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Research on the Protection Strategy of Pretensioner Seat-belt with the Active Braking Technology

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Abstract: Active safety and passive safety technology have been developed for many years in foreign countries. According to the studies by some foreign authorities, pre-crash seat-belt can protect the occupant in collision more effectively, and reduce the injury during the accident greatly. In this paper, sled tests and simulation were carried out to analyze the influence of pretensioner on the occupants. It analyzes the important parameters of motor driving belt. It carries out orthogonal experiment, and analysis of the results. From the influential factors, find the optimal combination of parameters. Compared with the simulation and pyrotechnical model, the WIC of optimized model reduces nearly 10%, which improving the safety performance of the seat-belt greatly. Compared with traditional pyrotechnical, the head injury index HIC36 reduces by 16.94%, HIC15 reduces by 20%. Compared with the sled test, the index of the optimal model decreases more than 25%. The effect of active preloaded on the head is more obvious.

1. Introduction

With increase of car ownership, traffic accidents have become one of the threats to our lives and health, each year more than one million people died in traffic accidents. According to a report published by WHO (World Health Organization) in 2013, about 1.2 million people worldwide died due to traffic accidents and 200-500 million were injured in road traffic accidents1[1]. Improving the safety of vehicles, reducing damages caused by traffic accidents and lowering the possibility of occupants injures in traffic accidents have been top concerns of the public nowadays [2-3]. As a passive safety device, seat belt restraint system in a car is one of the main components of vehicle’s passive safety system, playing an important role in reducing occupants’ injuries. In this paper, a study on combining car seat belt preloading device to active safety technology was conducted to better protect the persons in the vehicle [4-6].

This paper is based on the results from experiments. We build a front impact model for a vehicle in MADYMO software, and leverage this model to simulate the real scenarios of a car crash and analyze each scenario. For the full front impact and part impact with different speeds and different forces that applied to the active braking system, the pre-tightening time, speed and force for motor driven pretensioner seat belt are optimized. In addition, the control strategies compatible with active braking technologies and suitable for pre-tensioner seat belt are proposed to enhance the efficiency of restraint system for better protections for the occupants. Specifically, the study covers: verifying the protection of motor driven pre-tensioner seat belt, identifying the typical scenarios of traffic accidents, building simulation models and analyzing the results getting from the simulation models, etc.

2. The Testing Platform and Simulation Models for Front Impact

2.1 Testing Vehicle Platform

The testing vehicle contains car seats, a foot pedal and a simulated steering wheel. A Hybrid III 50th male dummy was placed in driver’ s seat and posed in driving state with his hands grabbing the steering wheel, before the impact, the vehicle was moving at 40 km/h [7]. The dummy is seated on the driving seat of the testing vehicle. There is no clearance between dummy’ s bottom and seatback. Dummy’ s hands are put on the steering wheel with its natural driving pose and his head is adjusted so that the accelerometer for x-axis is leveled horizontally. With all above are well set, the spatial locations for the dummy and testing vehicle are captured by a 3D coordinate measuring instrument. The configurations for the testing vehicle is showed in Fig 1.

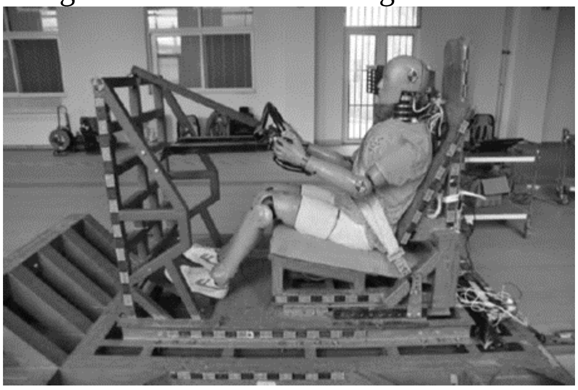


Fig 1. The Testing Vehicle and Its Configurations

2.2 MADYMO Simulation Models

According to the geometric parameters of the testing vehicle, a MADYMO simulation model is built, as shown in Fig 2 which includes a steering wheel, foot pedal, seat and seat belt system. Seat belt system model includes a belt retractor, guiding groove, seat height adjuster, D-shaped ring, buckle and anchor plate etc. Based on the relative positions of these components, the webbing pattern of the seat belt and how these components are connected are defined in the model. In building the seat belt model, multi-body dynamics and finite element method are employed, its structure is shown in Fig 3.

