DEVELOPMENT OF ADAPTIVE SUPPLEMENTAL RESTRAINT SYSTEM

Yefim Kriger

Fairfield University, CT

USA

Paper Number 19-0051

ABSTRACT

The article relates to methods of mitigating results of improper value of force applied to the occupant's body at a time of an imminent front vehicle collision and preventing fatalities as well as injuries that may be caused. More particularly, the present article relates to a new method of accurately weighing vehicle occupants that eliminates obstacles to improve their safety in the event of a collision.

The statistics show that the number of victims is indirectly proportional to their weight. It means that to significantly improve safety of the vehicle occupants, it is necessary to put stress on controlling the forces applied to the occupants' bodies by more accurately measuring their weights. It is noted in [1] that the weight of an occupant measured by an air bag system is not the entire weight of the occupant since some of the occupant's weight will be supported by feet which are resting on the floor or pedals. As result, there is overlapping of weight classes in the Passenger Classification System that creates malfunction of the air bag and decreases the number of properly working weight classes to 3 instead of 5. This is a problem that does not allow to accurately weigh a vehicle occupant in a supplemental restraint system to provide the possibility of an accurate control of the air bag inflation force depending on the real value of the occupant's weight (mass) and eliminate extra force applied to the occupant's body at the time of collision. NHTSA, Department of Transportation, published in August 2004 requirements of the final rule of Section §571.208 Standard No. 208; "Occupant crash protection" [2] to improve the security of the air bags for children and light women. An object of the article is to find ways to improve the accuracy of the safety system for differentiating the weight of older children from the weight of the light women passengers and support the documents provided by NHTSA that say the modern safety systems should provide improved protection for occupants of different sizes.

The method described in the present article provides the possibility to extend the current Passenger Classification System by accurately measuring occupant's weight and more accurately controlling the force applied to lighter weighing people and youngsters in case of accident. The article provides a method of accurately weighing occupants of different weights by employing an ADaptive MUlti-force Safety (ADMUS) system that improves the Passenger Classification System for minimizing the risk of injury or death from a possible improper extra force applied to them by air bags in case of accident especially for light adults in contemporary and self-driving or autonomous vehicles

The ADMUS system, with its accurate innovative occupant weight measuring KEF method [3, 4], provides higher protection to occupant bodies of different weights by keeping an extra force from them in case of accident. The weighing error of a vehicle occupant weight measuring drastically decreased in applications [5, 6] by employing the occupant weighing innovative KEF method and using this weighing method and technology based on it to eliminate the weighing error.

Research Question/Objective.

Practically all American cars are equipped by safety systems such as Supplemental Restraint System (SRS) comprising an air bag. When the vehicle includes an occupant safety restraint device arranged to protect the occupant during a crash involving the vehicle, it is connected to the weight measuring system and arranged to provide a variable deployment depending on the determined weight of the occupant. During a crash event, the vehicle's crash sensor and other sensors provide crucial information to the air bag Electronic Computing and Control Unit (ECU), including weight and position of an occupant, usage of the seat belt, severity of impact, etc. Using this information, the air bag ECU's crash algorithm determines if the crash event meets the criteria for air bag deployment and triggers various firing circuits to deploy one or more air bag modules within the vehicle.

THE WAYS TO IMPROVE AIR BAG TECHNOLOGY

To improve safety of passengers in case of a possible crash, adaptive and advanced duel-depth air bag systems and, according to them, the Passenger Classification Systems were designed. Adaptive air bag systems may utilize multi-stage air bags to adjust the pressure within the air bag. Information regarding the occupants and the severity of the crash are used by the air bag control unit, to determine whether air bags should be suppressed or deployed, and if so, at various calculated output levels**.** In the advanced duel-depth air bag, the first and second chambers of the air bag are selectively pressurized with a gaseous fluid. The design of the advanced duel-depth air bag system shows that the car manufacturers try to improve the vehicle occupant safety employing the Passenger Classification System [7] by multiplying the number of stages of an air bag.

STATISTIC OF CASUALTIES.

The present article relates to a problem of mitigating results of improper value of force applied to the occupant's body at a time of an imminent vehicle collision on the road by preventing fatalities as well as injuries that may be caused. More particularly, the present article relates to a new method of accurately weighing vehicle occupants that provides elimination of obstacles to improve their safety in the event of a collision. The problem of vehicle occupant safety has now become a nation-wide problem for the USA and other countries. The air bag by itself may cause injuries if it doesn't work properly. From 1990 to 2000, the United States National Highway Traffic Safety Administration (NHTSA) identified 175 fatalities caused by air bags. Most of these (104) have been children, while the rest were adults. 262 deaths from1990 to 2006 reportedly have been caused by air bags inflating in low severity crashes, most of them in older model vehicles. These deaths include 87 drivers, 13 adult passengers, 138 children, and 24 infants. In 2016 alone, 37,461 people died in motor vehicle crashes. In 2016 publication [8], NHTSA provided overall crash population for a period of 2010-2013. Today’s cars and trucks come with driver assistance technologies. The driver assistance technologies that include sensors, radars, cameras, GPS will help support Automated Driving Systems (ADS), more commonly referred to as “self-driving” [9] (SDV) or autonomous vehicles. These 2 types of vehicles in contrast to the contemporary vehicles might be able to take over all aspects of driving and may predict imminent crashes on the road and reduce vehicle crashes and resulting fatalities and injuries. The Table 1 was generated by this data.

Table 1.
Crashes in 2010 - 2013 and their results

2010 - 2013 Annually					2010 - 2013 total costs	
	Crashes	Fatalities	1-5 Injuries	Property damage	Costs for society	Total costs
1	Registered crashes for all vehicles					
	5.5 M	33,020	2.7 M	6.3 M	$195 B	$721 B
2	Related to the V2V technology (2 cars crashes - 69%)					
	3.8 M	13,329	2.1 M	5.2 M		
3	For LV2LV vehicles only (62% of all crashes) - that a new technology may save					
	3.4 M	7,325	1.8 M	4.7 M	$109 B	$319 B
4	Crashes and their results that will be not covered by the V2V technology					
	2.1 M	25,695	0.9 M	1.6 M	$86 B	$402 B

In the row 1 of the Table 1, is given the data published by NHTSA. Based on 2010-2013 General Estimates System (GES) and Fatality Analysis Reporting System (FARS), of the 5.5 million annually crashes, which would translate to 33,020 fatalities, 2.7 million Maximum Abbreviated Injury Scale (MAIS) 1-5 injuries, and 6.3 million property damage only vehicles (PDOVs). NHTSA estimated that safety applications enabled by self-driving technology could eliminate or mitigate the severity of up to 80 percent of crashes, including crashes at intersections or while changing lanes. Most of the automobile companies, technology companies, component makers, and organizations have begun developing or forming partnerships around self-driving technology to decrease the number of crashes, fatalities, and injuries on the roads.

The Tesla's hardware [10] for self-driving model S electrical car employed in the SDV to make driving vehicles safer . The V2V (vehicle-to-vehicle) communication technology described by NHTSA. Detailed information about DSRC-based V2V vehicle communication system see in [8]. As the statistics show, the number of the victims is indirectly proportional to their weight. The sensors have to measure weight of a vehicle occupant but not the size of the occupant because the energy accumulated by the occupant's body in the moving vehicle and which a restraint system has compensate during the crash, is proportional to the mass but not to the size of the body. In the contemporary Passenger Classification Systems, the force applied by an air bag to the adult occupant, especially to the driver, in the air bag system is the same as applied to the person whose weight is 102 Lb and applied to the person whose weight is even 215 Lb or higher. A light occupant in such situation may be injured and a heavy occupant may be not protected enough. This is the reason that it is necessary to provide more classes in the Passenger Classification System to differentiate the forces applied to children and adult occupants in case of collision according to their weight**.**

Methods and data sources

OCCUPANT WEIGHING ERROR

As was mentioned before, the weight of an occupant measured by an air bag system is not the entire weight of the occupant since some of the occupant's weight will be supported by his or her feet which are resting on the floor or pedals. Contribution of the lost weight of the foot part of the body to a total weight of a person during measurement may be evaluated very easily, and it is about 15 -30%% or more of the whole body weight. This is a problem that does not allow to accurately weigh a vehicle occupant in supplemental restraint system to provide the possibility of an accurate control of the air bag inflation force depending on the real value of the occupant’s weight (mass) and eliminate extra force applied to the occupant’s body at the time of collision. So, to accurately weigh a vehicle occupant, it is necessary to weigh the whole body of a vehicle occupant including the weight of a foot part of his/her body. NHTSA published in [2] requirements of the final rule of Section § 571.208 Standard No. 208; "Occupant crash protection" to improve the security of the air bags for children and light passengers. It is not made in the on-board vehicle safety system yet. It is a goal of the methods of the present article to improve the occupant safety system by more extensive preparations for overcoming an imminent vehicle collision on the road and preventing fatality as well as injuries of the occupants that may be caused by an unsafe force applied to their bodies by the restraint system in the event of a collision. A principal object of the present article is to improve the accuracy of the safety system for differentiating the weight of older children from the weight of the light women passengers and support the documents provided by NHTSA that say the modern safety systems should provide improved protection for occupants of different sizes. So, it is the object of the present article to provide a safety system for controlling the force applied to the occupant's body measuring not the size, but with the accurately measured weight of the occupant. An object of the present article is to provide an accurate measuring weight of the vehicle occupants in a safety system of the contemporary, self-driving and autonomous vehicles by an accurate occupant weighing technology because the statistics show that the number of the accident victims depends on their weight. This provides the possibility to extend also the current Passenger Classification System and more accurately control the force applied to lighter weighing people and youngsters in case of accident.

ADMUS SYSTEM

This article provides a safety method for protection of the different weight occupants of the self-driving or autonomous vehicle by applying different forces to their bodies at the moment of an accident that are more accurately controlled through the control signals depending on their weights that are modified depending on the morphological data and factors of the car trip in the current situation that influence the force applied to the occupant's body. The article provides method of accurately weighing occupants of different weights by employing an ADaptive MUlti-force Safety (ADMUS) system that improves the Passenger Classification System for minimizing the risk of injury or death from a possible improper extra force applied to them by air bags in case of accident especially for children and light adults in contemporary and self-driving or autonomous vehicles. The ADMUS system, with its accurate innovative occupant weight measuring KEF method [3, 4], provides higher protection to occupant bodies of different weights from applying an extra force to them in case of accident by more extensive preparations for overcoming possible negative consequences of an imminent vehicle collision on the road and preventing fatal accidents as well as injuries of the occupants that may be caused by an unsafe force applied to their bodies by the restraint system.

KEF METHOD

The weighing error of a vehicle occupant weight measurement may be drastically decreased by employing the occupant weighing innovative KEF method and using this weighing method and technology based on it to eliminate all the weighing error. In this case, the energy generated by the occupant's body at the time of collision may be accurately measured before the collision and used for safety purposes in the vehicle air bag system. Using the KEF method is important to provide effectiveness and accuracy for occupant weighing. It is based on a horwest (horizontal weighing stability) effect that states: the value of a weight measurement of an object located in a closed system on a weighing unit doesn't change while this object provides a bi-directional force in a horizontal direction of a predetermined value to a vertical surface of another object, which is a predetermined distance away [see 3,4]. The horwest effect can be used to implement the simplified weighing apparatus for accurate vehicle occupant weighing. Moreover, the innovative KEF method can provide a simplified and accurate occupant's weight measurement in a car or a motor vehicle, especially a passenger vehicle such as an automobile, a van, a self-driving car, a corporate vehicle, a limousine, or a truck equipped with an occupant safety device such as air bag Supplemental Restraint System (SRS) by employing a weighing unit (weight sensors) connected to the seat of the vehicle occupant, whose output is connected to the computing and control unit of the SRS, by pushing horizontally a switch of the weighing moderator, located above the waist of the occupant on a substantially vertical surface of the vehicle (for example, on a steering wheel, an instrument panel, or a dash board) at the beginning of the trip, and simultaneously, conveniently lifting feet above the floor and keeping them up during the weight measurement, measuring occupant's weight by the weighing unit. Subsequent processing of the collected weight of the vehicle's occupant by the computing and control unit while receiving the signal from the switch of the weighing moderator, modifying this original weight measurement of the vehicle occupant by the current values of the morphological data and factors of the car trip situation and transmitting this processed value of the vehicle occupant's weight to the air bag control unit to apply, in case of a collision, an appropriate force to the occupant's body, whose value will be calculated according to the modified and accurately measured occupant's original weight.

