Computer Crash Simulations in the Development of Child Occupant Safety Policies

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Objective: To address the predictability of injury from air bag activation by use of crash simulation software.

Methods: Using current, validated crash simulation software, the effect of air bag activation on injury risk was assessed for the 6-year-old child, both restrained and unrestrained. Results were compared with those for adult occupants in similar crash scenarios.

Results: For the unrestrained child passenger, crash simulations predicted serious head, neck, and chest injuries with air bag activation, regardless of crash severity. For the restrained child passenger, crash simulations predicted similar severe injuries for high-severity crashes only. No serious injuries were predicted for unrestrained male adults exposed to air bags or for child passengers restrained in the rear seat for the crash scenarios simulated.

Conclusions: Using current crash simulation software, this study demonstrated that the risk of air bags to school-aged children could be predicted. Our results confirmed the previously identified risks to unrestrained children and provided the first evidence that air bags, in their current design, are not beneficial to restrained children. This study illustrates that computer crash simulations should be used proactively to identify injury risks to child occupants, particularly when limited real-world data are available.


Editor’s Note: This study can have significant impact on the manner in which automobile crashes would cause air bag injuries. And it costs less than the dummy way. Catherine D. DeAngelis, MD

In the area of motor vehicle occupant injury prevention, computer simulation holds vast, yet unrealized, potential to supplement vehicle safety (crashworthiness) testing. Crashworthiness testing has been used for decades to evaluate the safety of motor vehicles and, as a result, vehicles are safer and people are surviving crashes once thought unsurvivable. Crashworthiness testing uses lifelike surrogates (“dummies”) in actual crash scenarios to predict injury risk. But the expense of crashworthiness testing has limited federally required test procedures to adult surrogates and to a meager number of crash scenarios. Although automobile manufacturers recommended the incorporation of child surrogates in crashworthiness test procedures in 1996 and federal regulations for this testing have been proposed, current regulations do not require their inclusion.

Computer crash simulations provide an efficient and economical approach to extending safety testing to include children and a far greater number of crash scenarios. They have been used as a standard, validated tool by vehicle and restraint manufacturers to evaluate the safety of new designs for occupants. With computer crash simulations, the forces and accelerations experienced by occupants during different crash scenarios can be measured. Through recognized mathematical relationships that were determined through extensive biomechanical testing, these engineering measurements can be translated into a predicted risk of biological and structural injuries for distinct body regions of either children or adults. Realizing the invaluable contribution of computer simulations as predictors in other areas of health, the Institute of Medicine (Washington, DC) has recently called for the increased use of computer simulation as an important tool for understanding injury causation to predict injury risk.

One current controversy in injury control is the safety of air bags for children. It is well accepted that air bags pose a substantial risk to young, unrestrained, school-age children (aged 5 to 7 years), but it is unclear whether restrained children in this age group are at a similar high risk. These children have recently outgrown their child safety seats (the upper weight limit for most child safety seats is 18 kg) and many parents have begun using seat...
MATERIALS AND METHODS
COMPUTER CRASH SIMULATIONS

MADYMO (Mathematical Dynamic Model; TNO, Delft, the Netherlands) is an engineering software tool that allows users to develop, design, and optimize safety systems and to assess injury risk to vehicle occupants. The validity of MADYMO has been demonstrated by verification studies using experimental test data. MADYMO is currently used by vehicle and restraint manufacturers to predict the risk of occupant injury under specified crash dynamics and occupant parameters, including air bag activation, impact speed, preimpact braking, occupant size, occupant position, and restraint usage. The effects of these different crash parameters are measured in terms of forces and accelerations experienced by different body parts of the occupants.

In this study, a model of a leading midsized sedan with a top-mounted, passenger air bag was developed as our test vehicle. Because air bags are designed to deploy in frontal crashes, a frontal crash into a rigid barrier was simulated. In addition, preimpact braking was included in the simulation because braking has been shown to be a common characteristic of air bag crashes with occupant fatalities. The rate of braking was simulated at 6.8 m/s², previously shown to be characteristic of average driver behavior. For all simulations, the vehicle seat was set at the rearmost position.

Two sizes of vehicle occupant surrogates were selected from standard databases supplied with the MADYMO program: a P6 child dummy model (“aged” 6 years) and a Hybrid III 50th percentile adult male dummy model. These surrogates are mathematical representations of the state-of-the-art in crash test dummies that can be used in computer simulations to represent occupants. The P6 child dummy model was chosen because this surrogate most closely approximated the age of children killed in actual air bag–related crashes and the age of interest for this study (the young, school-aged child). The Hybrid III 50th percentile adult male dummy model was chosen because current vehicle safety standards require protection of an occupant of this size against serious injuries. For clarity, this article henceforth refers to the P6 child dummy model as the “child passenger” and to the Hybrid III 50th percentile adult dummy model as the “adult male passenger.”

