MULTI-OBJECTIVE OPTIMIZATION OF VEHICLE OCCUPANT RESTRAINT SYSTEM BY USING EVOLUTIONARY ALGORITHM WITH RESPONSE SURFACE MODEL

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ABSTRACT

This research reports a vehicle occupant restraint system design by using evolutionary multi-objective optimization with response surface model. The vehicle occupant restraint systems are composed of restraint equipment, such as an airbag, a seat belt and a knee bolster. The optimization aims to improve the safety of the system by evaluating some indexes based on some safety regulations. Estimation models of the safety indexes are introduced for accelerating the optimization. The estimation models, which are called the response surface models, are constructed by using Gaussian Process, which is a kind of machine learning method. The Gaussian Process constructs the estimation model from sampling results, which are calculated by using multi-body dynamics simulation. Some helpful information for designing the restraint systems, such as trade-off information of safety performance and contribution of design variables for the safety performance, is obtained by analysing the Pareto optimal solutions.
Keywords: evolutionary algorithm, machine learning, multi-objective optimization, occupant safety.

1 INTRODUCTION

Since physical prototyping and testing at design and development of a vehicle consume huge time and cost, virtual prototyping and testing by using numerical simulation are employed at various phases of the design. At the virtual prototyping and testing, many draft designs' evaluation indexes, such as safety, rigidity, strength and weight, are calculated and then designers examine the draft design while referring trade-off and restraint of those indexes.

At occupant restraint systems design, analytical model of the occupant's behavior is constructed by using computer-aided engineering, CAE, such as finite element analysis and multi-body dynamics, and then impact responses at various crash conditions and various evaluation indexes based on safety regulations are calculated. Substituting such virtual evaluation by using CAE for physical crash testing has brought significant reduction of the time and the cost for design and evaluation of the occupant restraint system nowadays. Since the crash responses are highly nonlinear and multi-modal, it is difficult to optimize by using mathematical optimization technique commonly used. So, some optimization results, such as using response surface model and evolutionary computation, have been reported by Fu *et al.* [1, 2], so far.

The author have constructed an analytical model of an occupant behavior at a frontal crash by using multi-body dynamics simulation and conducted an evolutionary multi-objective optimization of the occupant restraint systems. Then some pieces of helpful information for designing the restraint systems, such as trade-off information of safety performance and contribution of design variables for the safety performance, have been obtained by analyzing the Pareto optimal solutions.

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The multi-body dynamics simulation is suitable for evolutionary computation, which requires repetitive computation, since computational load of the simulation is relatively low. However, huge calculation time has still been demanded, since 2,000 cases for evaluation have been calculated at one optimization. Therefore, for accelerating the optimization, we have constructed the response surface models from a few computational samples by using the Gaussian Process, which is a kind of machine learning method, and then, it has been confirmed that the accuracy of the response surface models have been good [3].

This paper reports some result of optimization by using the above response surface models.

2 RESPONSE SURFACE MODEL OF VEHICLE OCCUPANT RESTRAINT SYSTEM

In this research, injury criteria of an occupant at a frontal crash are estimated by using a machine learning method, Gaussian Process. The Gaussian Process is a Bayesian approach, based upon the expression of knowledge in terms of probability distribution [4]. This method is a powerful regression model specified by parameterized mean and covariance functions, and suitable for estimating non polynomial responses.

An occupant's behavior model of a full-frontal crash testing shown in Figure 1 is constructed by using the multi-body dynamics tool, MADYMO. The model is composed of a Hybrid-III dummy, surrounding equipment such as a seat and a steering wheel, and restraint equipment such as an airbag and a seatbelt. The model simulates the occupant's behavior at the crash for 0.12 s.

Input variables for controlling the behavior of the model consist of six design variables regarding the restraint equipment, which strongly affect safety indexes, an airbag, a seatbelt and a knee bolster. Definition of the design variables are shown in Table 1.