SOURCES

The accuracy of weighing a vehicle's occupant and, accordingly, providing an accurate value of the force applied to the different weights of the occupants' bodies may be improved up to 20-30% by employing KEF method. It is further noted that the priority documents of the current article, namely U.S. Pat. No. 9,566,877 [3], issued on Feb. 14, 2017, **allowed** U.S. Divisional patent application Ser. No. 15/430,219 [4] filed on Feb. 10, 2017, U.S. Pat. No. 10,131,308 [6] issued on Nov. 20 , 2018 and U.S. Provisional Application No. 61/956,059 [11] filed on May 30, 2013, can provide a more detailed description of the novel horwest effect and KEF method. The present article provides a method for a contemporary or a self-driving or autonomous vehicle having an air bag safety system to communicate with an innovative weighing KEF technology for use in the accurate weighing of an occupant based on a weighing moderator to prevent extra force applied to the occupant’s body in case of collision. The present article provides modification of the occupant's original weight accurately measured by the innovative weighing technology in a contemporary or a self-driving or autonomous vehicle before the beginning of a trip in accordance with the values of such parameters as the severity of the crash, position of the occupant, using a seat belt.

Results

As was noted above, the measured weight of an occupant is not the entire original weight of the occupant since some of the occupant's weight will be supported by his or her feet which are resting on the floor or pedals. This effect creates a weighing error. The value of this error in a total original weight of a person may be evaluated very easily, and it is about 15-30% or more of the whole body weight. In [12] this loss of the occupant's weight was given as 20%. Some data for the weighing error provided in the current article have been received in experiments and shown in Tables 2 , 3, and 4. The whole picture of the weight lost by a vehicle occupant during measuring his/her weight while one is sitting in the car seat and the feet are resting on floor or pedals and supporting the body, may be clear after receiving a statistical data. The weighing error is a problem that does not allow to accurately weigh a vehicle occupant in on-board vehicle safety restraint system to provide the possibility of an accurate control of the air bag inflation force depending on the real original value of the occupant's weight (mass). The weighing error does not allow also to eliminate improper force applied to the occupant's body at the time of collision by improving the Passenger Classification System and providing an improved accuracy of the safety system for differentiating occupants by weight, especially children from the light women. The weight measurements of occupants of different groups age, sex, positions were made by the author and provided in Table 2.

Table 2.

The occupant's weighing error

	Date	Weight (Lb)					
		Original weight, sex, age	Horizontal distance D (cm) from feet on the floor to the torso on the scale	Feet position (torso on the scale)			Percentage of the occupant's weighing error
				Hands are on the groins	Hands down in the air	Hands on the knees	
1	3.29.2018	151 Man, 82	70 max	128	126	115	15.2-23.8 %
			55 mid	121	114	112	19.9-25.8 %
			40 min	114	109	107	24.5-29.1 %
2	3.30.2018	182 Female, 77	60 max	155	154	150	14.8-17.6 %
			50 mid	150	149	147	17.6-19.2 %
			40 min	143	140	138	21.4-24.2 %
3	3.29.2013	148, Man, 77	D min			109	25.8-26.4 %
4	7.25.2014	151 Man, 78	D min			110	27.2%
5	9.24.2016	144, Man, 80	D min			120	16.7%
6	7.14.2018	221 Man, 45	D max	197	193	188	10.9 - 14.9 %
			D mid	189	178	173	14.5 - 19.5 %
			D min	173	166	160	21.7 - 27.6 %
7	11.10.2018	134 F 15	D min			93	30.6%
8	11.10.2018	91 F 11	D min			65	28.6 %

As we may see from Table 2, the value of an error of measuring weight of an occupant sitting in a seat of the contemporary on-board vehicle SRS air bag safety system may reach around 30% of original occupant's weight. For example, in the Table 2 in the range from 144 to 221 Lb of the original weights of occupants, the value of the mistake of occupant weight measurement reaches 29.1%. This means that some two classes in the Occupant Classification System SRS may be overlapped. In the Fig.1,a is given the Table S7.1.4 "Weights and dimensions of the vehicle occupants referred to in Standard § 571.208: Occupant crash protection"[2].

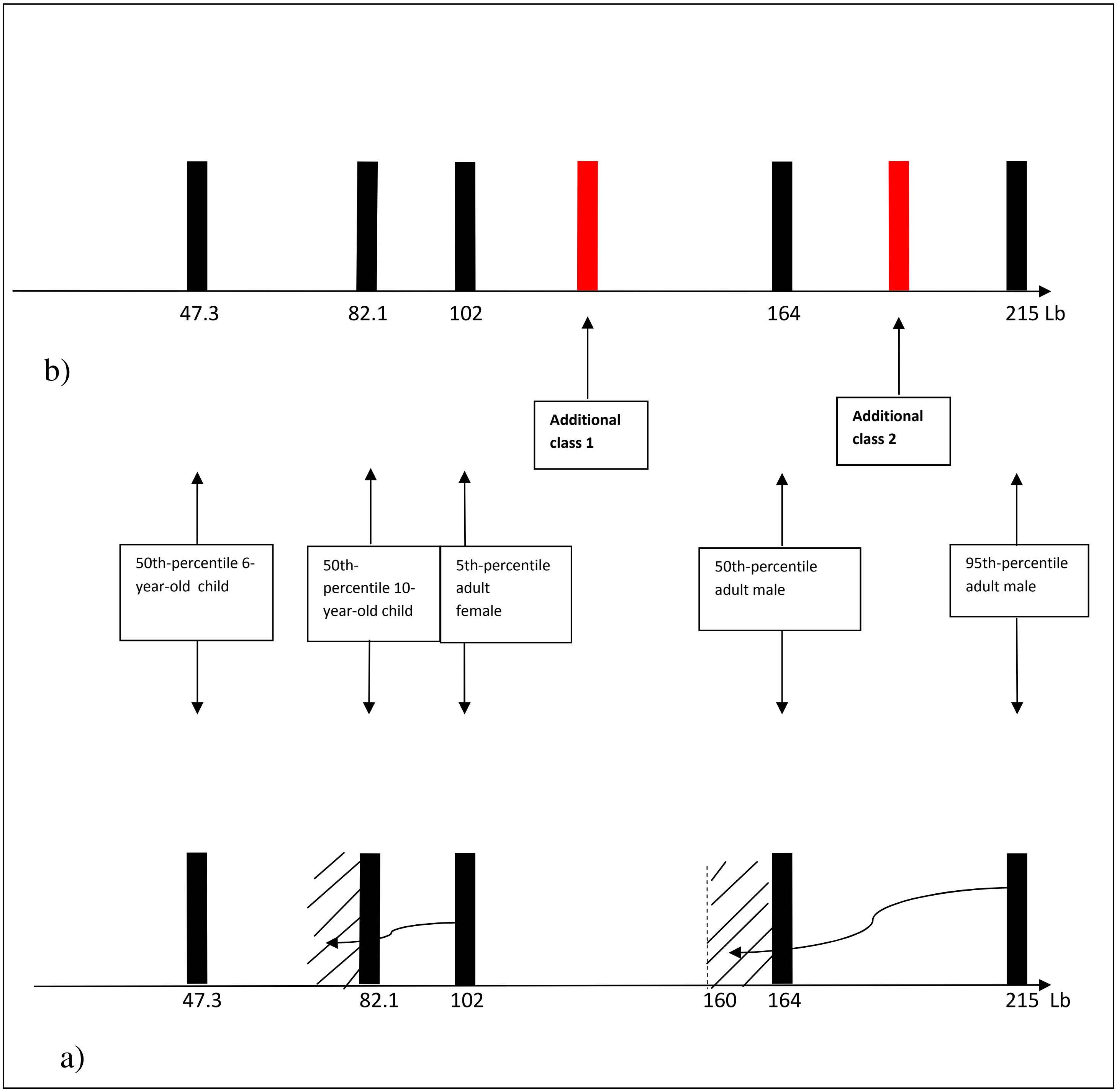


Fig.1. b) KEF method based Passenger Classification System
Fig.1. a) Overlapping in the Standard 208 Passenger Classification System

OVERLAPPING IN THE STANDARD §571 208

There are 5 classes of occupants in the Table S7.1.4 "Weights and dimensions of the vehicle occupants referred to in Standard § 571.208" [2] showed as 5 black bars in FIG.1,a:

50th-percentile 6-year-old child (47.3 Lb), 50th-percentile 10-year-old child (82.1 Lb), 5th-percentile adult female (102 Lb), 50th-percentile adult male (164 Lb), and 95th-percentile adult male (215 Lb). As we see from Table 2, in case of the 95th-percentile adult male whose original weight 221 Lb (that is close to the range 215 Lb) and its maximum variable weighing error value is 27.6%, 50th-percentile adult male class will be overlapped by the measured weight of the 95th-percentile adult male class**,** and the SRS air bag safety system will not recognize whom it is necessary to treat: 50th-percentile or 95th-percentile adult male, although the force applied to the bodies of these two different weight occupants should be different. For now it seems the worst case of overlapping is on the border of 50th-percentile 10-year-old child and 5th-percentile adult female. As in the previous example, in case of the 5th-percentile adult female whose original weight around 102 Lb (according to the Table S7.1.4 "Weights and dimensions of the vehicle occupants referred to in Standard § 571.208") and if its maximum variable weighing error value is more than 20%, the 50th-percentile 10-year-old child class will be overlapped by the measured weight of the 5th-percentile adult female class (see FIG 1, a). In this case, the air bag safety system will malfunction. It will suppress the air bag when it should be deployed because the 5th-percentile adult female is in the seat.

OVERLAPPING BY THE MEASURED DATA

Malfunction case was found in Table 3 when a group of adult people was checked for their value of weighing error. The weight measurement of this group of six adult women was provided by "ResCare" Adult Day Care Community Center, Hamden, CT. As we may see from Table 3, women ##5 and 6 may be related to the 5th-percentile adult females. Woman #5 has original weight of 113 Lb, and her measured weight in the simulator of the vehicle seat while her feet are on the floor, is 84 Lb. Her calculated weighing error is 25.7%. In case of the vehicle collision, the air bag system will recognize her as adult (84 Lb >82.1 Lb) and her air bag will be deployed. Woman #6 has original weight of 108 Lb, and her measured weight in the simulator of the vehicle seat while her feet on the floor, is 78 Lb. Her calculated weighing error is 27.8%. In case of her vehicle collision, the air bag system will malfunction by recognizing her as the 50th-percentile 10-year-old child (78 Lb <82.1 Lb), and her air bag will not be deployed.

Table 3.

The adult occupant's weighing error

No.	Date	Name	age	sex	Weight (Lb)			Percentage of the occupant's weighing error
					Original weight	Hands on the knees	Difference	
1	10.30.2018	Maya	82	F	154	110	44	28.6%
2	10.30.2018	Galina	79	F	148	101	47	31.8%
3	10.30.2018	Bella	81	F	135	103	32	23.7%
4	10.30.2018	Sophia	81	F	140	109	31	22.1%
5	10.30.2018	Angela	95	F	113	84	29	25.7%
6	10.30.2018	Inness	85	F	108	78	30	27.8%

The third such malfunction case was found in Table 4 when a group of 5th-percentile adult females was checked for their value of weighing error. The weight measurements in the Table 4 were provided by National Music Teachers Association (New Haven Chapter), a music studio in Woodbridge, CT.

As we may see from Table 4, women ##7 and 9 may be related by weight to the 5th-percentile adult females. Woman #7 has original weight of 105 Lb, and her measured weight in the simulator of the vehicle seat while her feet are on the floor, is 74 Lb. Her calculated weighing error is 29.5%. In case of her vehicle collision, the air bag system will malfunction by recognizing her as the 50th-percentile 10-year-old child (74 Lb <82.1 Lb) and her air bag will not be deployed.

Table 4.

The 5th-percentile adult females weighing error

No.	Date	Name	age	sex	Weight (Lb)			Percentage of the occupant's weighing error
					Original weight	Hands on the knees	Difference	
1	10.22.2018	Libby	12	F	77	54	23	29.8%
2	10.22.2018	Nell	13	F	83	59	24	28.9%
3	10.22.2018	Sienna	15	F	138	98	40	28.98%
4	10.22.2018	Mei	16	F	118	97	21	17.8%
5	10.23.2018	Sofia	15	F	158	108	50	31.6%
6	10.24.2018	Veronica	16	F	149	111	38	25.5%
7	10.24.2018	Sophia	13	F	105	74	31	29.5%
8	10.24.2018	Leila	14	F	158	105	53	33.54%
9	10.25.2018	Devin	12	F	102	74	28	27.45%
10	10.26.2018	Sophia	13	F	80	55	25	31.25%

Woman #9 in Table 4 has original weight of 102 Lb, and her measured weight in the simulator of the vehicle seat with her feet on the floor, is 74 Lb. Her calculated weighing error is 27.45%. In case of her vehicle's collision, the air bag system will malfunction because it will recognize her as 50th-percentile 10-year-old child (74 Lb <82.1 Lb), and her air bag will not be deployed.