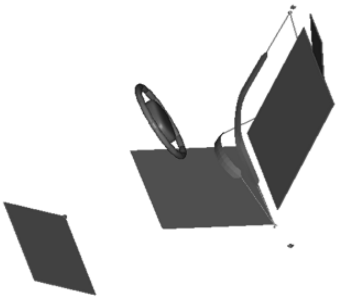


Fig 2. Basic Model of Vehicle Body

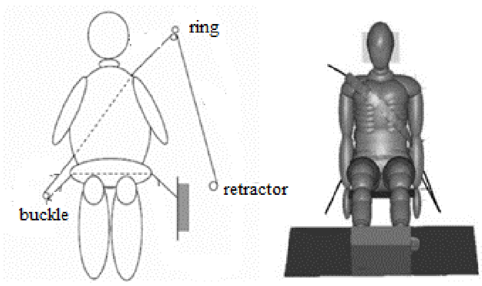


Fig 3. Structure of Seat Belt Model

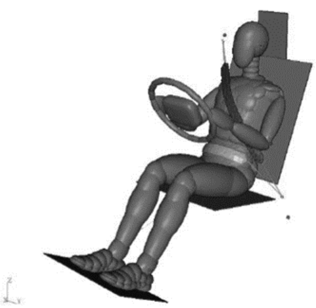


Fig 4. MADYMO Simulation Model

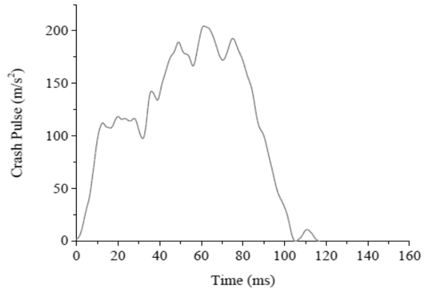


Fig 5. Acceleration Curve Applied to the Vehicle

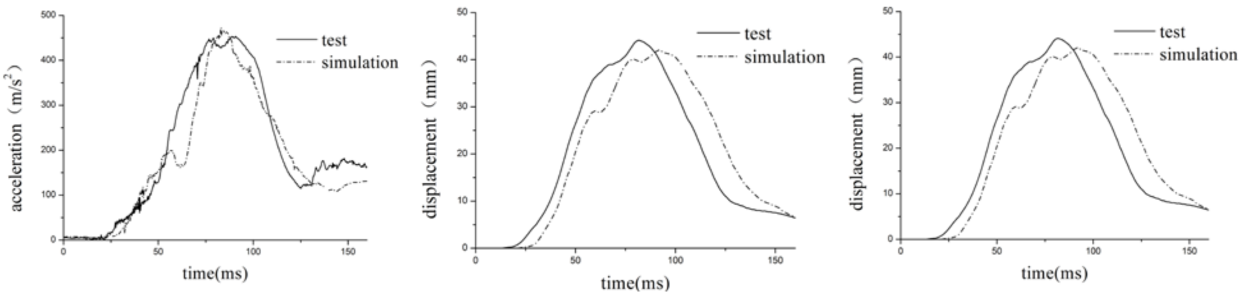
At last, we got the final model as shown in Fig 4. When a car crash happens, the deformation of cushion in car seats will affect the dummy’s respond to the impact. Based on this consideration, the cushion in the model is simplified - a curve that reflects the relationship between force and the collapse degree is defined to simulate the deformation of cushion in seat. For the vehicle in the model, a testing wave shown in Fig 5 will be applied to it along the negative direction of x-axis.

