International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:6, No:12, 2012

Optimization of Car Seat Considering Whiplash Injury

Wookyung Baik, Seungchan Lee, Choongmin Jeong, Siwoo Kim, and Myungwon Suh

Abstract**—**Development of motor car safety devices has reduced fatality rates in car accidents. Yet despite this increase in car safety, neck injuries resulting from rear impact collisions, particularly at low speed, remain a primary concern. In this study, FEA(Finite Element Analysis) of seat was performed to evaluate neck injuries in rear impact. And the FEA result was verified by comparison with the actual test results. The dummy used in FE model and actual test is BioRID II which is regarded suitable for rear impact collision analysis. A threshold of the BioRID II neck injury indicators was also proposed to upgrade seat performance in order to reduce whiplash injury. To optimize the seat for a low-speed rear impact collision, a method was proposed, which is multi-objective optimization idea using DOE (Design of Experiments) results.

Keywords**—**Whiplash injury, Dynamic assessment, Finite element method, Optimization, DOE (Design of Experiments), WSM (Weighed Sum Method).

I. Introduction

RECENTLY, a variety of researches and making policy are underway in order to reduce traffic accident casualties all over the world. As a result of these efforts, the number of deaths of occupants is gradually decrease compared with automobile accidents according to statistics of domestic during last decade, as shown Fig. 1. However, neck injury especially whiplash injury from low speed rear-end collision still remains a challenge in the car accidents. This tell us that research and development of safety devices for neck injury in rear-end collisions had been insufficient compared with development of safety devices against front-end and broadside collisions. In statistics we can see that the damage caused by rear-end collisions are still large proportion of the entire. According to Korean insurers statistics in 2006, claims related neck injury accounted for 46.3% of the entire accident data [1]. Foreign traffic accident pattern like above is similar to Korea. Rear-end collisions accounted for 15% of all accidents in EU-15 as shown Fig. 2. Because of this, more than 100,000 casualties from rear-end collision and economic loss as much as 5 hundred million to 10 hundred million Euro had occurred per year. Especially, in England, it has been reported that neck injury that requires long-term treatment costs 300 million found [2]. In case of Japan, it has been reported that 90% of Injuries from rear-end collision are whiplash injuries [3]. According to NASS (National Analysis Sampling System), almost 800,000 casualties related neck injury had occurred and 34% of them caused by rear-end collision in United States [2]. Therefore, Korean government decided to add car seat safety assessment to KNCAP (Korean New Car Assessment Program) in order to reduce neck injuries. Also internationally, GTR (Global Technical Regulation) No. 7 was enacted as standard of car safety in 2008 in order to induce production of safer seat little bit more forcibly [2]. Due to these efforts, the results of seat safety assessment since 2005 were improved. However, researches that design variables directly influencing neck injuries and design direction were insufficient. Therefore, research of optimization for car seat in order to reduce neck injuries is needed.

In this study, design variables which can affect neck injuries were decided. And orthogonal array was consisted using design of experiment. Also, Neck injuries about each experiment cases were evaluated using Finite Element Method. As a result, Optimization of car seat for whiplash injuries was performed.

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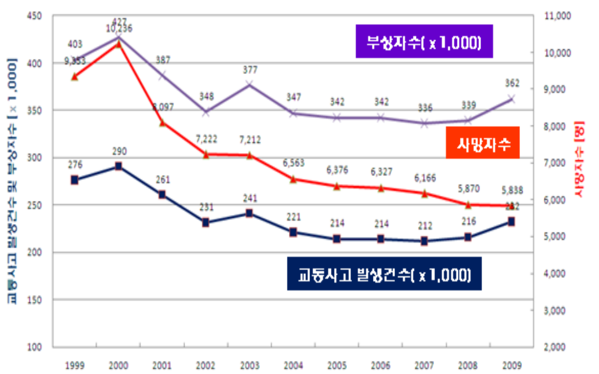