The variable weighing error may be used to predict, find, and eliminate by KEF method a malfunction of an air bag safety system (especially for 5th-percentile adult females) in a contemporary, self-driving, and autonomous vehicle where an accurate weight measuring KEF technology of an occupant will be employed.

As we may see from FIG. 1,a and Tables 2-4, to mitigate the negative consequences of a crash on a road for a 5th - percentile woman sitting in the contemporary, self-driving, or autonomous vehicle, it is necessary to know in advance or measure it at the beginning of the trip by KEF method an accurate original weight of this occupant and her measured weight when she/he is sitting in the seat. This last weight will be less than original weight because the feet are resting on the floor or pedals. If this weight overlaps a closest child weight range, it is necessary to eliminate the possible suppression of the air bag of the 5th -percentile woman before the vehicle's imminent crash during a trip. The time interval for regular weighing error measuring has to be established for contemporary, self-driving, and autonomous vehicles where the KEF weight measuring technology of an occupant is available.

FIG.1,b shows additional occupant's weight classes proposed in this ADMUS adaptive safety SRS system employing the accurate KEF occupant weighing technology. In the FIG.1,b seven weight classes proposed referred to ADMUS safety SRS system. Among these classes, there are all 5 classes (including children) that exist in the Table S7.1.4 "Weights and dimensions of the vehicle occupants referred to in Standard § 571.208: Occupant crash protection"[2]. The accuracy of KEF method and elimination of the weighing error, protects weight classes of Admus system from an overlapping that in turn provides room for at least 2 additional weight classes (red bars in the FIG.1,b).

The two additional classes may be used for the same purposes of applying different forces to the bodies of different (for example 125 and 190 Lb) weight occupants at the moment of an accident that are controlled through the control signals depending on their accurately measured weights and factors of the car trip in the current situation.

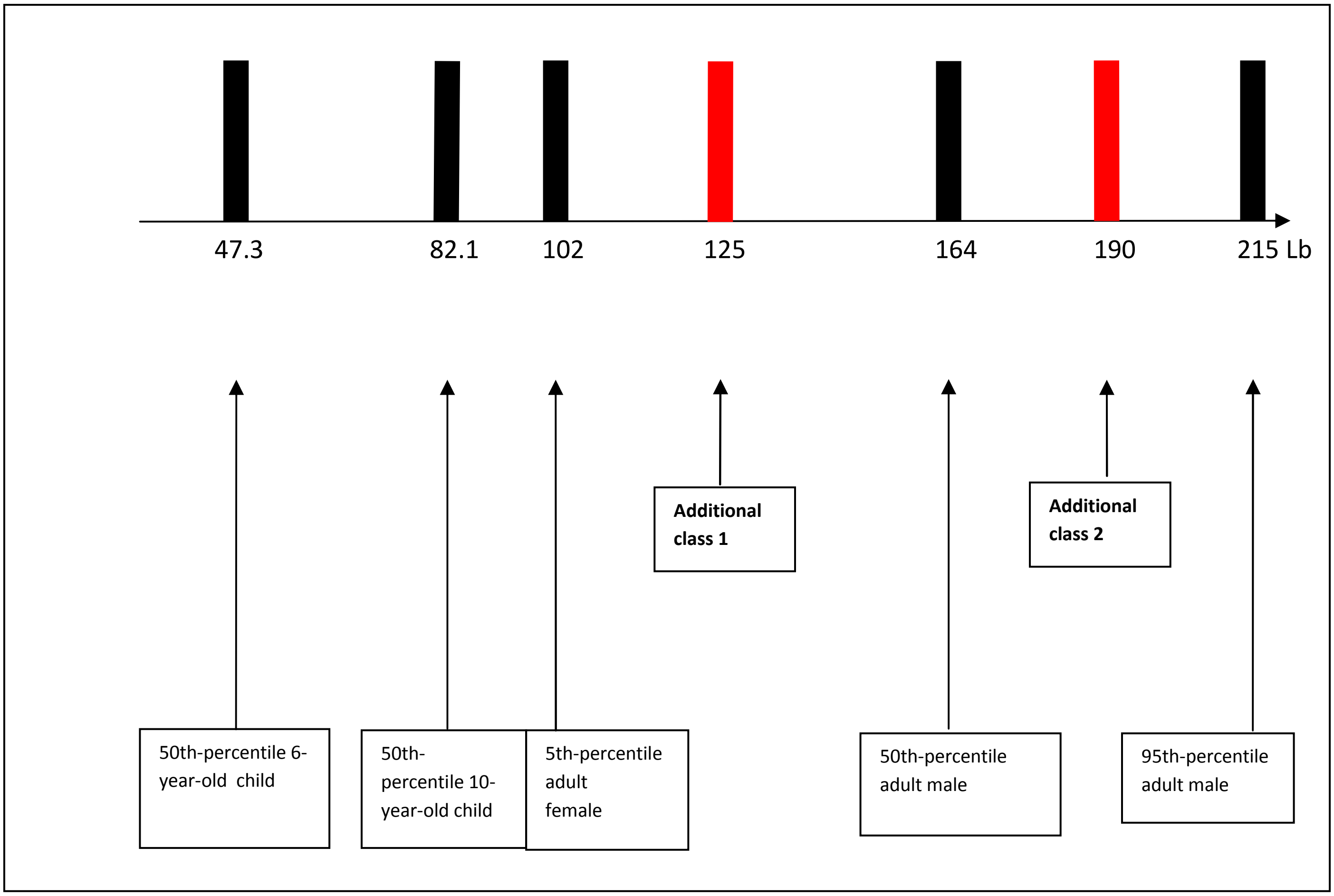


Fig.2. ADMUS Passenger Classification System

FIG.2 represents the proposed Passenger Classification System (PCS) based on accurate occupant's weight measuring KEF method and based in turn on this method the KEF technology that provide more accurate differentiation of different weight occupants and a safer restraint system. In Table 2 of [13], the number of passenger vehicles occupants that have been killed in crashes in 2016 is provided by age groups and restraint devices use. The ratio of the number of restrained passengers to the number of unrestrained passengers killed in the younger age groups such as <4 years old and 4-7 years old, and in the older aged groups 65 -74 and 75 + years old passengers, is 2-3 times higher than in other age groups despite that the percentage of known restrained was higher than the percentage of known unrestrained people killed in 2016. So, it seems that younger children group needs a more gentle restraint support during a crash, and proposed KEF method may help in this case also by extend the PCS.

Discussion and Limitations

Due to the of existence of the described above problem of overlapping and weighing error high value up to 30%, the number of properly functioning weight classes in the vehicles for adults in the Table S7.1.4 "Weights and dimensions of the vehicle occupants referred to in Standard § 571.208"[2] may really not be more than 3 classes that drastically decreases the accuracy of weighing occupants of a vehicle and their safety. This means it is necessary to provide a safety system for protection of the different weight occupants of the contemporary and self-driving or autonomous vehicles by applying different forces to their bodies that are more accurately controlled at the moment of an accident. The accuracy of the KEF technology of an occupant weighing improves safety system for differentiating the weight of older children from the weight of the light women passengers and supports the documents provided by NHTSA. The additional occupant's weight classes proposed in this ADMUS adaptive safety SRS system employing the accurate KEF occupant weighing technology that enhances safety (7 accurate weighing classes instead of 5) of the vehicle. These additional classes help to solve a problem of applying different forces to the bodies of different weight occupants by measuring weight of occupants accurately at a beginning of a trip and using these measurements at the moment of an accident to control the forces applied to the occupants' bodies depending on occupants' weights that are in the aftermath modified depending on the morphological data and factors in the current car trip.

.

Conclusions and Relevance to Session Submitted

Experimental data provided in the article clearly testifies that a weighing error of a vehicle occupants significantly reduces their safety by not restraining them by an accurate forces applied to their bodies. Additionally, weighing error, as shown in the article, leads to malfunction of the air bag for the 5th percentile of light women and for light old men. A simple KEF method of accurately weighing vehicle occupants provided in the article may help to avoid the weighing error in frontal and other types of crashes and enhance safety of vehicles. It is necessary to add that horrific numbers of child mortality provided in [13] forces us to make progress in this direction.

References.

1. U.S. Pat. No. 7,330,784. Johnson .W. et al. Weight measuring systems and methods for vehicles. February 12, 2008.
2. Final rule of Section § 571.208 Standard No. 208; Occupant crash protection. NHTSA. August 2004.
3. U.S. Pat. No. 9,566,877. Kriger Y. Technology and methods of on-board vehicle occupant accurate weighing by a simplified weighing apparatus based on weighing moderator and its applications in on-board occupant weighing systems, February 14, 2017.
4. U.S. Allowed Patent Application No.15/430219. Kriger Y. Technology and methods of on-board vehicle occupant accurate weighing by a simplified weighing apparatus based on weighing moderator and its applications in on-board occupant weighing systems, June 1, 2017
5. U.S. Pat. No. 10,017,078. Kriger Y. Relocatable/replaceable pad for accurate vehicle occupant weight measurement. July 10, 2018
6. U.S. Pat. No. 10,131,308. Kriger Y. Safety on-board vehicle multi-force restraint system employing a weighing moderator. November 20, 2018
7. U.S. Pat. No. 5,564,743. Marchant; Brent R. Multiple stage air bag inflator system. October 15, 1996.
8. Notice of Proposed Rulemaking. DOT of transportation NHTSA. 49 CFR Part 571 [Docket No. NHTSA-2016-0126] RIN 2127-AL55 Federal Motor Vehicle Safety Standards; V2V Communications.
9. NHTSA, " Driver assistance technologies". January 2018.
10. Tesla's Autopilot: The smart person's guide. By Hope Reese, TechRepublic, August 4, 2017.
11. U.S. Provisional Application No. 61/956,059. Kriger Y. filed on May 30, 2013
12. Development of occupant classification system. Tsutomu Takano, Nissan Motor Co., LTD 18 International ESV conference, Nagoya, May, 2003. Paper Number 206.
13. Traffic safety facts. 2016 data. DOT HS 812494. February 2018. NHTSA.

DRIVER AIRBAG DESIGN TO MITIGATE NECK AND CHEST INJURIES FOR US-NCAP AND OPTIMIZATION METHODS WITH A DYNAMIC META MODEL

Wonsuk Park
General Motors
USA

Paper Number 19-0094

ABSTRACT

The frontal airbag in a vehicle is considered supplemental to the safety belt restraint system and is important in lowering measured injury assessment values for Anthropomorphic Test Devices (ATD) during vehicle crash testing. The probability of neck and chest injuries is an important factor for a vehicle's performance rating under the United States-New Car Assessment Program (US-NCAP) protocol. A shorter lower tether was incorporated into the driver frontal airbag (DAB) to mitigate chest deformation injury, however higher neck injuries were observed with this change.

The purpose of this study is to identify the main factors influencing neck injury assessment values through the use of Design Of Experiments (DOE) techniques and find an optimum airbag design which mitigates neck and chest injury assessment values by using optimization techniques. Four different airbag designs were used in the first stage of the DOE, and one DAB design was chosen for the best performance in US-NCAP. Traditional meta model based optimization of the chosen DAB design followed.

The direct optimization method requires a great deal of computational resource, whereas meta model based optimization methods use comparatively little computational resource once there are sufficient sample data from the DOE. Dynamic meta model based optimization methods were introduced with combined CAE runs to reduce computing resource in this study. CAE runs were periodically sampled to update the meta model and provide improved accuracy. Two different optimization methods with dynamic meta models were demonstrated and compared with traditional meta model based optimization.

INTRODUCTION

Since the current US-NCAP rating protocol was introduced in 2006 [3], neck and chest deformation injuries became more important for both the frontal driver and passenger injury matrix than in the previous US-NCAP rating system. The seat belt restraint system is one of the main countermeasures for US-NCAP occupant injury performance, and a low level of Single Load Limiter (SLL) and Dynamic Locking Tongue (DLT) were successfully proven to lower chest deformation injury. The frontal airbag is considered a supplemental restraint to the safety belt restraint system and is still important in lowering measured injury assessment values for Anthropomorphic Test Devices (ATD).