2.3 Benchmarking for Simulation Model

Comparing the results getting from the vehicle testing and computer simulations, as shown in Table 1. The comparison shows that the damages in the simulation is not much as in the vehicle test. In Fig 6, the dummy's reactions for both vehicle testing and model simulation are shown. Judging from the curves shown in Fig 6, the pulse widths are almost the same. In the vehicle testing, the movement in chest is slightly higher than that in the simulation while no much difference in other curves. As for the head injure curve, there is a latency in simulation results. In Fig 7, the dummy's response at the special moments are shown.

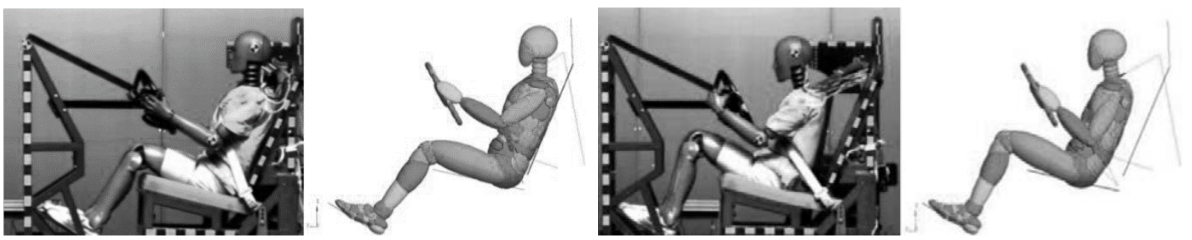
Table 1 Verifying in Simulation Model: Damage Response

Damage Response	Vehicle Test	Simulation Model	Differences
HIC15	204.00	193.01	5.54%
HIC36	443.66	416.16	6.40%
ahead (3ms)/g	449.89	440.35	2.14%
achest (3ms)/g	294.99	276.32	6.54%
Chest Deflection/mm	44.09	38.87	12.58%
CTI	0.76	0.68	11.11%
Nte	0.31	0.29	6.67%
Ntf	0.43	0.42	2.35%

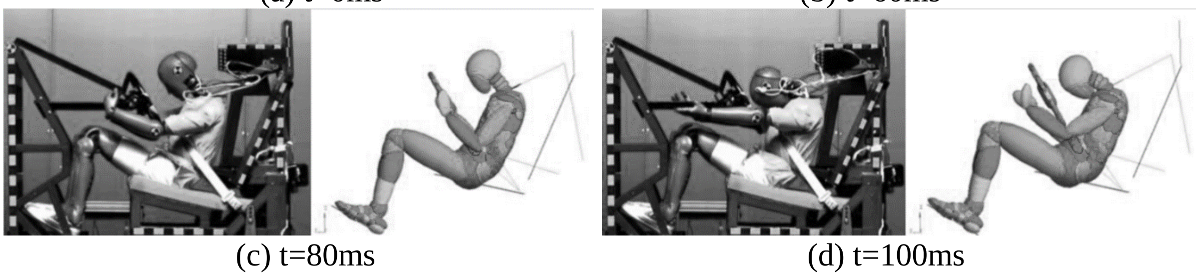


(a) Head (b) Chest (c) Chest Deflection

Fig 6. Verifying the Benchmarking for Simulation Model: Response Curve to Damages



