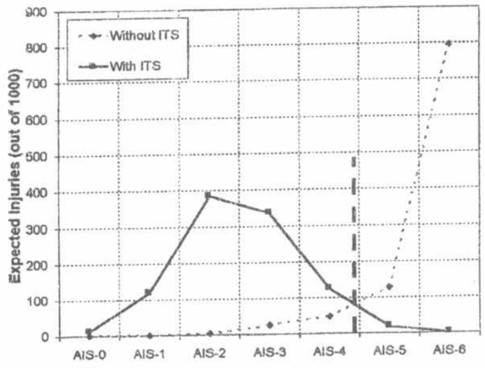
Fig. 6 – Severity Reduction for the MDB Impacts



(a) 32 *km/h* Impact

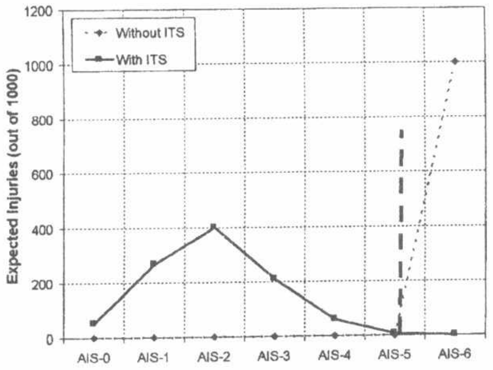


(b) 48 *km/h* Impact

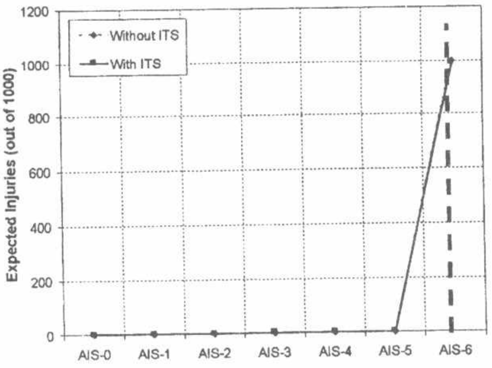


(c) 64 *km/h* Impact

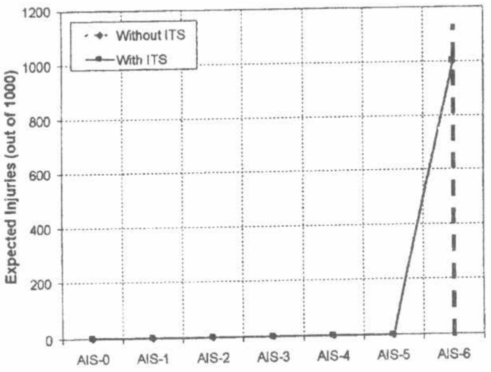
Fig. 7 – Expected No. of Injuries (Pole2, DP3)



(a) 32 *km/h* Impact

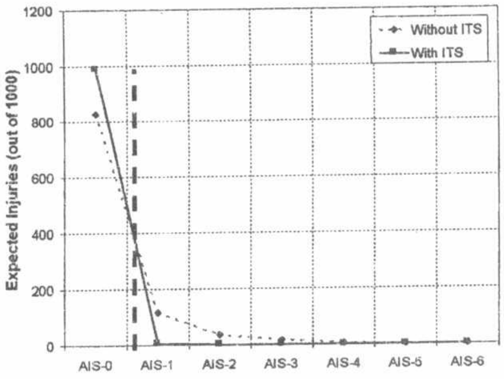


(b) 48 *km/h* Impact

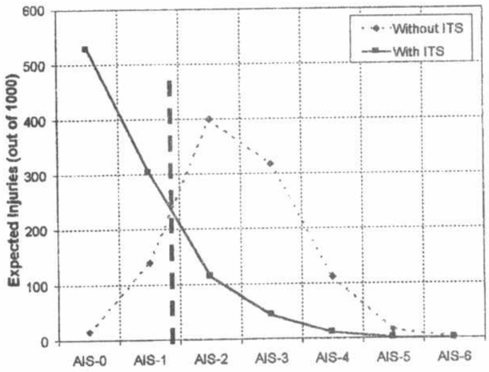


(c) 64 *km/h* Impact

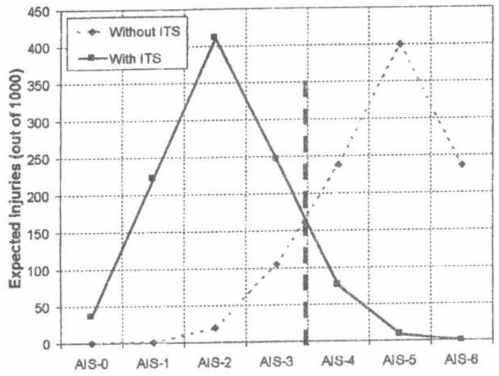
Fig. 8 – Expected No. of Injuries (Pole1, DP2)



(a) 32 *km/h* Impact



(b) 48 *km/h* Impact



(c) 64 *km/h* Impact

Fig. 9 – Expected No. of Injuries (MDB, DP3)