The purpose of this study is to find an optimum asymmetric airbag design which mitigates neck and chest injuries assessment values. A sled CAE model was built, and validation work was performed using physical tests. The base lower tether of the DAB was replaced by a shorter lower tether to mitigate chest deformation injury. Four DAB designs, differing according to the location of an upper tether attachment on the front panel of the DAB, were built and used as design factors in the DOE study. The relationship between the upper tether design and neck injuries was investigated, and the DAB design was chosen through a DOE study and meta model based optimization. A new asymmetric DAB was incorporated into the sled CAE model for the next airbag tether optimization process.

Meta models have been frequently used in place of time-consuming detailed CAE models. Usually, multiple CAE iterations are done before an optimization, and then a meta model is built and used for evaluation in optimization. Many researchers employed a dynamic learning approach utilizing a meta model [1], [4], [10], [11].

In this study, an initial DAB design was chosen from the first DOE, and another DOE was performed, which was then used to fit the meta model that is used for the following optimization. Meta model based optimization methods were used with an Elliptical Basis Function network algorithm (EBF) to reduce computing resource required. These meta models represented a dynamic learning approach that was periodically updated considering results from CAE iterations. Two approaches were demonstrated for airbag tether optimization work to improve US-NCAP performance.

CAE MODELING AND VALIDATION

An occupant sled CAE model was built from a full vehicle structure model. Vehicle pulse, pitching and z-drop motion were extracted from barrier test results and validation work was performed.

Occupant sled CAE model

A sled CAE model, which has a rigid body-in-white (BIW), for use with prescribed motion was built. Some benefits of this approach are that it is easy to apply a vehicle pulse extracted from full-scale hardware tests, and this requires relatively lower computing resources than a full vehicle occupant model would. One weak point of this approach is that it is difficult to mimic instrument panel (I/P) intrusion. In most instances, a small amount of I/P intrusion was observed for full frontal rigid barrier loading conditions. Figure 1 shows an occupant sled model with belted driver ATD for US-NCAP.

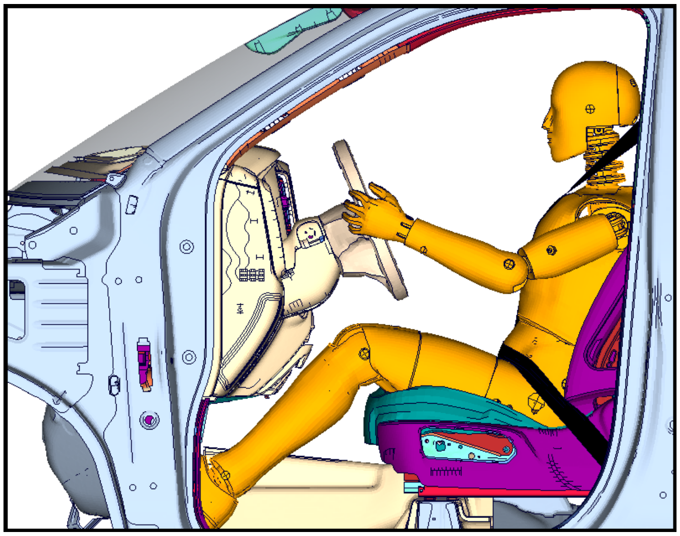


Figure 1. Occupant sled CAE model for frontal driver sides

Driver airbag model

Barrier tests were performed using an airbag design proposed by the airbag supplier. This airbag has an upper and a lower tether, and the tether length is 250mm for upper tether, and 220mm for lower tether. Typical tether length is 254mm (10") with traditional methods, such as 5"-30ms criterion [8], with the proposed target time to fire (TTF). One of the benefits of these upper and lower tether designs is easily controllable cushion depth for a vehicle crash test which has large pitching and vehicle z-drop motion. Tethers stretch during airbag deployment, because of the internal pressure of the airbag and airbag fabric material properties, and the magnitude of stretch depends on the characteristics of the selected airbag cushion fabric material and the number of fabric layers. Fabric materials have orthotropic characteristics [6] and usually have three axis loading component data, for instance, warp, weft and 45°. This airbag supplier uses a tether design which has a 45° direction and one layer fabric tether. This tether design showed greater stretched tether length compared to a warp or weft direction tether design from another airbag supplier. Figure 2 shows statically deployed airbags. Figure 3 shows expected tether stretch from CAE results.

Asymmetric or smiley DAB designs, which have a shorter lower tether than the upper tether are frequently used in order to mitigate chest deformation injury assessment values. Asymmetric or smiley DAB designs were considered for this work to improve US-NCAP performance for the next DOE study.

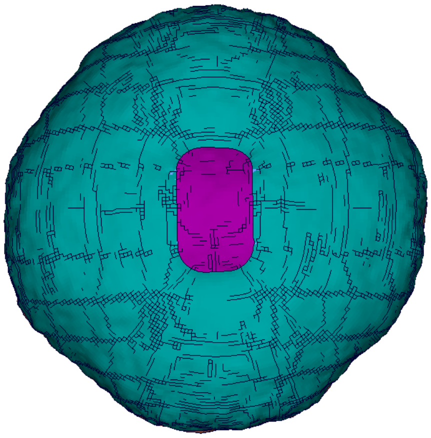


Figure 2.Static deployment of baseline airbag

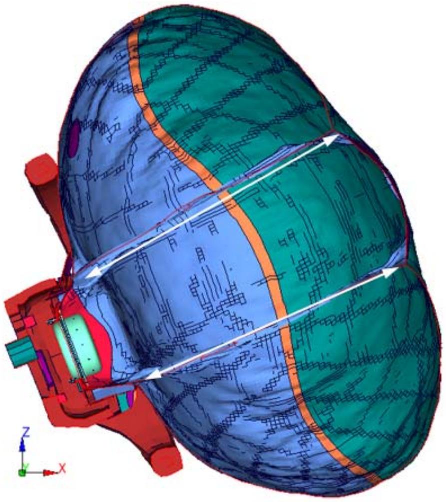


Figure 3. Tether stretch during deployment

Barrier test and validation work

It is important to verify the sled CAE model for subsequent optimization work. Validation work was performed with a belted 50th ATD in the 56kph full frontal loading condition, considering available data from a full-scale vehicle test. Figure A-1 and figure A-2 show the comparison between barrier test and the validated CAE model.

DOE STUDY

Asymmetric or smiley DAB designs, which have a shorter lower tether than the upper tether are frequently used in order to mitigate chest deformation injury assessment values. Airbag supplier proposed a smiley DAB for other vehicle program in past times and this asymmetric or smiley DAB design had been tried to mitigate chest deformation injury matrix, but these smiley DAB designs didn't lower chest deformation injury matrix significantly. It was hypothized that the attachment location on front panel of DAB for lower shorter tether was not appropriate, therefore smiley DAB had not lowered the chest deformation injury. Figure 4 shows proposed smiley (asymmetric) DAB by airbag supplier for other vehicle program in past time. Figure 5 shows interaction between smiley DAB and ATD from sled test, and figure 6 shows ATD's chest displacement transducer contact area on front panel of smiley DAB, it suggests that tether attachment location for lower tether didn't match to ATD's chest displacement transducer contact area in previous work. The neck injuries were changed with smiley DAB, but it was not clear upper or shorter tether changed the neck injuries.

Asymmetric or smiley DAB designs were considered for this work again. DOE technique [12] was used to identify the significant design factors on neck injuries.

A parameter CAE study was performed to find the recommended location for the lower tether attachment on the front panel of the airbag, which can lead to decrease chest deformation injury assessment values. Several new asymmetric airbag designs were proposed and used as design variables for the DOE study to identify the effect of upper tether location (design) on neck injuries. The main design factors, affecting injuries assessment values, especially neck injuries assessment values, were identified in this DOE study. Additionally, meta model based optimization was performed with these DOE sample data, and an asymmetric airbag design was chosen for subsequent airbag tether optimization work.

Figure 4. Smiley (asymmetric) DAB which was proposed by supplier

Figure 5. Interaction between asymmetric DAB and ATD chest

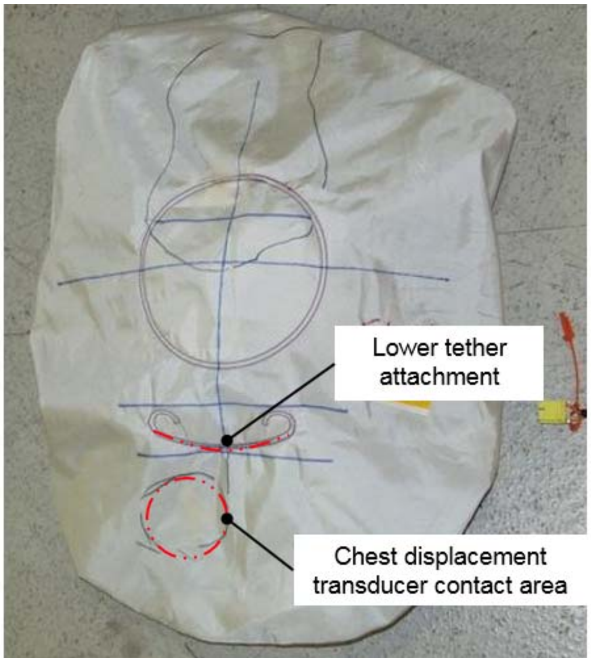


Figure 6. Lower tether attachment vs. chest potentiometer contact area with asymmetric DAB

New asymmetric airbag model

The results of several barrier tests showed higher neck and chest deformation injury assessment values than expected given the pulse severity. Therefore, the performance of the proposed occupant restraint systems resulted in a 4 star US-NCAP rating score. The motivation of this study was to find a better airbag design with the goal of improving US-NCAP performance rating without changing other restraint system components, such as the seat belt system.

Chest deformation can be lowered by removing pressure on the ATD chest, whereas chest acceleration injury can be lowered by using the ride down effect offered by the restraint systems [8]. One countermeasure to lower chest deformation is an asymmetric DAB design, which has a quite shorter lower tether length than upper tether length. A shorter lower tether length, 100mm, was incorporated into the baseline airbag by replacing the lower tether only. The internal airbag pressure may be high enough to tear this 45° angle fabric tether, so a warp or weft fabric direction tether with two or three layers of material was recommended. Proper location of the lower tether attachment on the front panel of the airbag was achieved by performing a parameter study. Figure 7 and figure 8 show the interaction between the airbag and ATD chest for the baseline DAB and asymmetric DAB, respectively.

The parameter study with 100mm lower tether length showed that chest deformation was significantly lowered, but neck assessment values, such as, Nij were increased contrarily. It was assumed that upper tether length and the location of the upper attachment on the front panel of the airbag might play a role in neck performance. Therefore, four different DAB designs were built by changing the location of the upper tether attachment on the front panel of the airbag with 250mm upper tether length. Figure 9 shows the proposed asymmetric DAB configurations, which were used as design variables in the DOE study (DAB #1, DAB #2, DAB #3, DAB #4).