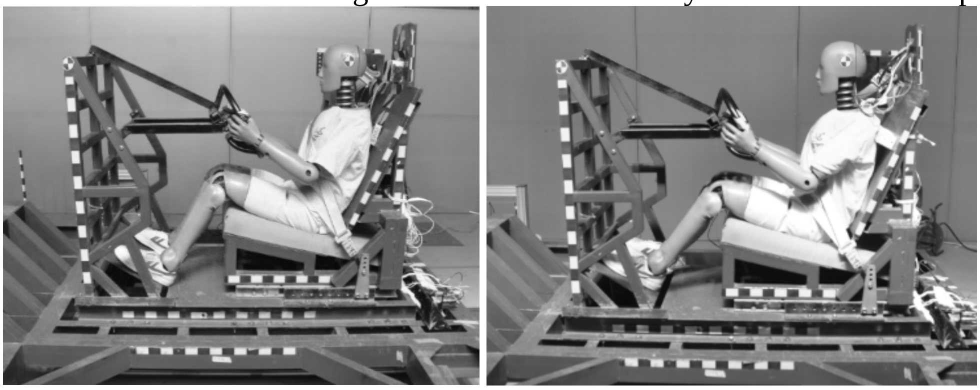
(a) t=0ms (b) t=60ms



(c) t=80ms (d) t=100ms

Fig 7. Verifying the Benchmarking for Simulation Model: Dummy's Posture is as in the Movement

In the simulation, the dummy's body movement aligned pretty well with those captured in vehicle testing, just a latency found in dummy's arm movements. This is because dummy's fingers are fixed to the steering wheel by adhesive tapes. To further verify the validity of the simulation model, the sitting postures of dummy in vehicle test and simulation are adjusted - a clearance of 25mm and 50mm respectively between the dummy's back and the seatback are set, as shown in Fig 8, to simulate the scenarios of the real driving where the drivers usually sit in a non-normal posture.



(a) 25mm (b) 50mm

Fig 8. Clearance between Dummy's Back and Seatback

In both vehicle tests, scenario of 25mm clearance is recorded as Scenario 1 while scenario of 50mm clearance is recorded as Scenario 2. To verifying Scenario 1, the results of damage response getting from vehicle test and computer simulation are compared in Table 2 and the comparison shows that, the damages in simulation is not much as in vehicle test. To verifying Scenario 2, the results of damage response getting from vehicle test and computer simulation are compared in Table 2 and the comparison shows that, the damages in simulation is not much as in vehicle test, too.

Table 2 Verifying Scenario in Simulation Model: Damage Response

Verifying Scenario	**Damage Response**	**Vehicle Test**	**Simulation Model**	**Differences**
1	HIC15	226.60	214.66	5.41%
	HIC36	391.00	381.03	2.58%
	ahead (3ms)/g	47.59	45.27	5.00%
	achest (3ms)/g	30.58	27.60	10.24%
	Chest Deflection/mm	30.58	27.60	0.70%
2	HIC15	226.60	191.42	7.36%
	HIC36	404.44	407.50	0.75%
	ahead (3ms)/g	49.94	44.90	10.62%
	achest (3ms)/g	30.83	27.58	11.12%
	Chest Deflection/mm	36.10	35.25	2.38%

By comparing the results getting from different scenarios and benchmarking model, we find that the simulation presents a lower value than vehicle tests, means that this is a systematic bias and acceptable. Therefore, we can conclude that the simulation model can reflect the dummy's response in a car crash well.

3. Verifying the Protection of Pre-tensioner Seat Belt and Optimization of Parameters

3.1 Choose Optimized Parameters

In this part, the protection strategies for motor driven pre-tensioner seat belt are researched. Given the fact that the parameters of pretensioner are closely related with the injures of dummy, pretensioning time, force and the amount of it are chosen as adjustable parameters. Currently, for the existing pyrotechnical pretightening seat belt and reversible pretightening seat belt, the pretightening time is usually restrained between 100ms to 500ms, while the amount of pretightening is set to 80mm to 300mm and the force of pretightening is controlled in a range of 200N to 500N[8]. In this thesis, Orthogonal Test is employed to verify the design of the simulated model. The range of the parameters used in Orthogonal Test are shown in Table 3 below.

Table 3 Designs at Parameter Level

	1	2	3	4
Pretensioning Time A/ms	100	250	350	500
Amount of Pretightening B/mm	80	150	250	300
Pretensioning Force C/N	200	300	400	500

3.2 Optimize Design of Tests

According to the rules of Orthogonal Test, the combined tests are designed, as shown in Table 4 [9].