Fig. 1 (a) Numbers of accidents & injury & fatal in Korea

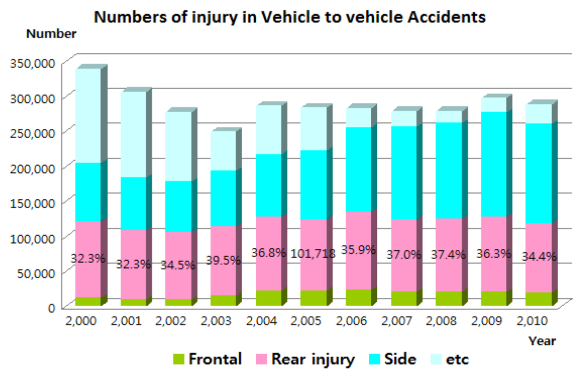

Fig. 1 (b) Numbers of injury in car to car accidents in Korea

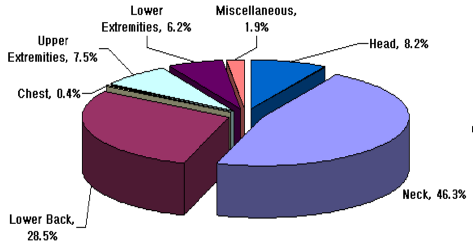

Fig. 2 (a) Statistic data on rear-end collision injury in EU (2006)

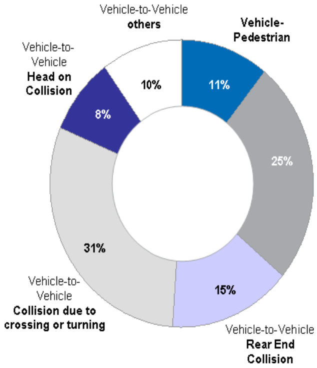

Fig. 2 (b) EU 15* number of accidents by collision type

II. Multi-Objective Optimization

Multi-objective optimization has more than 2 objective functions. In general, formulation is shown as (1). “k” means the number of objective functions. “j” means the number of constraints.

$$\begin{aligned} &Minimize \quad F=\{f_1(X), f_2(X),\ldots\ldots f_k(X)\} \\ &Subject\ \ to \quad g_j(X)\leq 0, \qquad j=1,2,\ldots..m \end{aligned} \tag{1}$$

Multi-objective optimization is a process in order to optimize objective function in feasible design region. But generally, optimal solutions that can minimize all objective functions are not existed as shown Fig. 3. Thus, optimal solutions are derived as form of Pareto set. And engineer has to select proper design point among derived Pareto set. Because of this, a variety of methodology has been studied in order to select proper solution using Pareto set. GA (Genetic Algorithm) and WSM (Weighted Sum Method) were widely used in order to find proper solution.

GA is a technique which simulates survival of the fittest by Darwin and was initially presented by Prof. John Holland of Univ. of Michigan in 1975 [10]. Users can obtain Pareto optimal solution without extra mathematical process by GA. So, it may be useful if engineers need optimal solution as form of Pareto set. However, problems which can apply GA are limited because of the time required and cost.

On the other hand, WSM is easy to understand and widely used because process of optimum is relatively simple[11]. Before deriving optimal solution, weighting factor is applied to each objective functions and sum. Then, optimization is performed. It means that multi-objective optimization is changed to single-objective optimization.

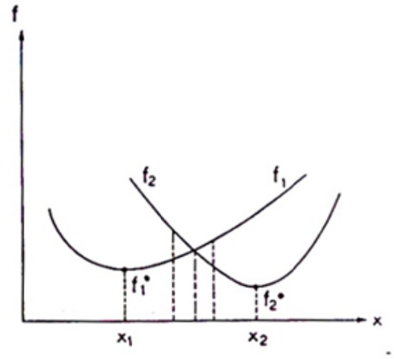

Fig. 3 An optimization problem with one variable and two objective functions

But, it has disadvantage that it can be hard to find converged optimal solution according to objective function as well as engineer has to decided weighting factor. Weighting factors are important to determine the optimal solutions but in most cases it is hard to set proper weighting factor. So, there are a lot of researches to overcome these limits. KIM I.Y suggested AWSM (Adapted Weighted Sum Method) which can derive uniform Pareto optimal solution using sequential weighted sum method [12]. Nakayama suggested STOM (Satisficing Trade-off Method) that engineers can change weighting factors as long as find satisfactory optimal solution [13]. Yoon J.M suggested using standard deviation of objective functions to determine weighting factors [14]. In this study, Neck injuries were evaluated using Finite Element Method. So, optimization technique which needs much iteration such as GA was not proper because Impact analysis required long time to get analysis results. Therefore, in this study, WSM was used to optimize neck injury.