Output variables are three safety indexes based on the Japan NCAP, head injury criterion, chest resultant acceleration and femur load. The head injury criterion, HIC is an index of head injury risk. The chest resultant acceleration, ChestG is measured by an accelerometer

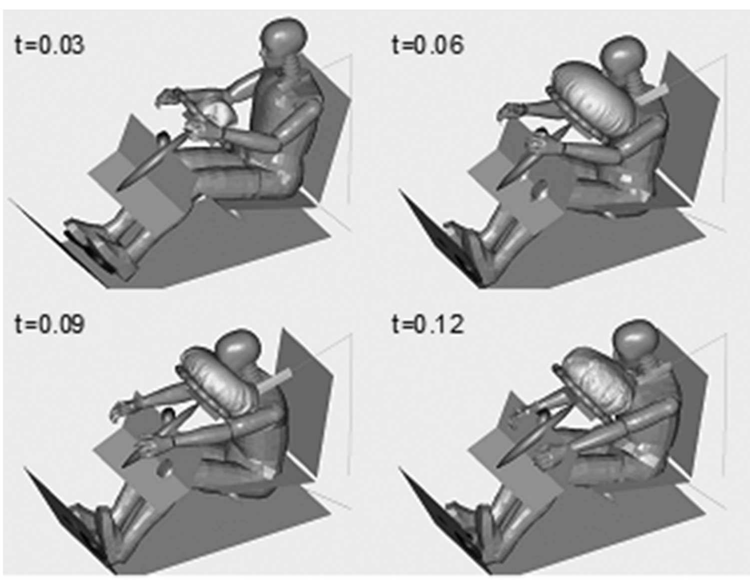

Figure 1: Occupant behavior model at frontal crash.

Table 1: Definition of design variables.

	Variable	Range and name
Airbag:	Time to fire (sec.)	0.015≦AB_TTF≦0.035
	Mass flow rate	0.5≦AB_MFR≦2.0
	Vent hole factor	0.5≦AB_VHF≦2.0
Seatbelt:	Time to fire (sec.)	0.01≦SB_TTF≦0.03
	Load limit (N)	2000≦SB_LL≦6000
Knee bolster:	Stiffness factor	0.5≦SF_KB≦2.0

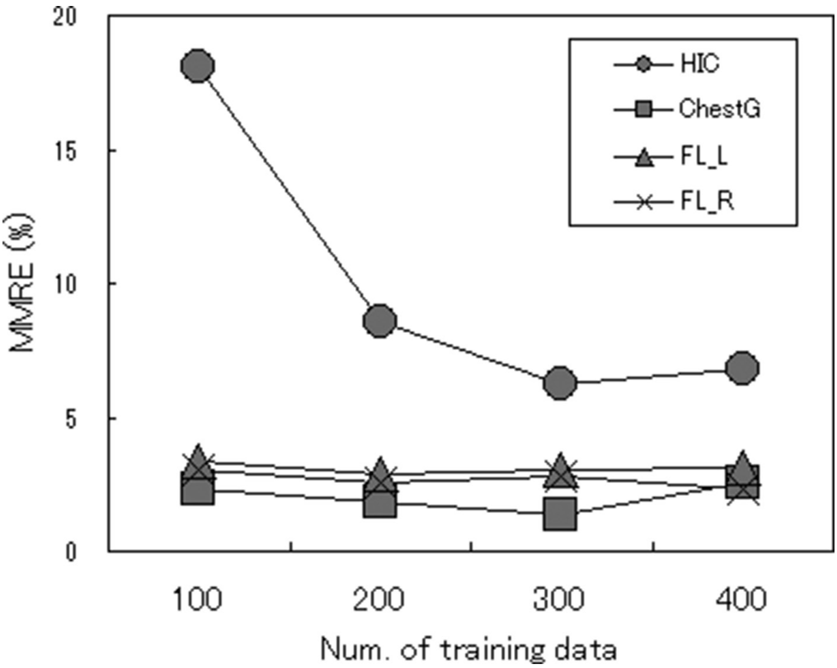

Figure 2: Evaluation of accuracy of response surface models.

mounted on center of mass of a crash dummy's chest. The femur load, FL is measured by load cells mounted on the dummy's left and right femurs.

In this research, four response surface models of the HIC, the ChestG and the left and the right FL, FL_L and FL_R, are constructed by using the Gaussian Process as criteria of an occupant's safety performance. The response surface models are constructed with changing the number of sampling of the training data set for 100, 200, 300 and 400. The accuracy of the response surface models shown in Figure 2 is evaluated by using mean magnitude of relative error, MMRE, between the actual value and the estimated value of the testing data set. The testing data consist of 100 samplings and are obtained randomly. The response surface models, which are constructed by 300 of the number of sampling of the training data set, obtain the most accurate results and then they are used for the following optimization.