Table 4 Arrangements for Parameter Tests

Test No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A	1	1	1	1	2	2	2	2	3	3	3	3	4	4	4	4
B	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
C	1	2	3	4	2	1	4	3	3	4	1	2	4	3	2	1

3.3 Optimizations

In this thesis, WIC is chosen as the indicator to evaluate how serious the occupant is injured [10]. WIC features with wide assessment range. In WIC evaluation, injures in different part of the body will be weighted differently, which has been proved to be of great value in identifying the degrees of personal injuries. The formula for calculating WIC is:

$$WIC = 0.6\left(\frac{HIC_{36}}{1000}\right) + 0.35\left(\frac{C_{3ms}}{60} + \frac{C_{comp}}{0.076}\right)/2 + 0.05\left(F_L^{femur} + F_R^{femur}\right)/20$$

Where, HIC36 is 36 integral value for head injury criterion; C3ms means standard acceleration at chest for 3ms, measured in g (acceleration of gravity, 1g =9.80m/s^2), Ccomp is compression in chest, measured in m, FLfemur and FRfemur are maximum axial forces born by left leg and right leg respectively, measured in KN. In this formula, the value in each denominator is the threshold of such injury criterion. Therefore, in the calculation that follows, HIC is calculated as per FMVSS-208 Code, and the integral value for head injury criterion is specified as 15ms with a threshold of 700.

As arranged in Table 5, tests are run and following results are gained and shown in Table 5.

Table 5 Results from Simulated Injury

Tests No.	**HIC**	**C3ms (g)**	**Ccom(mm)**	**FFCL (kN)**	**FFCR(kN)**	**WIC**
1	178.08	32.278	43.402	0.142	0.129	0.3474
2	205.08	32.044	43.735	0.135	0.116	0.3712
3	220.27	31.571	43.153	0.114	0.095	0.3807
4	231.75	32.051	42.543	0.085	0.075	0.3904
5	200.44	31.320	42.836	0.146	0.122	0.3624
6	187.27	31.989	43.123	0.157	0.136	0.3538
7	289.15	31.257	41.068	0.085	0.099	0.4340
8	276.22	31.929	42.808	0.085	0.110	0.4289
9	188.45	31.302	42.151	0.110	0.094	0.3503
10	188.69	31.382	42.123	0.101	0.081	0.3507
11	188.00	32.032	42.875	0.152	0.134	0.3540
12	205.97	31.447	43.209	0.150	0.127	0.3684
13	208.72	31.348	39.797	0.075	0.085	0.3623
14	216.44	31.47	39.829	0.088	0.088	0.3694
15	232.73	32.651	39.069	0.093	0.100	0.3851
16	213.76	32.46	40.521	0.131	0.115	0.3718

Range method is the most wildly used method for analyzing the results from Orthogonal Test. In this method, each factor that affects the test will be computed to identify its influence, and then the best parameters for such factor will be chosen to achieve a fully optimized combination [11].

Rm is the Rang of factors in Column M, e.g. when specified with different values, the difference between maximum and minimum for each factor.

$$R_m = \max(\overline{K_{m1}}, \overline{K_{m2}}, ..., \overline{K_{mn}}) - \min(\overline{K_{m1}}, \overline{K_{m2}}, ..., \overline{K_{mn}})$$

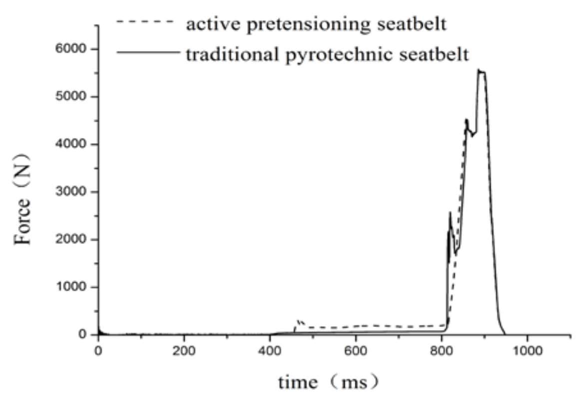
Rm reflects the changes of factors in Column M, e.g. the variation range for the tested factor. The greater Rmis, the more influence this factor will be, in another word, the more important it will be. Thus, the importance of each factor can be identified according to the value of Rm [12-14].