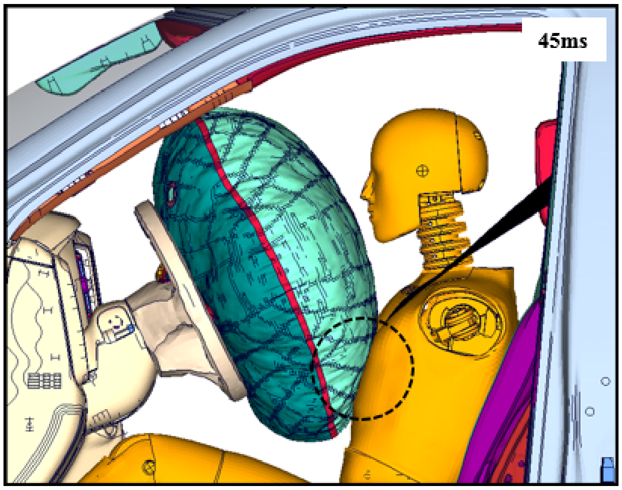


Figure 7. Interaction between baseline DAB and ATD chest

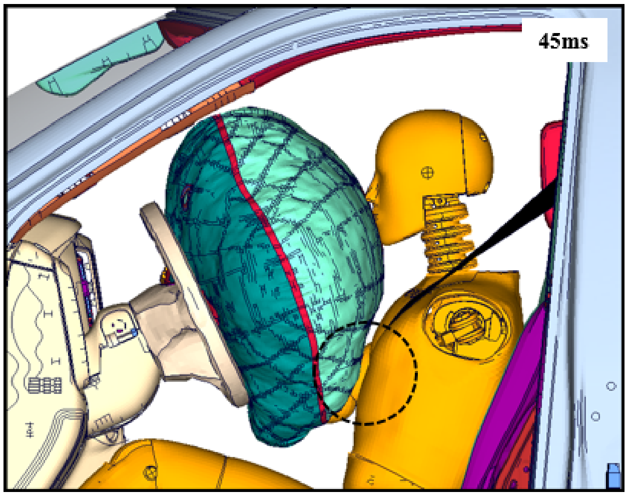


Figure 8. Interaction between asymmetric DAB and ATD chest

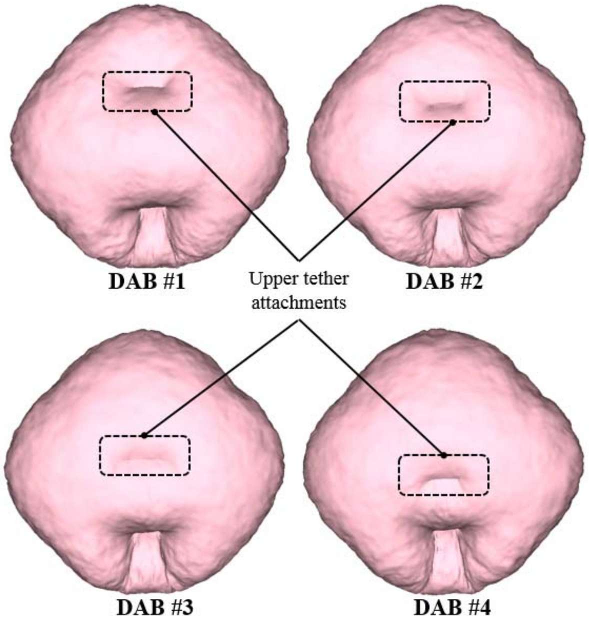


Figure 9. Asymmetric DAB, which were used as design variable in DOE

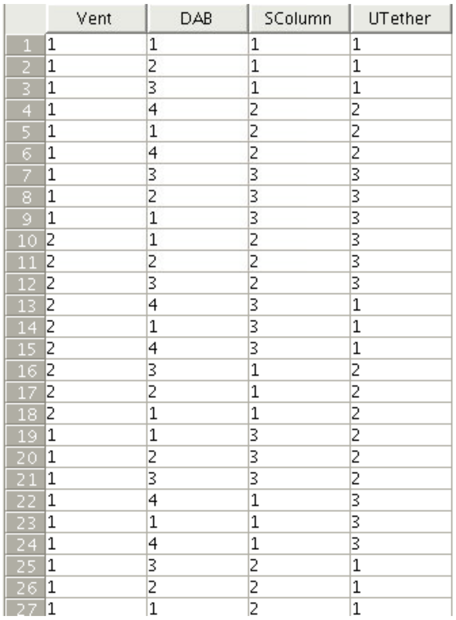
Design variables and DOE matrix

The purpose of this DOE work is to identify the main factors contributing to neck assessment values and to find the best DAB design through meta model based optimization. Four discrete design variables were defined. Vent size was one of the variables, because airbag internal pressure has a strong relationship with ATD measured assessment values. The variable name 'DAB' in the study represents different DAB designs according to the location of upper tether attachment. Upper tether length was also considered as one of the design variables in order to find the relationship between neck performance and upper tether length. An L27 orthogonal matrix was used for DOE sampling. Table-1 shows the variables and Table-2 shows the L27 orthogonal DOE matrix. A polynomial-base meta model [5] was built with L27 DOE sample data.

Table 1. Loading condition and design variables of DOE matrix

Loading condition and DOE matrix		
Matrix		L27 Orthogonal matrix
Loading condition	Speed	56kphFF US-NCAP
	Occupant	Driver 50th
	Belt condition	Belted
Design variables	Vent (2 x ϕmm)	35, 40
	DAB (UT attch location)	1, 2, 3, 4
	S/Column load (kN)	2.0, 3.0, 4.0
	Upper tether length (mm)	150, 200, 250

Table 2. L27 orthogonal DOE matrix



	Vent	DAB	SColumn	UTether
1	1	1	1	1
2	1	2	1	1
3	1	3	1	1
4	1	4	2	2
5	1	1	2	2
6	1	4	2	2
7	1	3	3	3
8	1	2	3	3
9	1	1	3	3
10	2	1	2	3
11	2	2	2	3
12	2	3	2	3
13	2	4	3	1
14	2	1	3	1
15	2	4	3	1
16	2	3	1	2
17	2	2	1	2
18	2	1	1	2
19	1	1	3	2
20	1	2	3	2
21	1	3	3	2
22	1	4	1	3
23	1	1	1	3
24	1	4	1	3
25	1	3	2	1
26	1	2	2	1
27	1	1	2	1

Sensitivity analysis and main design factors

The US-NCAP rating score consists of probability of head (Phead), neck (Pneck), chest (Pchest), and femur injuries (Pfemur) for the frontal impact loading conditions, and all of these four injury components are combined as "joint probability of injury (Pjoint)" [3]. Figure 10 shows that barrier test results suggest the following.

- The probability of neck injuries is the most important factor on NCAP
- The second most influential factor is the probability of chest injury

Neck assessment values, such as Nij [3], are calculated from upper neck moment and axial force. Figure A-1 and figure A-2 (in the Appendix) show that neck tension flexion moment (Ntf) is the major factor influencing the probability of neck injury for this specific vehicle. Figure 11 and figure 12 show that the main factors for Ntf are upper tether length (UTether) and the location of the upper tether attachment on the front panel of the airbag (DAB). Also, neck tension force was highly dependent on the location of the upper tether attachment, whereas neck flexion moment was highly dependent on the upper tether's length. Main effect plots suggests that DAB #4 design showed the best performance.

There were interaction effects between upper tether length (UTether) and the location of the upper tether attachment (DAB) on head, neck tension force, and neck flexion moment values. This suggests that a conventional DOE approach using a first order polynomial response surface model (RSM) would not work well to identify the best design configuration. Figure 13 shows interaction plots for head, neck tension force and neck flexion moment.

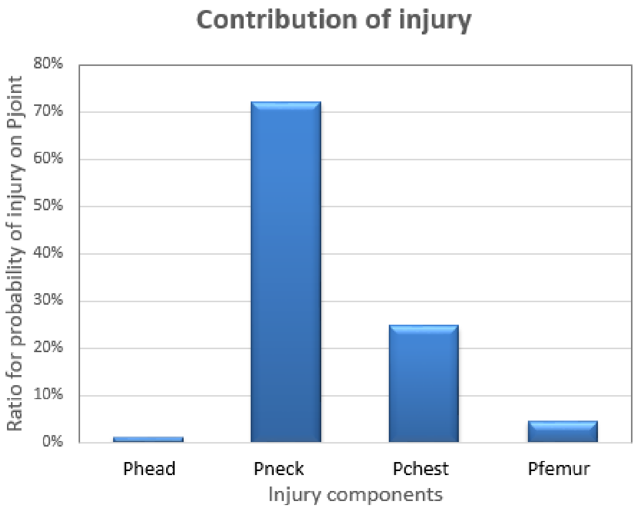


Figure 10. Comparisons for probability of injury on NCAP rating score (Pjoint)

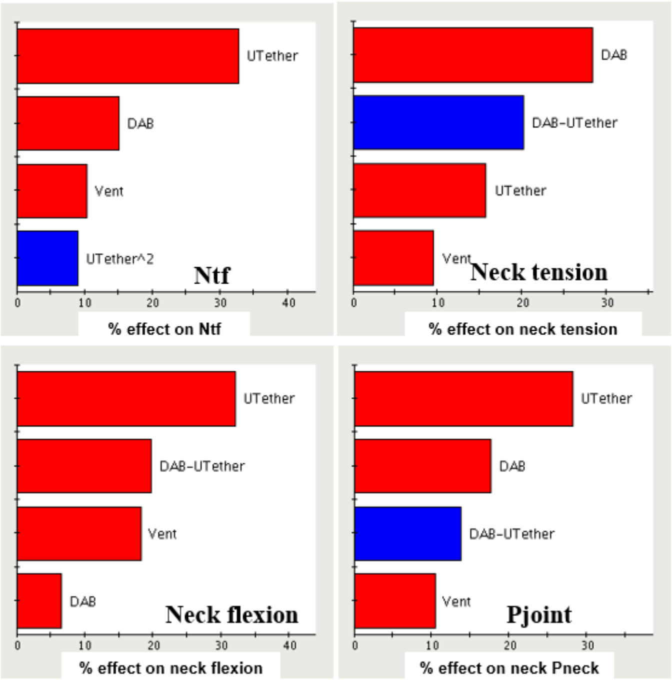


Figure 11. Pareto graph for neck assessment values and Pjoint

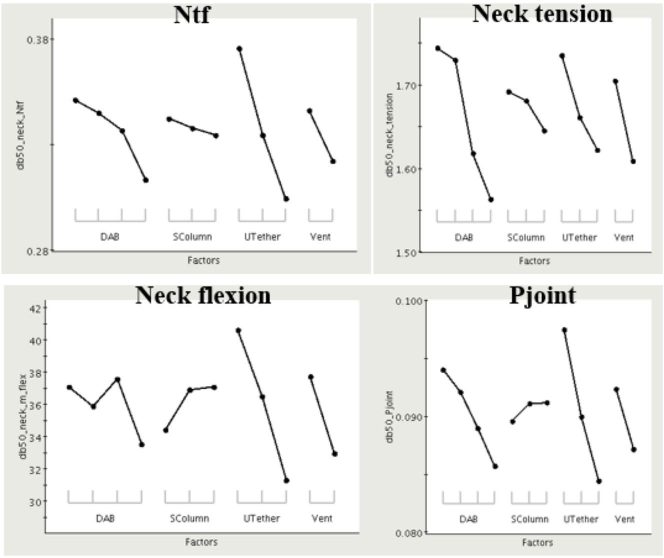


Figure 12. Main effect plots for neck assessment values and Pjoint

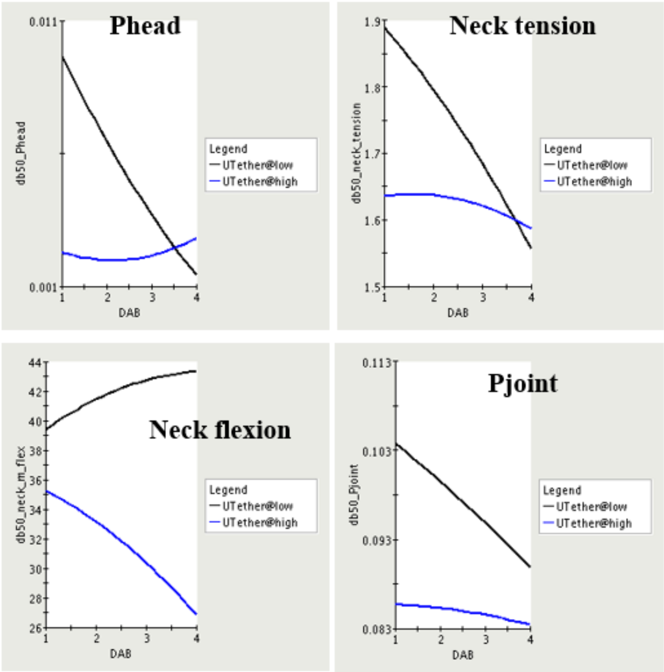
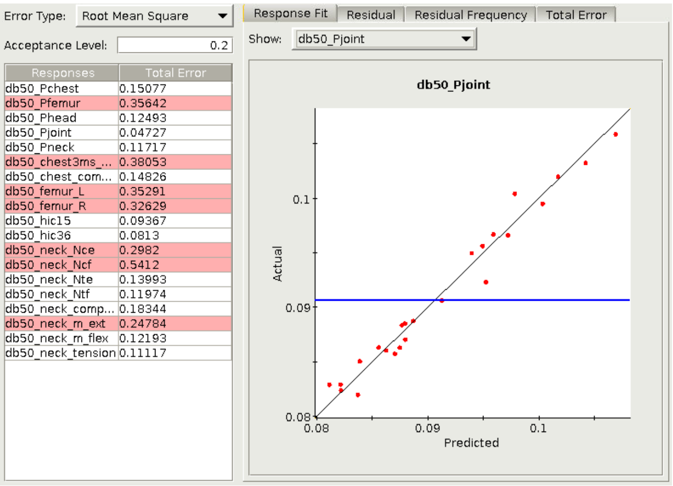


Figure 13. Interaction plots for Phead, neck tension force, neck flexion moment and Pjoint

Optimization by polynomial meta model

A polynomial 3rd order meta model was built with L27 DOE sample data. A Root Mean Square Error (RMSE) was used with leave-one-out cross validation analysis. Figure 14 shows errors are less than 15% for neck and chest deformation performance, but error for femur injury matrix is high, 36%, because there was not significant contact loading by knee-bolster, the femur loads were mainly caused by floor interaction to feet. A Genetic Algorithm (GA), such as NSGA-II algorithm [2], [5] was used for meta model based optimization [13], because occupant analyses have non-linearity. The predicted joint probability of injury (Pjoint) is

0.0823 based on meta model based optimization, and the corresponding confirmation CAE run showed 0.0820 of Pjoint. Table-3 shows the injury comparison between baseline DAB and the new asymmetric DAB design. Figure 15 shows a bar chart comparison of US-NCAP performance.