3 RESULTS OF MULTI-OBJECTIVE OPTIMIZATION BY USING EVOLUTIONARY ALGORITHM

Here, the above four response surface models of the HIC, ChestG, FL_L and FL_R were used for optimization of the vehicle occupant restraint systems. The optimization problem was defined as 2-objective minimization problem. The objective functions were HIC and ChestG. The FL_L and the FL_R were set as constraints. Adaptive Range Multi-Objective Genetic Algorithms, ARMOGA [5], one of the evolutionary multi-objective optimization algorithms, was selected for this optimization.

Firstly, the optimizations were performed 10 times with changing the initial populations. 157 non-dominated solutions were collected from the optimizations and then the solutions were classified into three groups, A, B and C. The non-dominated solutions, which were collected and classified, are shown in Figure 3.

Secondly, factors of controlling the trade-off relationship at each group were understood by analyzing the correlations among the objective functions and the design variables. The correlation coefficients among the HIC and the design variables are shown in Table 2 and the correlations among them are shown in Figs 4–9, respectively, as an example.

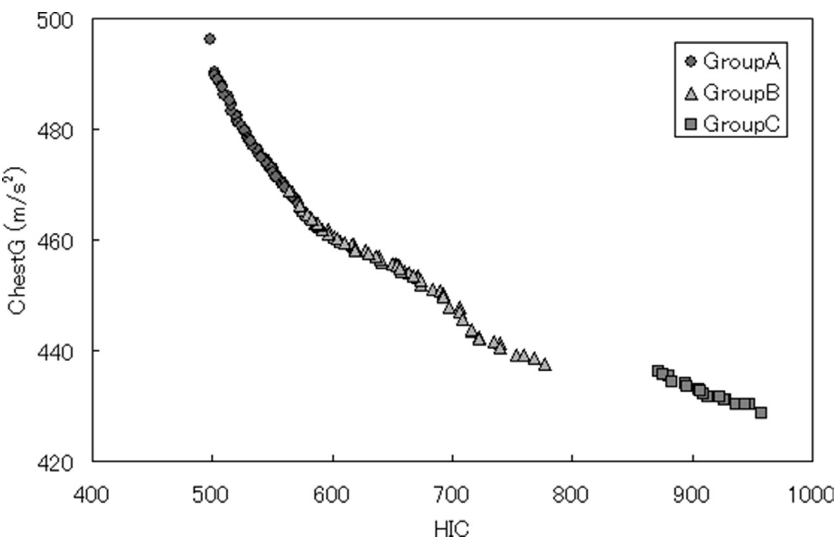

Figure 3: Non-dominated solutions on Pareto optimal front.

Table 2: Correlation coefficients among HIC and design variables.

	Group A	Group B	Group C
AB_TTF	−0.80	0.20	0.08
AB_MFR	−0.82	−0.99	−0.39
AB_VHF	0.90	−0.02	−0.25
SB_TTF	0.77	0.75	0.99
SB_LL	−0.92	−0.23	0.32
KB_SF	0.86	0.40	−0.05

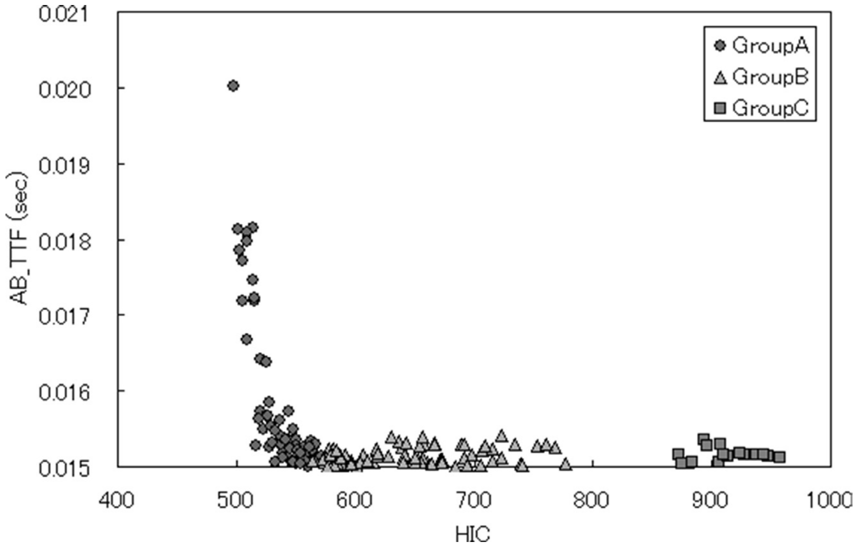

Figure 4: Correlation between HIC and time to fire of airbag (AB_TTF).

