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Avoiding Sub-optimized Occupant Safety by Multiple Speed Impact Testing

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Abstract

Car manufacturers carrying out crash tests at only one speed and with only one occupant size run the risk of sub-optimizing their safety systems. This is discussed occasionally, but often in such all-embracing terms that a car designer is often left without any advice as to how the sub-optimization can be reduced.

This risk will be illustrated through an assumed case. An existing belt system is compared with some new, hypothetical designs. Depending on which test strategy is chosen, the safety properties of one of the new designs can be found to be either better, or worse, than the existing system. This shows that the consequences of an inadequate test strategy for new safety systems can be, that instead of achieving a reduction in injuries, the result might be an increase in the number of injuries out in the real traffic environment.

The illustration is done using a method whereby accident injury statistics can be correlated with dummy responses from crash tests in the laboratory and with dummy responses in the MADYMO Simulation Program.

Different collision speeds and variations in occupant size should therefore be considered when test strategies for occupant protection systems are defined. Also, legislators and consumers should pay more attention to safety performance in different circumstances.

Introduction

The purpose of this paper is:

1 - To show how a limited test strategy and some unfortunate characteristics of a belt system might lead to sub-optimization of the occupant protection system.

2 - To introduce a new tool which permits us to demonstrate the risk of sub-optimization. By using this tool it is also possible to optimize protection systems. The result will then be a minimizing of the expected total injuries over a wide spectrum of traffic speeds and occupant sizes.

3 - To spread knowledge about the importance of a well-optimized crash protection system for a whole range of crash speeds.

Background

There exists an opinion that the performance requirements in the motor vehicle standards will imply a threshold between the level of no injuries and the level where a certain injury or fatality may occur, regardless of occupant size, age and general physical condition. This is truly not the case.

If, for example, the standards require that vehicles comply with certain performance requirements for any speeds up to 30 mph, this should imply that the vehicle should give full protection for its occupants up to that particular speed. Using this logic, by requiring the vehicles to comply with the same performance requirements for a higher test speed, the protection of the occupants would be improved. However, the performance requirements in the standards only indicate a certain probability of an occupant escaping injury during a crash.

Over the years, several authors have pointed out that impact tests carried out at only one speed run the risk of leading to sub-optimization. Many interesting contributions have been made, of which Horsch's (1)[1] and Korner's (2) are two of the most detailed studies to have been carried out in recent times.

This paper continues the discussion by showing that there exists a risk of sub-optimizing safety systems if the crash performance of the vehicles is optimized towards a single high crash speed and a single occupant size.

The risk becomes higher the more the test speed is raised. This is due to the fact that the vast majority of crashes occur at an impact speed that is lower than the maximum speed in the safety standards, e.g. 30 mph in FMVSS 208.

The problem becomes even more emphasized when considering the rating programs performed by government agencies, consumer organizations and the media. These ratings are normally carried out using only one test speed that is higher than the speed in the safety standards. The test results from the ratings have received extensive attention from the media and from the car-buying public.

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[1] Numbers in parenthesis refer to literature listed at the end of the paper.

A good rating result is normally perceived as being an indication of a well-performing and well-optimized occupant protection system, considering ALL crash speeds, occupant sizes, etc, up to and including the speed used in the rating. Although this may be the case, this paper shows that the rating results may be deceiving if an occupant protection system of a car that has performed well in a rating test is optimized towards only ONE impact speed and ONE occupant size.

However, few test methods have been developed and carried out at lower speeds. Do the companies and organizations concerned believe, perhaps, that these accident situations are taken care of by a demonstrated protection at high speeds?