Error Type: Root Mean Square

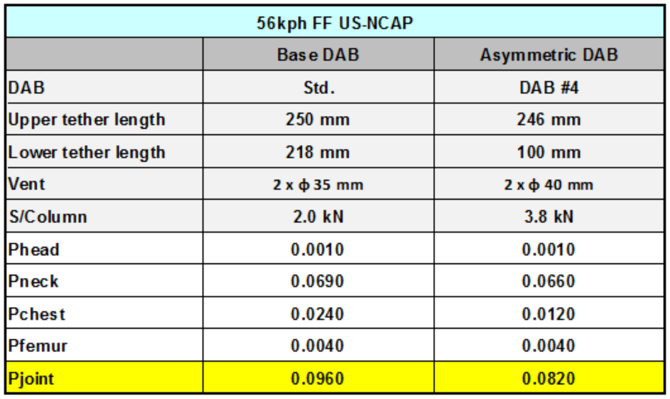
Acceptance Level: 0.2

Responses	Total Error
db50_Pchest	0.15077
db50_Pfemur	0.35642
db50_Phead	0.12493
db50_Pjoint	0.04727
db50_Pneck	0.11717
db50_chest3ms_...	0.38053
db50_chest_com...	0.14826
db50_femur_L	0.35291
db50_femur_R	0.32629
db50_hic15	0.09367
db50_hic36	0.0813
db50_neck_Nce	0.2982
db50_neck_Ncf	0.5412
db50_neck_Nte	0.13993
db50_neck_Ntf	0.11974
db50_neck_comp...	0.18344
db50_neck_m_ext	0.24784
db50_neck_m_flex	0.12193
db50_neck_tension	0.11117

Show: db50_Pjoint

Figure 14. Error analysis for polynomial 3rd order meta model

Table 3. Injury comparison between baseline DAB and asymmetric DAB



56kph FF US-NCAP		
	Base DAB	Asymmetric DAB
DAB	Std.	DAB #4
Upper tether length	250 mm	246 mm
Lower tether length	218 mm	100 mm
Vent	2 x ϕ 35 mm	2 x ϕ 40 mm
S/Column	2.0 kN	3.8 kN
Phead	0.0010	0.0010
Pneck	0.0690	0.0660
Pchest	0.0240	0.0120
Pfemur	0.0040	0.0040
Pjoint	0.0960	0.0820

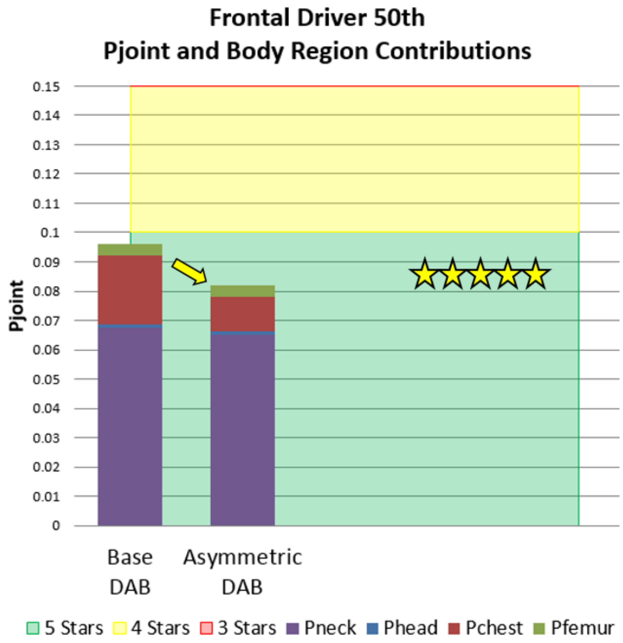


Figure 15. Bar chart comparison of US-NCAP performance

DYNAMIC META MODEL BASED OPTIMIZATION

Optimization was performed again with the goal of optimizing an upper and a lower tether length with new asymmetric airbag design, which was chosen from the DOE study section. Meta model based optimization was chosen with consideration of high computational cost. Traditionally, a meta model is built over the design space, and it is used in optimization. A dynamic learning approach was proposed with artificial neural network algorithms for time consuming water resource simulation models [10]. A Dynamic Kriging method was demonstrated to improve the accuracy of the meta model by dynamically selecting the optimal set of the basis function of the universal Kriging meta model [1], [11]. An adaptive meta model using a neural network algorithm was demonstrated. The meta model was initially built with the Latin Hypercube sampling method. Sequential designs using an adaptive error-based sampler were used to train the meta model [4].

In this study, meta model based optimization was combined with the dynamically trained meta model. Two approaches were compared and demonstrated.

Design variables and sampling method

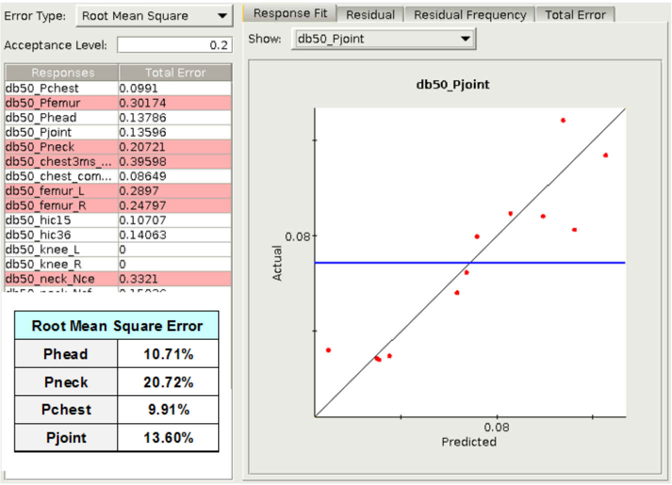
Two continuous variables for the length of an upper and a lower tether were defined as design variables, and two discrete design variables for vent size and steering column collapse load were defined. Optimal Latin Hypercube [5] was used as the sampling method. The sampling number is twelve (3 times of the number of design variables). Table-4 shows the loading condition and continuous and discrete design variables.

Table 4. Loading condition and design variables for DOE sampling run

Loading condition and DOE matrix			
Matrix		Optimal Latin Hypercube 12	
Loading condition	Speed	56kphFF US-NCAP	
	Occupant	Driver 50th	
	Belt condition	Belted	
Design variables	Vent (2 x ϕmm)	30, 35, 40	
	S/Column load (kN)	2.0, 2.5, 3.0, 3.5, 4.0	
	Upper tether length (mm)	200 <	< 300
	Lower tether length (mm)	75 <	< 125

Meta model

Radial Basis Function network (RBF) is a kind of neural network algorithm which can be trained [9]. Mak, et al proposed the Elliptical Basis Function network (EBF) by replacing the base function of RBF and compared it to the original RBF [7]. In this study, EBF meta model was used after a comparison of accuracy between RBF and EBF with same sample data. Figure 16 shows the error analysis for an EBF meta model with 12 CAE data samples. The target of RMSE is less than 20%, but the error for Pneck is high, 20.72%, and exceeding 20% at initial EBF meta model output.



Error Type: Root Mean Square

Acceptance Level: 0.2

Responses	Total Error
db50_Pchest	0.0991
db50_Pfemur	0.30174
db50_Phead	0.13786
db50_Pjoint	0.13596
db50_Pneck	0.20721
db50_chest3ms_...	0.39598
db50_chest_com...	0.08649
db50_femur_L	0.2897
db50_femur_R	0.24797
db50_hic15	0.10707
db50_hic36	0.14063
db50_knee_L	0
db50_knee_R	0
db50_neck_Nce	0.3321

Root Mean Square Error	
Phead	10.71%
Pneck	20.72%
Pchest	9.91%
Pjoint	13.60%

Show: db50_Pjoint

Figure 16. Error analysis for EBF Meta model with 12 CAE sample data

Optimization by dynamic meta model

The NSGA-II (Non-Dominated Sorting Genetic Algorithm) [2], [5] was used with the EBF meta model. The size of population = 12, the number of generations = 10, crossover probability = 0.9, crossover distribution index = 10, mutation distribution index =20. Two optimization methods were demonstrated. Method #1; perform optimization with meta model only; confirmation CAE run with optimized design, and update samples and meta model. Loop this process nine times. Method #2; 75% of populations were evaluated with the meta model and 25% of populations were evaluated by CAE runs, updating samples and meta model for each generation in order to get improved accuracy. Figure 17 shows work flow of optimization method #1, and Figure 18 shows work flow of optimization method #2.

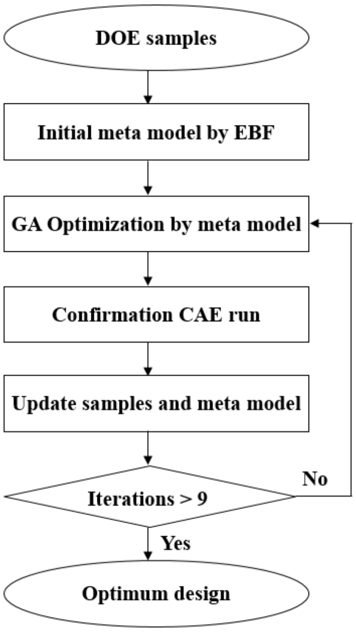


Figure 17. Work flow of optimization method #1

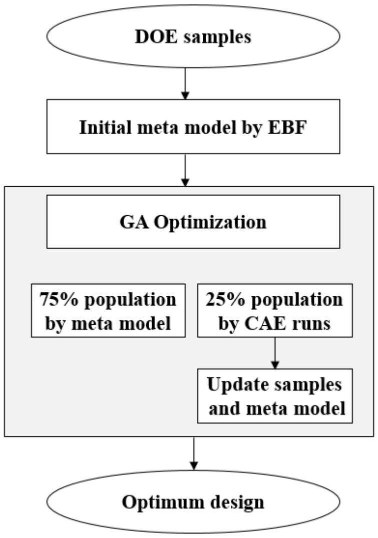


Figure 18. Work flow of optimization method #2

RESULTS

The accuracy of the EBF meta model was improved for both method #1 and method #2. Joint probability of injury was successfully lowered for both optimization methods. The accuracy of the meta model was better for method #2 with more sample data than method #1. The predicted joint probability of injury (Pjoint) by meta model is 0.0765 from method #2, and the corresponding confirmation CAE run showed Pjoint of 0.0770. Table-5 shows the comparison for the accuracy of the meta model between initial meta model and final meta models from method #1 and method #2. Table-6 shows the optimized design configuration and probability of injuries comparison, and figure 19 shows bar chart comparison of US-NCAP performance.