III. Dynamic Assessment of Car Seat

Whiplash, although officially classed as a minor injury, is the most commonly occurring injury in motor car crashes. In order to evaluate whiplash, Spitzer of Quebec Task Force classified symptoms from whiplash and made 4 grade of whiplash as shown Table I [4]. “NIC” (Neck Injury Criteria) and “Nkm” are commonly used to evaluate whiplash. “NIC” is based on the relative horizontal acceleration and velocity of the occipital joint relative to thorax 1 as shown (2). It was developed by Bostrom in 1996 and validated up through animal experiments [5].

$$\begin{aligned} &a^{rel} = a_X^{T1} - a_X^{Head} \\ &V_X^{rel} = \int a^{rel}(t)dt, \quad t=0 \sim t \\ &NIC = 0.2\times\left(a^{rel}(t)\right)+\left[V_X^{rel}(t)\right]^2 \end{aligned} \tag{2}$$

“Nkm” was developed to supplement “NIC” by Schmitt in

2001. It is based on a combination of moment and shear forces, using critical intercept values for the load and moment as shown (3). "Fx (t)" and "My (t)" are upper neck shear force and moment.

$$N_{km}(t) = \frac{|F_X(t)|}{F_{\text{int}}} + \frac{|M_Y(t)|}{M_{\text{int}}} \tag{3}$$

TABLE I
NECK INJURY GRADE PROPOSED BY QUEBEC TASK FORCE

GRADE	CLINICAL PRESENTATION
0	No complaint about the neck, No physical sign(s)
1	Neck complaints of pain, stiffness or tenderness only No physical sign(2)
2	Neck complaints and musculoskeletal signs
3	Neck complaints and neurologic signs
4	Neck complaints and fracture or dislocation

They are measured from load cell which was installed in upper neck. "Fint" and "Mint" are standardized threshold. Muser reported that "Nkm" is effective whiplash assessment criteria in 2003 [6]. Kullgren recommended using "NIC" and "Nkm" together to evaluate whiplash in 2003 [7]

IV. Construction of Finite Element Model

In this study, data of whiplash assessment criteria was obtained by performing Finite Element Method. To do this, Construction of Finite Element model, conducting impact analysis, and correlation analysis results with test results were performed. Skin model for construction of finite element model was made by CATIA. Finite element model of car seat has 128,852 elements and 108,603 nodes. All mounting point including weld was modeled as rigid element since impact analysis does not have to consider mounting point in detail. In case of dummy, FAT BioRID ll version 2.5 was used which has 189,556 elements and 148,479 nodes. BioRID ll that has detail modeled neck, spine, and pelvis was developed based on Hybrid lll. Yahuchi[8], Linda[9] suggested that BioRID ll is the best suited model to simulate rear-end collision. Input for analysis is same as input for dynamic assessment shown in Fig. 4. Positioning dummy is conducted reference to tolerance which is listed in Table II. Test model is shown Fig. 5. Finite element model is shown Fig. 6.

V. Finite Element Analysis

A commercial program, LS-Dyna, was used to Perform impact analysis. Dynamic assessment was performed while in contact with head and head restraint. Thus, Analysis end time was set to 200ms by considering the time of separation of head and head restraint.

TABLE II
BIORID II DUMMY POSITION LOCATION

PARAMETER	H-POINT	TOLERANCE
X-COORDINATE AT H-POINT	FORWARD +20mm	±10mm
Z-COORDINATE AT H-POINT	0mm	±10mm
PELVIS ANGLE	26.5°	±2.5°
LEVEL THE HEAD PLANE	0°	±1°
BACKSET	FORWARD +15mm	±5mm