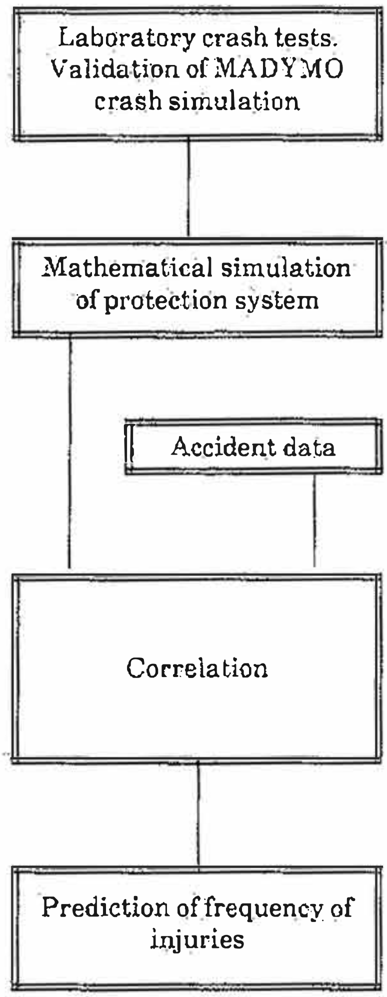
In Volvo's opinion this is unsatisfactory. Through several years of following up accidents (3) we have revealed a picture of a large quantity of personal injuries at crash speeds way below the test speeds which are often used. The normal tests do not give enough indication of the risk of injury and the protection effects at the speeds at which the majority of injury-producing accidents occur.

There is, admittedly, a technical international discussion regarding safety at other speeds than those prescribed in the authorities' test methods. However, the conclusions from the debate have primarily been indicative, and without sufficient substance for the development of practical design tools for our car design engineers.

That is in contrast to this paper, where we demonstrate a case of sub-optimization risk with the aid of a helpful tool - the Injury Prediction Model.

THE INJURY PREDICTION MODEL

The Model has been developed over several years at Volvo (2, 4). Comments on the development will follow in the section of the paper entitled Discussions and Conclusions. Fig. 1 shows the different stages of the Model. Each stage will be described in detail in the following sections. The description will use some of the data from the sub-optimization case.



Baseline data is taken from laboratory tests with a known car model and a known occupant protection system. Dummy responses and the performance data from the protection systems in the car are used to validate the MADYMO model.

Simulated crash tests are performed in the MADYMO model for the selected protection system.

Volvo's database provides injury data for car occupants with relevance to the selected accident scenarios and car models.

For the baseline system, a correlation is established between:

1) the dummy responses from the simulations, and
2) the occupant injury risk from the accident injury material.

With the correlation known, an injury frequency can be predicted for a proposed new protection system, provided that laboratory data is available for the new system.

Figure 1. The Injury Prediction Model and its Stages.

Laboratory Crash Tests and Validation of MADYMO Crash Simulation

Crash tests in the form of full-scale impact tests and Hyge sled tests were run in the laboratory in order to achieve the required input data to validate the simulation model. A large quantity of data was recorded and used for the validation. For this paper, we will only make use of the dummy protection responses, in other words HIC36[2] and Cr[3].

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[2] i.e. HIC with 36 ms limit (5)

[3] i.e. the resultant chest acceleration

In order to connect the laboratory tests with the greatest possible amount of data from real crashes in the field, the Volvo model 240, European version, was chosen for the crash tests.

Four cars were crashed, in frontal collisions against a fixed barrier. The crashed cars were equipped with three-point retractor belts, and were as identical as possible in all other aspects. Two 50 percentile Hybrid III (Part 572E) dummies were placed in the cars according to FMVSS 208, in the driver's and passenger's positions. The crash speeds chosen were: 15, 25, 35 and 40 mph.

Using our knowledge from other tests with 240 cars, it was considered that the measurement results now obtained were representative and could be used as a basis for our conclusions in this study.

In addition to the full-scale tests, two Hyge sled test series were run to further study the movement of the dummy and protection criteria during a crash. These were carried out with 50 percentile and 5 percentile Hybrid III dummies. The tests were only run at two crash speeds, 25 and 35 mph, but in general with the same conditions as in the full-scale tests, i.e. the same vehicle type, crash pulse, belts, etc. Some of the tests were run with the dashboard and steering wheel fitted in the body shell. In the tests, those parts were placed in the most rearward position they assumed during the corresponding full-scale tests.