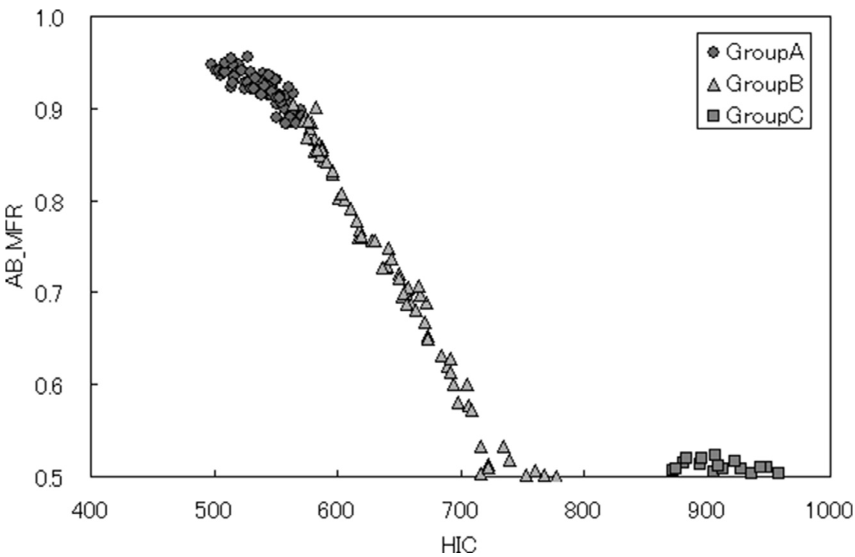

Figure 5: Correlation between HIC and mass flow rate of airbag (AB_MFR).

At the group A, since all design variables are correlated to the HIC strongly, complicated combination of the variables are demanded to control the trade-off relationship between the HIC and the ChestG.

On the other hand, some specific design variables affect strongly at the groups B and C. At the group B, the AB_MFR and the SB_TTF are correlated to the HIC strongly, and the other

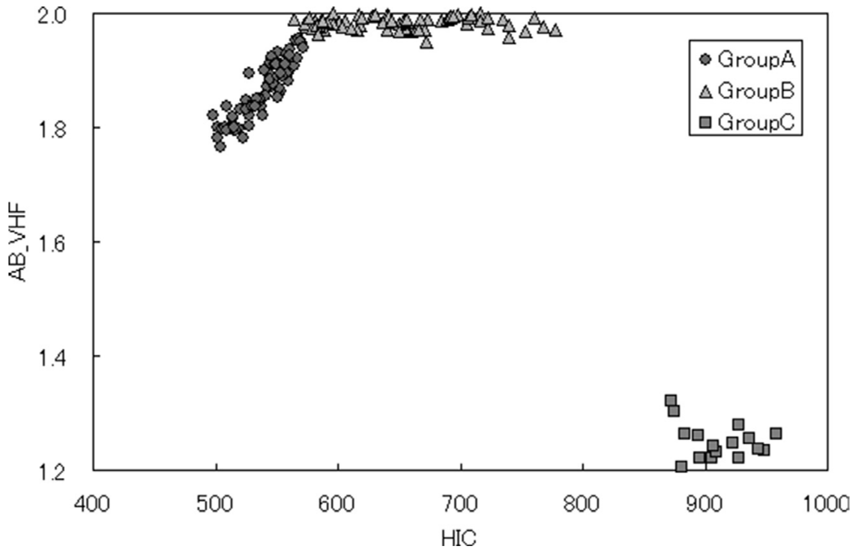

Figure 6: Correlation between HIC and vent hole factor of airbag (AB_VHF).