Table 5. Comparison of meta model accuracy: RMSE with leave-one-out cross validation

Root Mean Square Error			
Probability of injuries	Initial 12 samples	Method #1 12 + additional 8 samples	Method #2 12 + additional 28 samples
Phead	10.71%	9.11%	7.93%
Pneck	20.72%	13.73%	10.79%
Pchest	9.91%	7.98%	7.74%
Pjoint	13.60%	10.35%	7.76%

Table 6. Optimized design variable with dynamic meta model method

56kph FF US-NCAP				
	Base DAB	Asymmetric DAB	Optimization method #1	Optimization method #2
DAB	Std.	DAB #4	DAB #4	DAB #4
Upper tether length	250mm	246 mm	290 mm	296 mm
Lower tether length	218mm	100 mm	125 mm	78 mm
Vent	2 x ϕ 35 mm	2 x ϕ 40 mm	2 x ϕ 40 mm	2 x ϕ 40 mm
S/Column	2.0 kN	3.8 kN	2.5 kN	2.0 kN
Phead	0.0010	0.0010	0.0004	0.0005
Pneck	0.0690	0.0660	0.0631	0.0637
Pchest	0.0240	0.0120	0.0134	0.0093
Pfemur	0.0040	0.0040	0.0044	0.0045
Pjoint	0.0960	0.0820	0.0800	0.0770

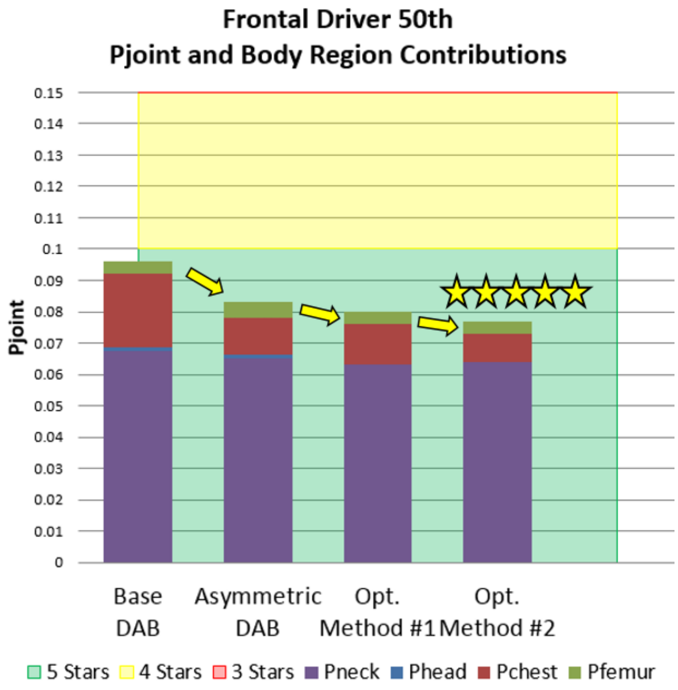


Figure 19. Bar chart comparison of US-NCAP performance

SUMMARY AND CONCLUSIONS

In this paper, an asymmetric airbag design was proposed with the goal of mitigating chest deformation and improving US-NCAP performance. The DOE technique was used to identify the main design factors for neck assessment values, and meta model optimization was performed to choose the location of an upper tether attachment on the front panel of the DAB. The DOE study shows; axial neck tension force was highly dependent on the location of upper tether attachment on the front panel of the DAB, whereas neck flexion moment was highly dependent on an upper tether's length. Meta model based optimization was performed to optimize tether length again, because a DOE study suggested that tether length has a role in neck flexion injuries. An initial EBF meta model was built with 12 data samples, and used for the evaluations. During the optimization, sample data and meta models were updated. Two methods using dynamic meta model were demonstrated, showed the accuracy of meta models were improved, and successfully found solutions. Method #2 shows better performance than method #1 with more sample data. For the future work, this asymmetric or smiley DAB needs to be verified for other loading conditions, for example, 40kph full frontal unbelted 5th and 50th. And low risk deployment performance also needs to be confirmed by actual hardware tests. There were arguments about performance with this asymmetric or smiley DAB in field condition, because the steering wheel can be rotated at real world field conditions and can show different performance.

REFERENCES

[1] Choi, K., Lee, I., Zhao, L., Noh, Y., Lamb, D., "Sampling-based RBDO using stochastic sensitivity and dynamic Kriging for broader army applications". NDIA ground vehicle systems engineering and technology symposium 2011.

[2] Deb, K., Agrawal, S., Pratap, A., Meyarivan, T. "A fast elitist non-dominated sorting genetic algorithm for multi-objective optimization: NSGA-II". IEEE Transactions of evolutionary computation, Vol. 6, No. 2, 2002.

[3] Docket no. NHTSA-2006-26555, www.regulations.gov

[4] Gorissen, D., Hendrickx, W., Dhaene, T., "Adaptive Global Metamodeling with Neural Networks". ESANN' 2007 proceedings – European Symposium on Artificial Neural Networks.

[5] Isight user's manual, version 5.9

[6] LS-DYNA user's manual volume 2, 262-273, version 7.1

[7] Mak, M., Li, C., "Elliptical Basis Function Networks and Radial Basis Function Networks for Speaker Verification: A Comparative Study". Neural Networks, IJCNN '99. International Joint Conference, 1999.

[8] Hwang, M., 2002 "Vehicle crash mechanics" 33-38, 74-77, CRC Press LLC

[9] Orr, M., "Introduction to Radial Basis Function Networks". https://www.cc.gatech.edu/~isbell/tutorials/rbf-intor.pdf, accessed Aug. 2017.

[10] Yan, S., Minsker, B., "Optimal groundwater remediation design using an Adaptive Neural Network Genetic Algorithm". Water resources research, Vol 42, W05407, doi:10.1029/2005WR004303, 2006.

[11] Zhao, L., Choi, K., Lee, I., "Metamodeling Method Using Dynamic Kriging for Design Optimization". AIAA Journal Vol. 49, No.9, September 2011.

[12] Park, G., 2007 "Analytic Methods for Design Practice", 312-317, 327-340, 360-367, Springer-Verlag London.

[13] Ryberg. A., 2013 "Metamodel-Based Design Optimization", 11-12, LiU-Tryck, Linkoping, Sweden ISBN 978-91-7519-721-0 ISSN0280-7971.

APPENDICES

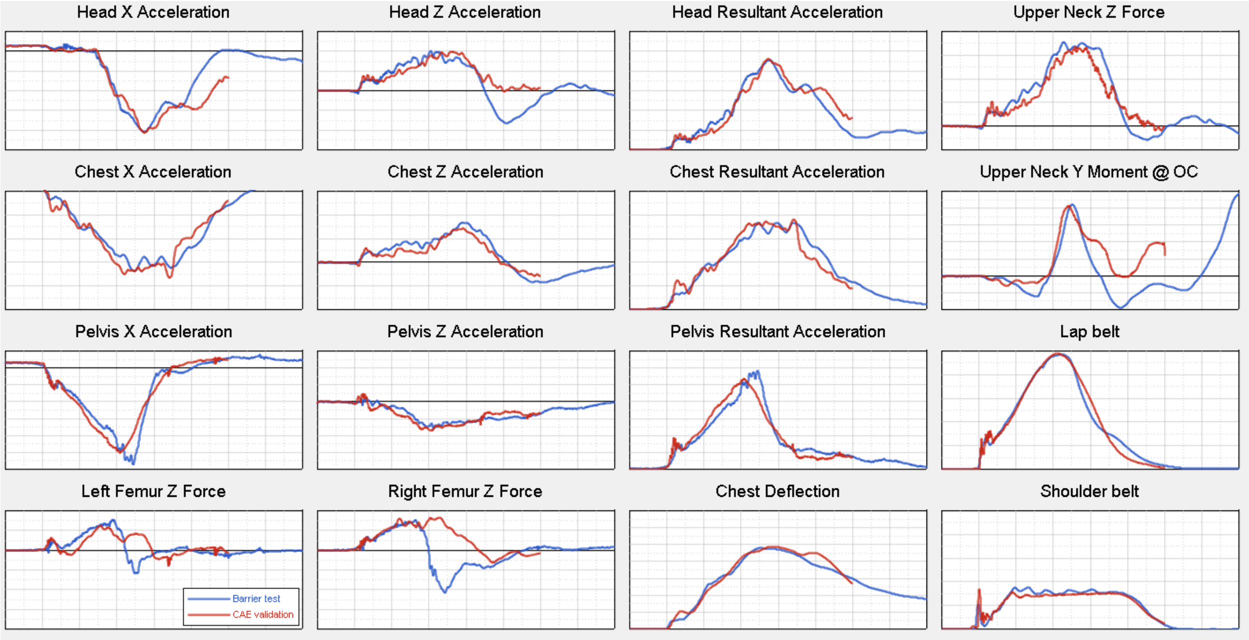


Figure A-1. Comparison between barrier test and validated CAE model for US-NCAP (blue: test, red: CAE)

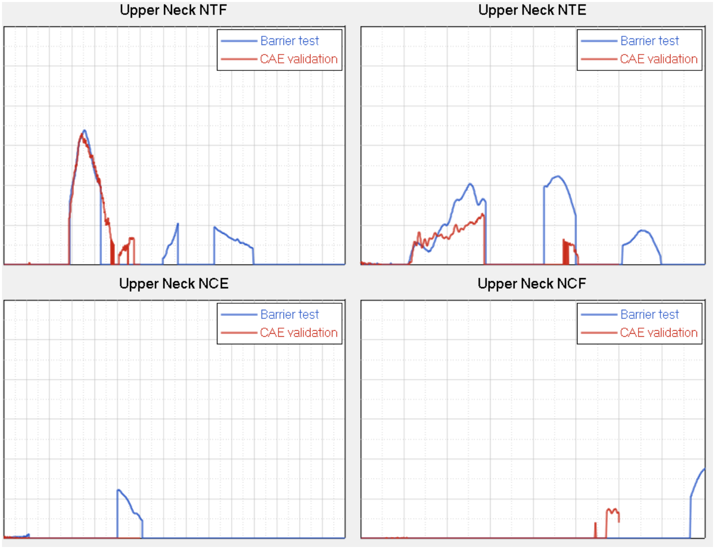


Figure A-2. Comparison between barrier test and validated CAE model for US-NCAP (blue: test, red: CAE)

INTERIOR AND RESTRAINT SYSTEMS MODELING FOR OBLIQUE OFFSET FRONTAL IMPACT

Mahendran, Paramasuwom
Velayudham, Ganesan
EDAG Inc
United States of America

Harjinder, Singh
United States Steel Corporation
United States of America

Paper Number 19-0133

ABSTRACT

National Highway Transport Safety Administration (NHTSA) has been investigating oblique offset frontal impact test conditions. This research developed a validated occupant interior and restraint systems that could be used to evaluate the kinematics and injury implications for frontal crash test conditions. The objective was to develop validated oblique offset crash simulations using both Test device for Human Occupant Restraint (THOR) dummy model and human body models. The vehicle selected for this Computer Aided Engineering (CAE) study was a 2014 Honda Accord. The vehicle interior was scanned and modeled and restraint characterization tests were conducted. The occupant interior finite element (FE) model was developed and validated against available test data. FE models for THOR dummies were seated in driver and passenger seats and validated against both left and right oblique offset test results. Subsequently, the 50th percentile FE Human body model from Global Human Body Models Consortium (GHBMC) was seated in the vehicle and the kinematics was compared against the THOR dummy model. The outcome of this study was to develop realistic FE models that could be used to investigate how crash test conditions can affect optimal occupant restraint system design. The results predicted from the CAE simulations of the baseline vehicle model demonstrated similar safety performance to the available vehicle test results in terms of vehicle acceleration and intrusion responses in NCAP frontal, IIHS moderate overlap, IIHS small overlap test procedures, and left and right NHTSA oblique frontal tests. The CAE simulation results compared well with test results for THOR dummy model accelerations and injury criteria. A comparison of occupant kinematics, belt loads and injury criteria against the simulations using the GHBMC model also was done. The CAE simulation results using the GHBMC also compared well with test and CAE results of using THOR dummy model.

INTRODUCTION

The occupant safety performance in some of the newer frontal crash test conditions, particularly oblique frontal crash tests, is dependent on the occupant interaction with the intruding vehicle components and the vehicle restraint system. It is desirable to develop full vehicle finite element models that can be used to study how changes in frontal crash test conditions can affect the occupant interaction with the restraint systems and the occupant injury outcomes. In this research, it was intended to develop a full vehicle finite element model, including the vehicle interior and occupant restraint systems for the driver and front seat passenger simulations using THOR dummy model and human body models.

The selected vehicle for this research was the 2014 Honda Accord as the CAE model was readily available from NHTSA's structural countermeasure program [1]. The chosen vehicle met the structural intrusion requirements of "Good" in both IIHS small and moderate overlap and 5-star in NCAP rating. The test procedure for CAE simulation used involves a high-speed oblique moving deformable barrier (OMDB) hitting a stationary vehicle with a 35-percent overlap at an angle of 15 degree from collinear, in both left and right. This test was conducted to replicate vehicle damage and occupant kinematics based on one of the common configuration crashes with belted occupant fatalities in vehicles with airbags [2].

The oblique frontal crash test currently uses the THOR dummy for evaluating occupant responses in the test vehicles. Currently, there are two finite element models available for THOR dummy. One version is publicly available from the University of Virginia, another is commercially available for lease from Humanetics, Inc. For this study, the University of Virginia THOR dummy model V2.1 of 50th percentile male occupant was used.