The compatibility between the full-scale tests and the sled tests is judged as being very good.

Validation of MADYMO Crash Simulation A MADYMO model (6) of the crashing Volvo 240 car and its restrained occupants was set up. Three different occupant sizes were modelled.

* M50, the male 50th percentile Hybrid III dummy. Data according to (7) was used.

* F5, the female 5th percentile Hybrid III dummy. Data was based partly on a scaling of the M50 dummy, and partly on data obtained by measurements on one of Volvo's dummies. C.f. Fig. 2.

* M95, the male 95th percentile Hybrid III dummy. Data was based on a scaling of the M50 dummy.

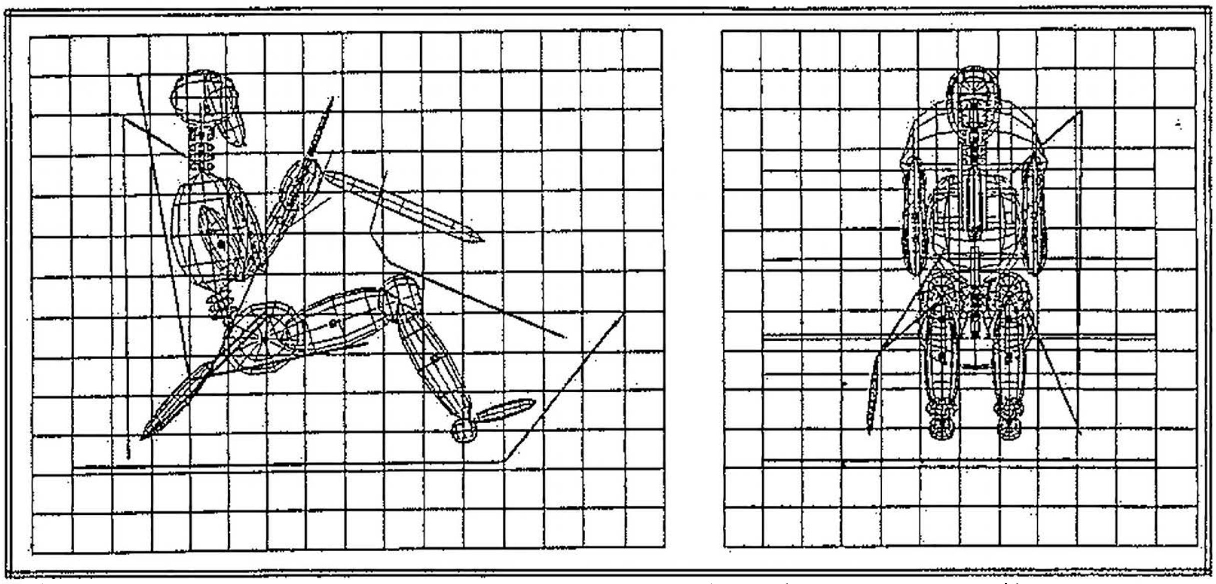

Figure. 2. The MADYMO 3D model of the female 5th percentile Hybrid III dummy in the driver position of a Volvo model 240.

The MADYMO model was validated against the crash and sled tests. Fig. 3 shows an example of the correlation between two dummy response signals recorded in one of the laboratory crashes at 35 mph and MADYMOs simulation of the same crash.