In addition to size of the occupant, 4 other independent variables were simulated: air bag activation (air bag activated or air bag deactivated), occupant position (front passenger seat or rear seat), restraint usage (unrestrained, lap-only belt, or lap-shoulder belt), and crash severity (high or low). The low-severity crash was specified by a speed change (also known as Delta V) of 5.28 m/s (19 km/h) and the high-severity crash was specified by a speed change of 10.28 m/s (37 km/h), as defined in a previous report.

OUTCOME MEASURES

From the computer crash simulations, the risk of injury was assessed using measurements of crash forces and accelerations for the head, chest, and neck of vehicle occupants. Head injury risk was measured using the Head Injury Criterion (HIC), a nondimensional parameter calculated from the occupant head acceleration and time over which the acceleration occurs. When the HIC exceeds the accepted injury tolerance limit of 1000, a risk of concussion for frontal impact is predicted. A chest acceleration above the accepted tolerance limit of 588.72 m/s² (60 g) sustained for 3 milliseconds predicts severe chest injury. Injury tolerance limits for neck tensile and shear loads have not been universally accepted. Since limits of 1490 to 2900 N in tension and 1200 N in shear for the P6 child dummy model surrogate are currently proposed by the National Highway Traffic Safety Administration (Washington, DC) for crashworthiness testing, measurements exceeding these proposed limits were used in this study to predict neck injury.

RESULTS

The computer crash simulations predicted that air bag activation propels an unrestrained front-seat child passenger rearward and upward (Figure). The simulations showed a complex relationship between independent variables (the size of the occupant, air bag activation, occupant position, restraint usage, and crash severity) and injury risk, as described below for the head, chest, and neck.

The effects of air bag activation on injury risk are summarized in Table 1. For a child passenger, injury risk to the head, neck, and chest increased or remained the same with air bag activation, independent of re-

belts for these children. In addition, parents may be questioning the continued need to place the child in the rear seat. Current research indicates that 30% of the children in this age group are restrained in the right front seat at the time of a crash. Is this a safe practice in passenger air bag–equipped vehicles?

Most safety recommendations are based on crash test results and early injury experience using the device. There were very limited crash test data regarding children and air bags and, as a result, there was no initial recommendation to place young, school-aged children in the rear seat of passenger air bag–equipped vehicles. Now, after the report of numerous child deaths due to air bags, double-paired comparison methods using Fatal Analysis Reporting System data have provided some evidence for the risk of injury to children from front passenger air bags. But children had to die before these analyses could be conducted. The prediction of injury risk using crash simulation software affords the possibility that proactive safety policy might be set before children sustain injury from new technology.

The objective of this study was to address the predictability of injury from air bag activation by use of crash simulation software. Using standard, validated crash simulation software, we evaluated the effect of front passenger air bags on child passengers—both restrained and unrestrained—in crashes of high and low severity and in crashes where children were placed in the front passenger seat vs the rear seat.
strain use and crash severity. For the unrestrained adult male passenger, air bag activation decreased or did not change injury risk for all body regions in high-severity crashes; however, it increased injury risk (although not above the accepted tolerance limits) for low crash severities. Of importance, rear seat placement was beneficial for all children as evidenced by reductions in injury parameters. It must be noted that these simulations were run with preimpact braking and an unrestrained child in the rear seat during the braking phase slides up closer to the cushioned padding of the front seat back. This reduces the momentum/forces from the impact. The effect of air bag activation and rear seat placement on each body region is displayed in Tables 2, 3, 4, and 5.

HEAD INJURY RISK

The simulations revealed that air bag activation increased the risk of head injury for a child passenger, as predicted by the HIC values. For low-severity crash with air bag activation, only the unrestrained child passenger experienced HIC values above the suggested tolerance limit. For high-severity crash, all child passengers exposed to air bags produced HIC above the threshold for serious injury. The rear-seated child passenger, regardless of restraint use or crash severity, experienced HIC values well below the accepted tolerance limit (Table 2).

In all scenarios, the unrestrained adult male passenger displayed HIC values below the accepted tolerance limit. For low-severity crash, the risk of head injury for adult males increased marginally with air bag activation. For high-severity crash, on the other hand, the risk of head injury decreased from near threshold limits without air bag activation to lower measures with air bag activation.