In this thesis, WIC is chosen as the tested factor, Range method is leveraged and the results are gained and shown in Table 6.

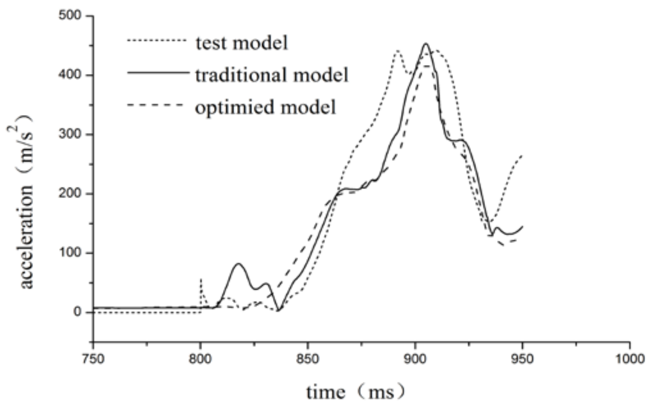
Table 6 Data Processed Results

	A	B	C	Remark
K1	1.4897	1.4224	1.4270	Weighted Injury Criterion (WIC) and Average Value
K2	1.5791	1.4451	1.4871	
K3	1.4234	1.5538	1.5293	
K4	1.4886	1.5595	1.5374	
K1Average	0.3724	0.3556	0.3568	
K2Average	0.3948	0.3613	0.3718	
K3Average	0.3559	0.3885	0.3823	
K4Average	0.3722	0.3899	0.3844	
R (Range)	0.0389	0.0343	0.0276	The Value for Averaged Range
Optimum	3	1	1	

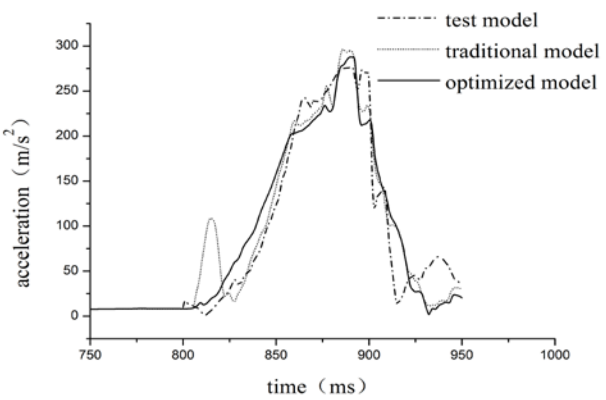
Judging from the results of Range Method shown in Table 7, we can conclude that the best combination is A3B1C1, which was not presented in original simulation. We run a simulating computing for this combination, the optimal indicators for occupant's injury are achieved and the used simulation model is used to simulate the operation of traditional pyrotechnic pretensioner seat belt. The simulated results is compared in Fig 9.



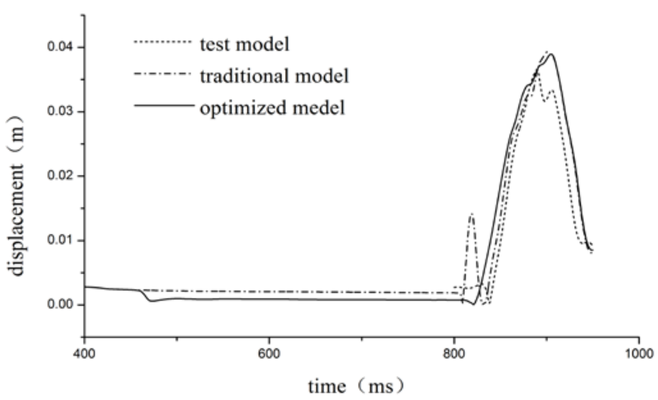
(a) Restraint Force of Shoulder Harness in Seat Belt