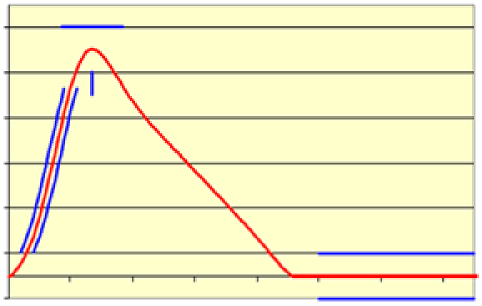

Fig. 4 KNCAP sled pulse

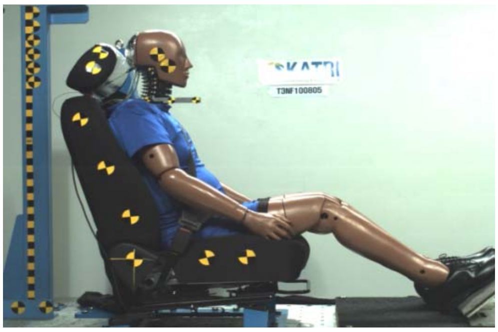

Fig. 5 BioRID II test picture

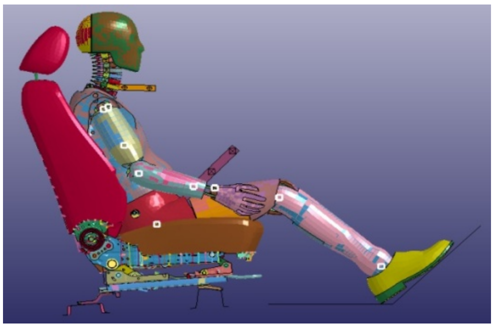

Fig. 6 BioRID II FEM picture

VI. Correlation the Result

After performing impact analysis, correlation with test data was carried out in order to obtain proper result of optimization. Test was performed 3 times. FE model of car seat was modified in order to obtain analysis result about whiplash assessment criteria as follows "HRCT", "T1g", "Fx", "Fz", "HRV" as close as possible to the test result. "NIC", "Nkm" were excluded because they are composite index consisting of the

"T1g", "Fx", Moment of upper neck, and acceleration of head. Correlation data with modified car seat was shown in Fig. 7.

VII. Objective Function and Design Variables

Car seat is consisted of a variety of components. Thus, complex mechanisms have to be considered when optimization is performed in order to reduce whiplash injury. To do this, design variables which can directly be affected to whiplash have to be determined. Backset, height of head restraint, stiffness of head restraint stay, and thickness of side member were determined considering existing researches. 3-leveled design of experiments was consisted to optimize shown as Table III.

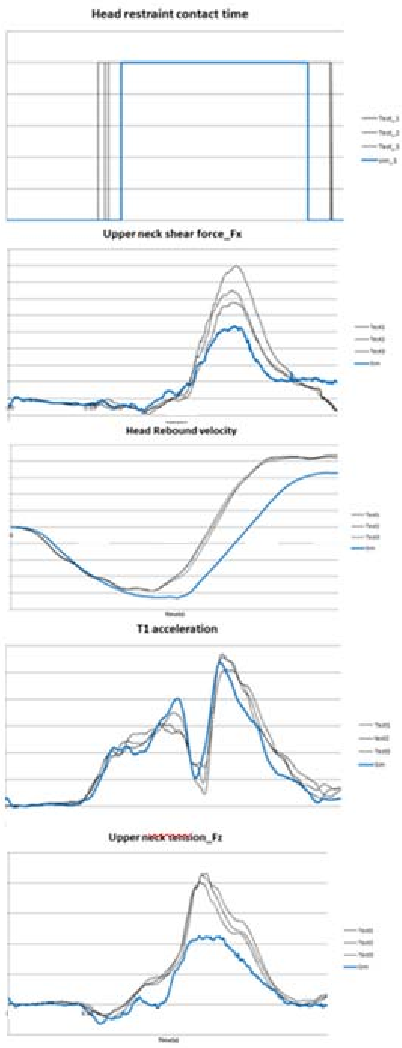

Fig. 7 Correlation analysis result with test result

Level 1, Level 2, and Level 3 respectively mean lower level, base level, and upper level. Objective functions are "NIC", "Nkm" as well as "Fx" (upper neck shear force), "Fz" (Upper neck tension), "HRCT" (head restraint contact time), "T1g" (thorax 1 x acceleration), and "HRV" (head rebound velocity) which are needed to calculate "NIC", "Nkm" shown as Table IV.

VIII. Design of Experiment

Orthogonal array L_9 (3^4) was used to perform sensitivity analysis shown as Table V. Design variables are Backset, height of head restraint, stiffness of head restraint stay, and thickness of side member. Sensitivity analysis was performed with orthogonal array. The results of the objective functions in each experiment were calculated as shown Table VI. Through sensitivity analysis, Upper neck tension had the largest variation. And considering new design variables would be needed to reduce head rebound velocity because it had the smallest variation.