Additionally, there is considerable interest in using finite element models of the human body to compare their response and kinematics against the test dummies. Human body models that are commonly used for automotive research include the GHBMC model and the Total Human Model for Safety (THUMS) model from Livermore Software Technology Corporation. For this study the GHBMC 50th percentile male occupant Version 4.5 for LS-DYNA was leased from Elemance, LLC.

This paper describes the stages of CAE modeling and simulations. The initial step in the study was to obtain correlation between the actual oblique offset test performed by NHTSA and the CAE simulation. The parameters observed during the correlation task were THOR dummy model kinematics, airbag deployment and behaviors, seatbelt resistance force and occupant injury measures. When the simulations were correlated, the THOR models were replaced by GHBMC model and comparisons were made between the simulations of using THOR and GHMBC models.

VEHICLE INTERIOR MODEL DEVELOPMENT

The vehicle model was updated with vehicle interior and occupant restraint systems for the driver and front-seat passenger. White light scanned computer aided design (CAD) data for the interior of 2012 MY Honda Accord was used to represent the interior geometry of all relevant parts: instrument/dash panel assembly, center console, driver, and passenger seat. Occupant restraints system included airbags and seatbelts. Airbags and seatbelts were tested by conducting physical tests such as airbag deployment test and seatbelt pull test. They were then validated with the CAE simulations before integrating them in the full vehicle model. The details of FE modeling of interiors and restraint systems testing is out of the scope of this paper.

VEHICLE OBLIQUE OFFSET FRONT TEST SIMULATION – THOR AND HUMAN MODEL (GHBMC)

This test is used to determine the crashworthiness of the vehicle to protect occupants in offset frontal impact crash cases. The test consists of an oblique moving deformable barrier (OMDB) that weighs 2,490.2 kg traveling at a target speed of 90.12 km/h into a stationary vehicle as shown in Figure 1. The struck vehicle is positioned 15 degrees relative to the moving barrier and impacted 35 percent of the left or right side of the vehicle.

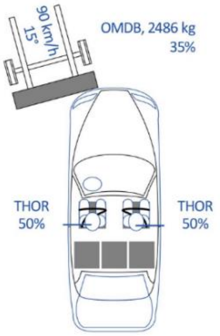


Figure 1. NHTSA Oblique Offset Setup.

THOR dummy model was duplicated into two models to have both driver and passenger. The two THOR dummy models were positioned on the vehicle driver and passenger seat respectively. It should be noted that the seat cushion foams were pre-deformed to accommodate dummies pelvic shape. Two-dimensional (2D) shell element seatbelts were modeled by routing over the shoulder and lap parts of the dummy models. The full vehicle model with the occupant models and restraint systems were checked for standard finite element model quality requirements such as connectivity, time-step and outputs. The model was run in LS-DYNA crash simulation solver for 200 milliseconds.

After the crash simulations with THOR dummy models were performed, using the THOR dummy models, another set of FE model were created by replacing the THOR dummy models by GHBMC models. Likewise, for this purpose, GHBMC model was duplicated into two models, respectively for driver and passenger. Once again, the full vehicle model with GHBMC models were run in LS-DYNA for 200 milliseconds. A comparative simulation results of test, THOR dummy models and GHBMC models are discussed in the following section.

CAE RESULTS DISCUSSION

At first the CAE results of full vehicle model oblique offset frontal impact case using THOR dummy models are compared to the test results. Next, the CAE results of the same using THOR dummy models are compared to CAE results of using GHBMC models.

Figure 2 shows crash simulations using THOR dummy models at 0ms (before crash) and at 120ms (after crash) comparing the test and CAE of THOR dummy models. It can be observed that both driver and passenger airbag deployed at 14ms and curtain airbag deployed in 42ms. Also, at 14ms, the seat belt pre-tensioner fired and tightened any slack defined as length of 25mm. At 120ms the driver dummy's head got sandwiched in between the driver airbag and curtain airbag, meanwhile the passenger dummy's head impacted the dashboard. Overall the kinematics of the CAE simulations and THOR dummy models show good correlation with the test results.

Figure 2. Test vs CAE simulations using THOR dummy models at 0ms (before crash) and 120ms (after crash).

Similarly, Figure 3 shows crash simulations using GHBMC models at 0ms (before crash) and at 120ms (after crash) while comparing THOR dummy models and GHBMC models. It can be observed that the deployment time of airbags and seatbelt pre-tensioner are similar to the simulation using THOR dummy models. In terms of kinematics, the behavior of the GHBMC models was found to be similar to the THOR dummy model except for the seatbelt behavior on the passenger side. Unlike THOR dummy models, in the GHBMC model, the seatbelt did not completely slip off the shoulder, resisting it to impact on the dash.

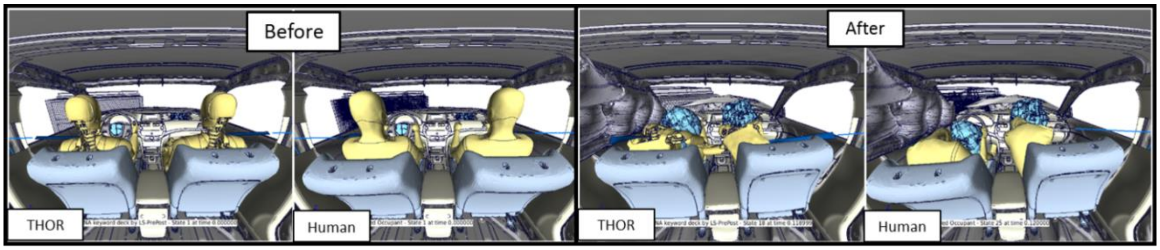


Figure 3. CAE-THOR vs CAE-GHBMC at 0ms (before crash) and 120ms (after crash).

Figure 4 compares the CAE results' head CG acceleration of the driver and passenger with that of test results. For the driver side, the overall trend of the acceleration curves shows a decent correlation among all three events. The passenger side did not correlate well due to the different seat-belt behavior while slipping off the shoulder which was observed in the test. In the THOR dummy model simulation, even though the seatbelt slip-off occurred, the seatbelt still provided some resistance that reduced the head impact to the dash. In the GHBMC model simulation, the seatbelt did not slip-off due to high friction with the skin, hence stopping the GHBMC model from moving forward and contacting the dash.

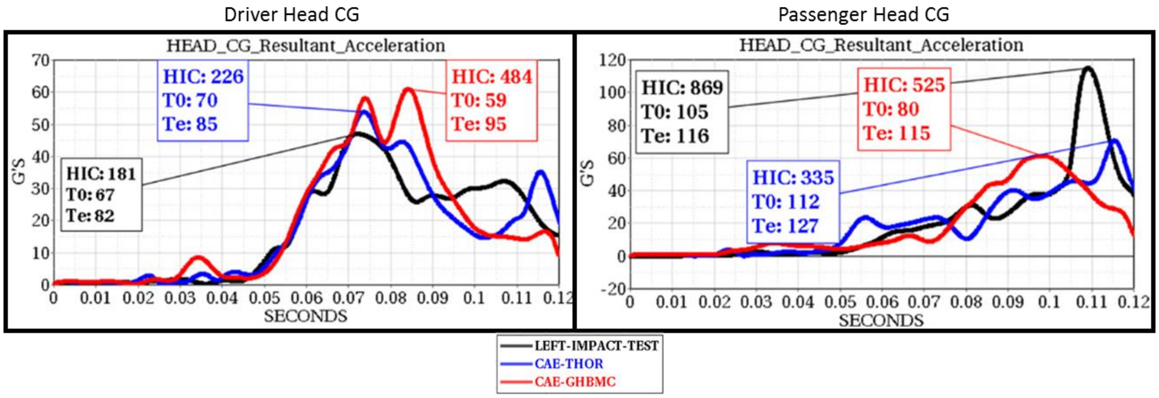


Figure 4. Driver and Passenger Head CG Acceleration.

Figure 5 shows the driver and passenger femur forces. In the THOR dummy model, the force was measured from a beam element that connects two metal sockets moving axially between each other along the femur. In the GHBMC model, the force was taken from a cross-section force of the actual femur bone made of solid elements. The GHBMC model seemed to experience more load through the femur compared to the THOR dummy model.

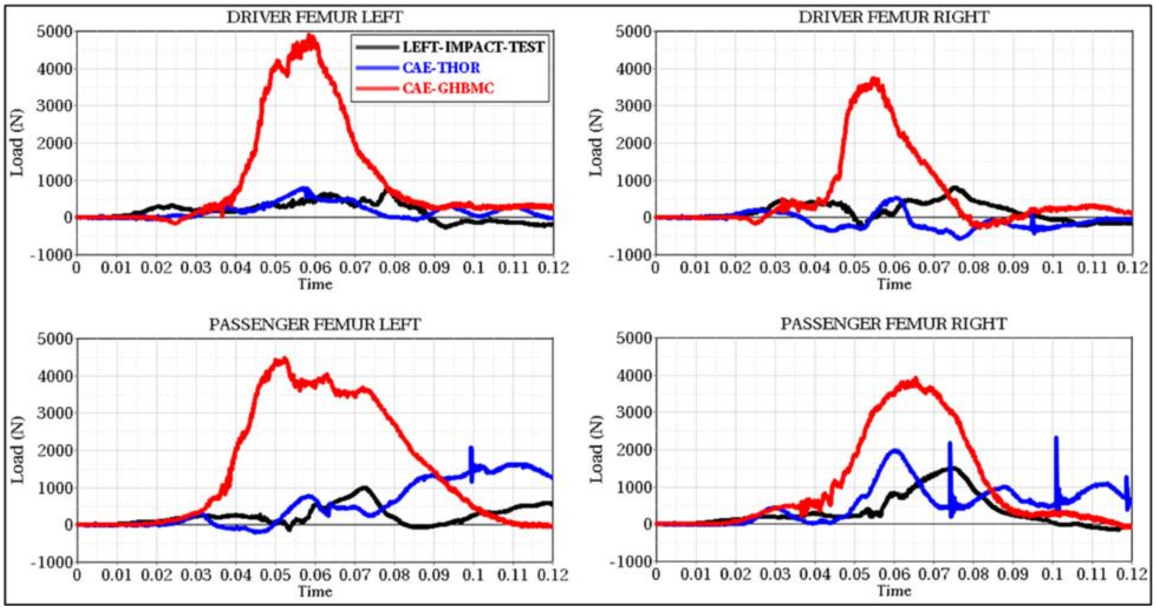


Figure 5. Driver and Passenger Femur Force.

More comparisons such as pelvic accelerations, seatbelt forces, and detailed timeline images of crash and complete right-side impact of oblique offset test can be referred in the full project report [3].

CONCLUSION

Full vehicle finite element models representing 2014 Honda Accord including interior trims and occupant restraints system were developed in this research. The occupant restraint system such as the airbags and seatbelt were tested and validated with the CAE models before they were integrated into the model. The full vehicle used THOR 50th percentile male dummy model to represent both driver and passenger. NHTSA’s Oblique Offset front impact test simulations were carried out for both left and right-side impacts. The overall dummy kinematics of THOR dummy model in CAE simulation correlated well with the test. There was a slight difference found in the head to dash interaction due to the difference in seatbelt behavior during the event whether it slipped off the shoulder of the passenger or not. The simulations were repeated by replacing THOR dummy models by GHBMC models. GHBMC models showed similar overall kinematic behavior during the crash event compared to THOR dummy models. Unlike THOR dummy model, in case of passenger side GHBMC model, the seatbelt did not slip off the shoulder due to high friction with the skin, causing it to resist the forward motion. This prevented the GHBMC model head to collide with the dash as seen otherwise in the passenger THOR dummy model. It was also observed that the GHBMC model femur forces were much higher compared to THOR dummy femur forces.

REFERENCES

[1] Singh, H., Ganesan, V., Davies, J., Paramasuwom, M., Gradischnig, L., Wood, P., et al. (2018). Structural Countermeasure/ Research Program: Mass and Cost Increase Due to Oblique Offset Moving Deformable Barrier Impact Test. NHTSA.
[2] Bean, J. D., Kahane, C. J., Mynatt, M., Rudd, R. W., Rush, C. J., & Wiacek, C. (2009, September). Fatalities in frontal crashes despite seat belts and air bags – Review of all CDS cases – Model and calendar years 2000-2007 –122 fatalities (Report No. DOT HS 811 102). Washington, DC: National Highway Traffic Safety Administration.
[3] Singh, H., Ganesan, V., Davies, J., & Paramasuwom, M. G. (2018). Vehicle Interior and Restraints Modeling Development of Full Vehicle Finite Element Model Including Vehicle Interior and Occupant Restraints Systems for Occupant Safety Analysis Using THOR Dummies. NHTSA.