(b) Head Acceleration



(c) Chest Acceleration



(d) Chest Deflection

Fig 9. Comparison Curves for Each Indicator

Fig 9 (a) recorded the change of shoulder harness force in two different pretensioning ways. The braking mechanism begins to work at 800ms before the impact; at 350ms before the impact, active pretensioner seat belt begin to work and the force on shoulder harness begins to accumulate and reach to peak value of 200N, providing protections to the driver until the impact happens at 800ms, at that very moment, the force on shoulder harness increases immediately and reaches to about 2000N. Due to the presence of load limiter, which is set to Class I Limitation, both these two pre-tesioning forces are dropped a little at the peak value of 4000N. With the forces on shoulder harness increase to similar peak value of 5500N, they will drop again. Fig 9 (b), (c), and (d) show the comparison of injury indicators in head and chest, we can see that, compared with traditional pretensioner seat belt, the injury indicators for active pretensioner seat belt are lower, meaning this kind of pretensioner seat belt can provide better protection to the occupants; judging from the curves of head acceleration and chest acceleration, the dummy with pretensioner seat belt buckled experienced a shorter accelerating process, which means pretensioner seat belt can provide better protection to the occupants[15].

The optimized model, benchmarking model for vehicle simulation and their comparison to traditional pyrotechnic pretensioner seat belt are shown in Table 7.

Table 7 Comparison of Injury Indicators Pre/Post Optimization

Category	**HIC36**	**HIC15**	**C3ms (g)**	**Ccomp(mm)**	**FFCL(KN)**	**FFCR(KN)**	**WIC**
Standard	≤1000	≤700	≤60	≤76	≤10	≤10	≤1.0
Benchmarking Model for Vehicle Simulation	416.16	193.01	28.17	36.13	0.18	0.16	0.33
Model for Traditional Pyrotechnic Pretensioner	276.67	177.20	30.01	38.89	0.18	0.17	0.32
Model for the Best Active Pretensioner	229.81	144.03	29.24	38.42	0.15	0.13	0.29
Improvement with Optimization Compared to Benchmarking Model	44.78%	25.3%	-3.8%	-6.4%	17.9%	18.5%	10.2%
Improvement with Optimization Compared to Traditional Medel	16.94%	18.7%	2.5%	1.1%	18.3%	24.5%	9.4%

In optimized model, active pretensioner is added and the pretensioning time is shortened compared with traditional pyrotechnic pretensioner, thus the amount of pretensioning, as well, the force of pretensioning are all optimized. From the comparison, we can know that, in the model for the best active pretensioner, WIC decreases 10% in average, providing a better protection for the occupants. Compared to traditional pyrotechnic pretensioner, the head injury criterion HIC36decreases 16.94%; HIC15 decreases 20%; compared to the benchmarking model of vehicle, the HIC decreases more than 25% that we can conclude that, active pretensioner will provide a better protection to occupants' heads.

4. Conclusion

Being verified by the vehicle tests and corresponding simulation computing, the following conclusions can be drawn from the study conducted in this thesis. 1) Compared with seat belt without pretensioner, the dummy with pretensioner seat belt buckled in experienced a softer acceleration process in which the peak acceleration lasts a short time in head and chest, means that the pretensioner seat belt can provide a sound protection to the occupants. 2) Compared with seat belt that employed traditional pretensioner, the active pretensioner seat belt presents a relative lower injury indicators. 3) WIC for the optimized model of active pretensioner seat belt decreases 10% on average means this kind of equipment can improve the protections for the occupants. 4) Compared to traditional pyrotechnic pretensioner, the head injury criterion HIC36 decreases 16.94%; HIC15 decreases 20%; compared to the benchmarking model of vehicle, the HIC decreases more than 25%.

Acknowledgments

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