CHEST INJURY RISK

For the restrained child passenger, air bag activation did not influence chest accelerations, regardless of restraint use or crash severity, and all chest accelerations were below the threshold. For the unrestrained child passenger, air bag activation produced chest accelerations above the accepted tolerance level, regardless of crash severity. The rear-seated child passenger, regardless of restraint use or crash severity, experienced chest accelerations below the injury limit. For the unrestrained adult male passenger, chest accelerations were below the accepted tolerance limits in low-severity crash simulations regardless of air bag deployment. In the high-severity crash simulations, the air bag reduced the chest injury risk for the adult to below the tolerance limit (Table 3).

NECK INJURY RISK

For low-severity crashes, the restrained child passenger experienced neck tensile forces (elongation) (Table 4) and shear forces (sliding) (Table 5) below the proposed tolerance limit with air bag activation. For high-severity crashes, the forces increased substantially, exceeding pro-
posed tolerance limits. The unrestrained child passenger experienced substantial neck tensile and shear forces with air bag activation, regardless of crash severity. In most cases, placing a child passenger in the rear seat reduced the risk of neck injury, except in the case of the unrestrained child in the rear seat who hit the back of the front seat and experienced high neck forces. 

For the unrestrained adult male passenger, neck tensile forces were below the proposed tolerance limits with air bag activation. Shear forces were below the proposed tolerance limits in low-severity crash simulations, regardless of air bag activation. For the high-severity crash, air bag activation reduced the neck injury risk.

### COMMENT

Using current computer crash simulation software, this study demonstrated that the risk of air bags to school-aged children could be predicted. Our results confirmed the previously identified risks to unrestrained children and provided the first evidence that front passenger-side air bags, particularly those that are fully powered, are not beneficial to restrained children. This study illustrates that computer crash simulations should be used proactively to identify injury risks to child occupants, particularly when limited real-world data are available.

For unrestrained children, our simulations predicted occupant movement and resultant injuries that agreed with investigations of child fatalities due to air bags.5,19-24 Our model predicted serious head, neck, and chest injuries. The reported injuries sustained by children as a result of air bag exposure included head injuries (extracranial hemorrhage, parenchymal brain injury, cerebral edema, brain swelling, intracranial hemorrhage, brain herniation, and skull fracture), neck injuries (cervical cord injury, cervical spine dislocation, subluxation, and fracture), and thoracic injuries (infrarenal aortic disruption, pulmonary hemorrhage, pulmonary contusions, inferior vena cava laceration, and sternal fracture). Although very limited data exist for restrained children injured by air bags, serious, nonfatal injuries have been reported to the head, neck, and chest.25,26

When air bag–equipped vehicles first appeared on the market, no recommendation existed regarding the placement of school-aged children in these vehicles. It was not until the first deaths of unrestrained children from air bags in 1993 that the current recommendation, seating children in the rear, was made by the National Highway Traffic Safety Administration and other safety advocates.3,23,27-29 Initially, this recommendation included only infants in rear-facing infant seats.20 Rear seat placement for all children less than 12 years of age was recommended until 1996 after several toddler and school-aged children sustained fatal injuries from air bag interaction.21 If simulations similar to ours had been available when air bags were introduced, the risk of air bags to children could have been assessed sooner and appropriate policy set proactively. Safety decisions based on information from sources other than real-world crashes are made every day when consumers choose new vehicles based on laboratory tests from the federal government, the Insurance Institute for Highway Safety (Arlington, Va), and the Consumer Union (Younkers, NY).

The current simulations involved one vehicle with the P6 child dummy model. The advantage of computer simulations is that these parameters are readily modifiable. Future simulation enhancements should include additional classes of vehicles and children of other sizes to generalize our findings to other configurations.

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### Table 3. Chest Acceleration* for the Child Passenger and Adult Male Passenger as Predicted by the Computer Crash Simulations

<table>
<thead>
<tr>
<th>Crash and Passenger Types</th>
<th>Front Seat Passenger With Air Bag</th>
<th>Front Seat Passenger Without Air Bag</th>
<th>Rear Seat Passenger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-severity crash†</td>
<td>Lap-shoulder–belted child 28</td>
<td>27</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Lap-only belted child 19</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Unrestrained child 183‡†</td>
<td>24</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Unrestrained adult male 36</td>
<td>8</td>
<td>NA§</td>
</tr>
<tr>
<td>High-severity crash‡</td>
<td>Lap-shoulder–belted child 50</td>
<td>44</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>Lap-only belted child 35</td>
<td>35</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>Unrestrained child 252‡†</td>
<td>113‡†</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>Unrestrained adult male 60</td>
<td>72‡†</td>
<td>NA§</td>
</tr>
</tbody>
</table>

* Chest acceleration is a measure of acceleration due to gravity that is used to assess chest injury risk. A value above 60g indicates a significant risk of serious chest injury for both adults and children.
† The low-severity crash was specified by a speed change of 5.28 m/s (19 km/h) as defined in a previous report.16
‡ Above tolerance level.
§NA indicates not applicable.
||The high-severity crash was specified by a speed change of 10.28 m/s (37 km/h) as defined in a previous report.16