TABLE III
Experimental Design Variables and Levels

No.	Design variable	level 1	Level 2	Level 3
A	H/Rest height	-10mm	0mm	+10mm
B	Backset	-5mm	0mm	+5mm
C	H/Rest stay stiffness	-10%	0%	+10%
D	Side member thickness	-0.2mm	0mm	+0.2mm

TABLE IV
Objective Function

No.	1	2	3	4	5	6	7
Objective Function	HRCT	T1g	Fx	Fz	HRV	NIC	Nkm

IX. Analysis of Mean

Sensitivity was analyzed by performing analysis of mean (ANOM) using the results of D.O.E as shown Fig. 8. Backset was the most sensitive factor to head rest contact time, Upper neck shear force and "NIC". Thickness of side member was the most sensitive factor to thorax 1 x-acceleration. Height of head restraint was the most sensitive factor to upper neck tension. Stiffness of head restraint stay is the most sensitive factor to head rebound velocity. However, "Nkm" was not affected by determined design variables.

X. Multi- Objective Optimization

Based on the results of ANOM optimal solutions about design variables were derived. Pareto set was consisted as weighting factors were applied to objective functions for multi-objective optimization. Weighting factors were determined by considering KNCAP score about BioRIDⅡ. Based on the test results, low-scored objective function had relatively high weighting factor. Analysis of objective functions about BioRIDⅡ was shown Table VII. Each index is out of 1.5 points. Weighting factors were applied differently relatively high scored objective functions such as No. 1,2,3,7 and relatively low scored objective functions such as No. 4,5,6. weighting factors were Calculated using (4). According to equation (4), w1, w2, w3, and w7 are 0.035. Other weighting factors can be having 0.172, 0.344, 0.516. Optimal solutions according with applied weighting factors were shown Table VIII. In Table VIII, Fobj is relative variation about sum of objective functions. As a result, the optimal solution is No.7 model in orthogonal array. Comparison of result between initial model and optimal model was shown Table IX. All of objective functions were reduced except for head rebound velocity and "Nkm". In case of head rebound velocity and "Nkm", other design variables are need to optimize them.

$$w_1 = w_2 = w_3 = w_7 = \frac{\left[\sum_{j=1}^{4}\left(\frac{P_{max} - P_j}{\sum_{i=1}^{7}(P_{max} - P_i)}\right) + \left(\frac{P_{max} - P_7}{\sum_{i=1}^{7}(P_{max} - P_i)}\right)\right]}{4} \tag{4}$$
$$w_4 + w_5 + w_6 = [1 - (w_1 + w_2 + w_3 + w_7)]$$

TABLE V
ORTHOGONAL ARRAY

Exp. No.	H/R Height	Backset	H/R stay Stiffness	Side member thickness
1	1(-10mm)	1(-5mm)	1(-10%)	1(-0.2mm)
2	1(-10mm)	2(0mm)	2(0%)	2(0mm)
3	1(-10mm)	3(+5mm)	3(+10%)	3(+0.2mm)
4	2(0mm)	1(-5mm)	2(0%)	3(+0.2mm)
5	2(0mm)	2(0mm)	3(+10%)	1(-0.2mm)
6	2(0mm)	3(+5mm)	1(-10%)	2(0mm)
7	3(+10mm)	1(-5mm)	3(+10%)	2(0mm)
8	3(+10mm)	2(0mm)	1(-10%)	3(+0.2mm)
9	3(+10mm)	3(+5mm)	2(0%)	1(-0.2mm)

TABLE VI
RESULTS OF EXPERIMENTS (NORMALIZED WITH AVERAGE)

Exp. No.	HRCT (s)	T1 x-acc (g)	Fx (N)	Fz (N)	HRV (m/s)	NIC	Nkm
1	-0.004	-0.16	-3.79	+102.35	+0.03	+0.13	0
2	0	+0.72	+1.83	+166.72	+0.09	+0.91	0
3	+0.041	+1.55	+4.24	+221.43	+0.11	+2.39	0
4	-0.004	+0.94	-5.01	+10.21	+0.08	-1.19	0
5	0	-0.38	-3.75	+11.04	+0.10	+1.64	0
6	+0.04	+0.31	+0.05	+10.59	+0.04	+3.07	0
7	-0.003	-0.05	-7.94	-136.59	+0.16	-1.51	0
8	0	-0.16	-2.47	-147.83	+0.02	+0.07	+0.05
9	+0.039	-0.9	-0.57	-111.88	+0.13	+2.96	0