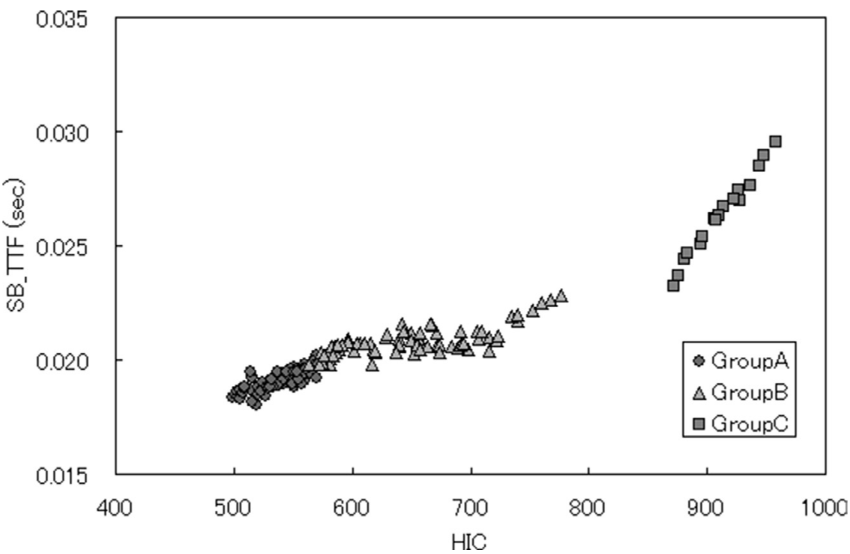

Figure 7: Correlation between HIC and time to fire of seat belt (SB_TTF).

variables are converged to some constant values. At the group C, the SB_TTF is the main factor of controlling the trade-off relationship between the objective functions.

As the above consideration, analyzing the non-dominated solutions obtained by some optimization affords understanding of the factors which control the trade-off relationship between the objective functions.

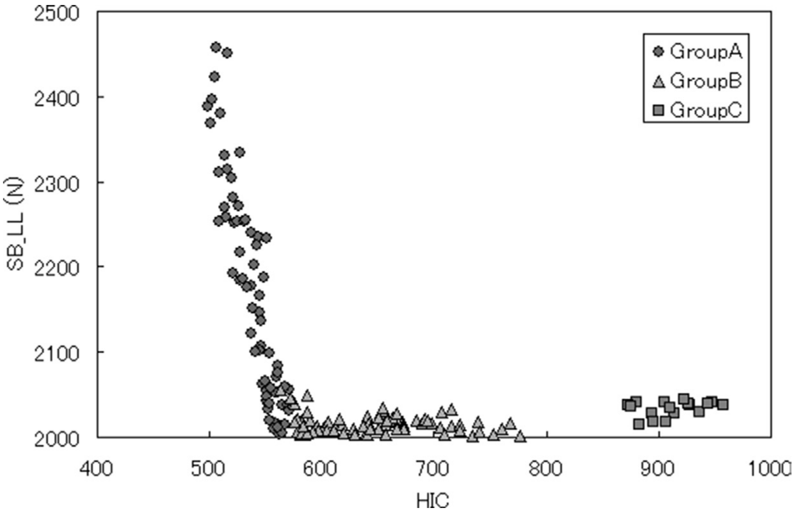

Figure 8: Correlation between HIC and Load Limit of seat belt (SB_LL).

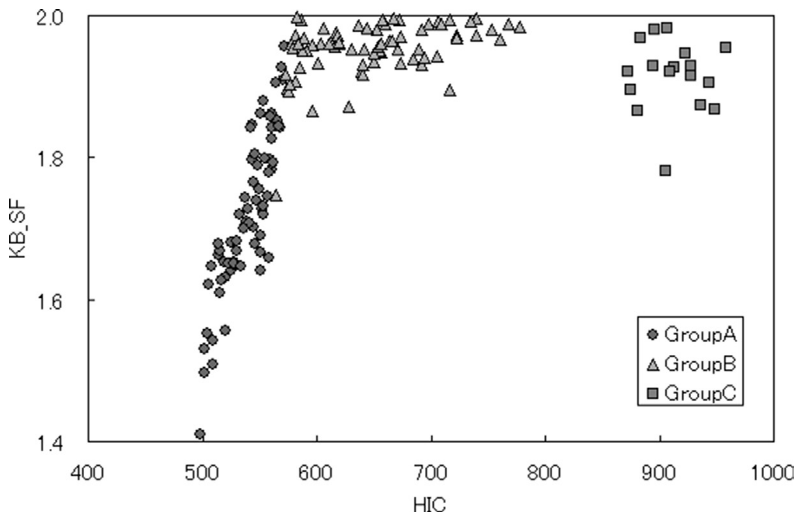

Figure 9: Correlation between HIC and stiffness factor of knee bolster (KB_SF).

4 CONCLUDING SUMMARY

In this research, the response surface models were introduced for accelerating the evaluation of design cases to evolutionary multi-objective optimization of the vehicle occupant restraint systems design. Appropriate accuracy of the constructed response surface models was confirmed. The factors of controlling the trade-off relationship between the objective functions were understood by analyzing the non-dominated solutions.

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