### Table 4. Neck Tensile (Elongation) Loads* for Child Passenger and Adult Male Passenger as Predicted by the Computer Crash Simulations

<table>
<thead>
<tr>
<th>Crash and Passenger Types</th>
<th>Front Seat Passenger With Air Bag</th>
<th>Front Seat Passenger Without Air Bag</th>
<th>Rear Seat Passenger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-severity crash†</td>
<td>Lap-shoulder–belted child 500</td>
<td>400</td>
<td>384</td>
</tr>
<tr>
<td></td>
<td>Lap-only belted child 760</td>
<td>490</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>Unrestrained child 9850‡†</td>
<td>1139</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>Unrestrained adult male 3697</td>
<td>1548</td>
<td>NA§</td>
</tr>
<tr>
<td>High-severity crash‡</td>
<td>Lap-shoulder–belted child 1800‡</td>
<td>1400</td>
<td>1187</td>
</tr>
<tr>
<td></td>
<td>Lap-only belted child 2300‡</td>
<td>1300</td>
<td>1100</td>
</tr>
<tr>
<td></td>
<td>Unrestrained child 10 700‡</td>
<td>3825‡</td>
<td>185</td>
</tr>
<tr>
<td></td>
<td>Unrestrained adult male 3410</td>
<td>4109</td>
<td>NA§</td>
</tr>
</tbody>
</table>

* Neck tensile (elongation) loads is a measurement in newtons used to assess risk of distraction injuries to the neck. A value higher than 1490 to 2900 N indicates a significant risk of serious neck distraction injury for children and a value higher than 6500 N indicates a substantial risk for adults.
† The low-severity crash was specified by a speed change of 5.28 m/s (19 km/h) as defined in a previous report.16
‡ Above tolerance level.
§NA indicates not applicable.
||The high-severity crash was specified by a speed change of 10.28 m/s (37 km/h) as defined in a previous report.16
In all areas of health research, the unique developmental characteristics of children are being recognized. In particular, the National Institutes of Health, Bethesda, Md, now requires consideration of children in all research study protocols. Recently, the National Highway Traffic Safety Administration has proposed the use of child dummies in one subset of crashworthiness tests: those studying occupant safety related to air bags in front-seat passenger air bags. We acknowledge the financial support of State Farm Insurance Companies (Bloomington, Ill) and the National Highway Traffic Safety Administration (Washington, DC). This work was presented by Dr Lee at the annual conference of the American Academy of Pediatrics, New Orleans, La, May 2-4, 1998.

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REFERENCES


Table 5. Neck Shear (Sliding) Loads* for Child Passengers and Adult Male Passengers as Predicted by the Computer Crash Simulations

<table>
<thead>
<tr>
<th>Crash and Passenger Types</th>
<th>Front Seat Passenger With Air Bag</th>
<th>Front Seat Passenger Without Air Bag</th>
<th>Rear Seat Passenger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-severity crash†</td>
<td>370</td>
<td>1900†</td>
<td>351</td>
</tr>
<tr>
<td>Lap-unbelted child</td>
<td>970</td>
<td>680</td>
<td>300</td>
</tr>
<tr>
<td>Unrestrained child</td>
<td>576‡†</td>
<td>369</td>
<td>600</td>
</tr>
<tr>
<td>Unrestrained adult male</td>
<td>1786</td>
<td>1359</td>
<td>NA§</td>
</tr>
<tr>
<td>High-severity crash‡</td>
<td>2220‡</td>
<td>2300‡</td>
<td>933</td>
</tr>
<tr>
<td>Lap-unbelted child</td>
<td>3400‡</td>
<td>1100</td>
<td>900</td>
</tr>
<tr>
<td>Unrestrained child</td>
<td>936‡</td>
<td>2165‡</td>
<td>800</td>
</tr>
<tr>
<td>Unrestrained adult male</td>
<td>1595‡</td>
<td>355‡</td>
<td>NA§</td>
</tr>
</tbody>
</table>

* Neck shear (sliding) loads is a measurement in newtons used to assess risk of dislocation injuries to the neck. A value higher than 1400 N indicates a substantial risk of serious neck dislocation injury for children and a value higher than 3100 N indicates a substantial risk for adults.
† The low-severity crash was specified by a speed change of 5.28 m/s (19 km/h) as defined in a previous report.‡
‡ Above tolerance level.
§ NA indicates not applicable.
¶ The high-severity crash was specified by a speed change of 10.28 m/s (37 km/h) as defined in a previous report.