TABLE VII
KNCAP POINT OF BASE MODEL

Neck injury indicators	KNCAP point
HRCT	1.5
T1 x-acc	1.24
Fx	1.2
Fz	0.6
HRV	0.5
NIC	1.06
Nkm	1.5
Point Sum	7.6

International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
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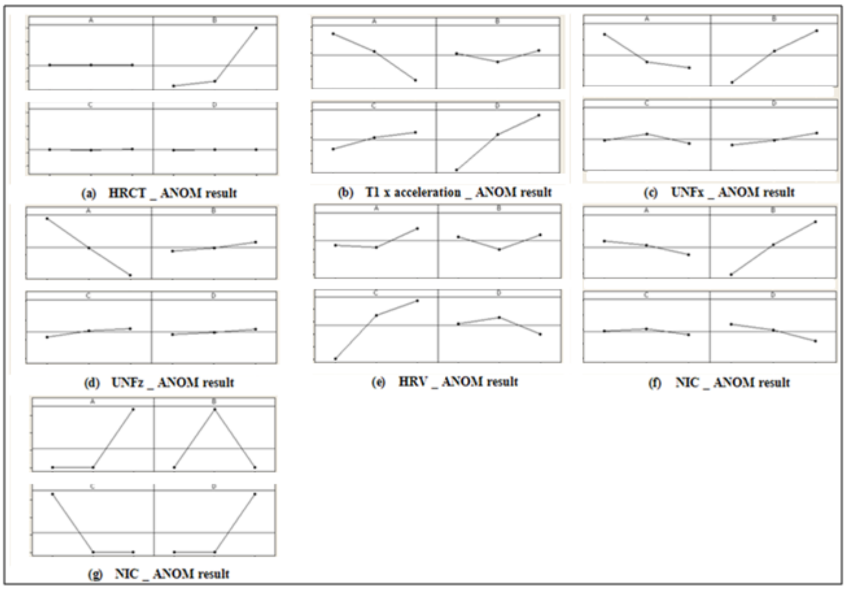

Fig. 8 ANOM result

TABLE VIII
OPTIMUM DESIGN VARIABLE SET OF SEAT BY DOE

No.	X1	X2	X3	X4	W1=W2=W3	W4	W5	W6	W7	Optimum Exp. No.	Fobj
1	+10mm	-5mm	+10%	0mm	0.035	0.516	0.172	0.172	0.035	7	0.814
2	+10mm	0mm	-10%	+0.2mm		0.172	0.516	0.172		7	0.916
3	+10mm	+5mm	0%	-0.2mm		0.172	0.172	0.516		7	0.855
4	0mm	-5mm	0%	+0.2mm		0.172	0.344	0.344		7	0.886
5	0mm	0mm	+10%	-0.2mm		0.344	0.172	0.344		7	0.835
6	0mm	+5mm	-10%	0mm		0.344	0.344	0.172		7	0.865

TABLE IX
COMPARISON OF KNCAP POINT BETWEEN BASE MODEL AND OPTIMUM DESIGN MODEL

.	BioRID II Neck injury indicators							KNCAP Point
	HRCT (s)	T1 x-acc (g)	Fx (N)	Fz (N)	HRV (m/s)	NIC	Nkm	
Improve rate (%)	5.6%	0.5%	21.0%	26.0%	-3.4%	10.2%	0.0%	6.5%

XI. CONCLUSION

This study was conducted to optimize whiplash injury caused by rear-end collision. To do this, finite element model was constructed which was had proper material properties. And impact analysis was performed with same condition as dynamic assessment test by KNCAP. Also design variables and objective functions were determined. Finally, optimal solution was derived using design of experiment. Weighted Sum Method was used to get optimal solution because Car seat neck injury optimization is a multi-objective optimization. Through the results of Weighted Sum Method, 5 of 7 objective functions were improved compared to base model. The improvement of methodology about car seat assessment and Production of neck injury optimized car seat are expected using this study.

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