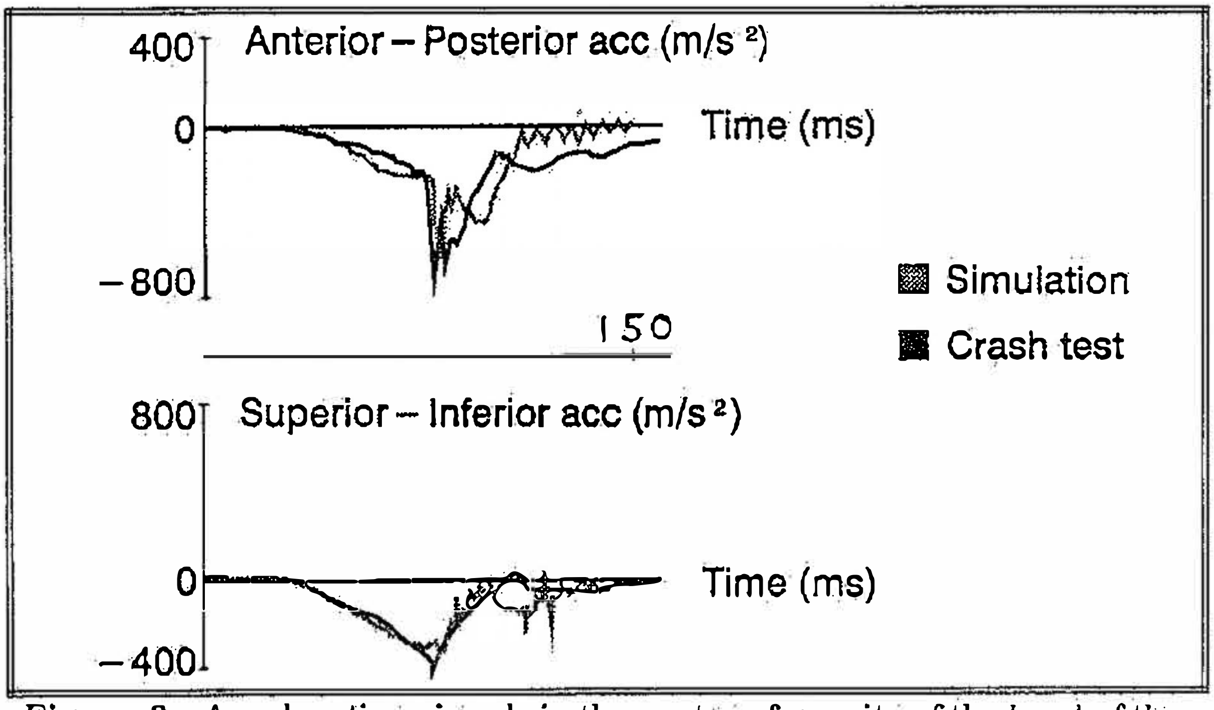

Figure. 3. Acceleration signals in the centre of gravity of the head of the 5th percentile dummy during crash tests.

Mathematical Simulation of Protection System

Several crash tests were then performed in the MADYMO model for the baseline belt system. In this case the simulated tests were made at crash speeds of 15, 25, 25 and 40 mph and with the three occupant sizes. The output was 24 groups of dummy responses: three dummy sizes, four crash speeds and two front seat positions.

Accident data

From the statistical material on accidents - 2547 frontal collisions with Volvo 240 cars where the driver and front seat passenger used a seat belt - we obtain the statistical distribution of crash severity (i.e. crash speed) and occupant height and information regarding the range of injuries for these occupants. An injury risk (8, 9) can be calculated from the material for each crash speed, position in the car and passenger size for every relevant body part and injury type. For our purpose here, we chose the level AIS2+ as the threshold between non-significant and significant injuries. If, instead, the analysis is done for AIS3+ or AIS4+, very similar results are obtained.

Correlation

The next stage in the Injury Prediction Model is to establish a correlation between the accident injury data and the dummy response numbers from the MADYMO simulations. Such a correlation is valid under conditions which Korner (2) has formulated: "Provided that the crash mode of the laboratory tests is equivalent to the real life accident type, and that a valid crash severity parameter is used, and that the protection criterion is a valid measure of injury production, then this correlation is generally applicable".

The correlation is determined with the aid of the SAS statistical software (10). The dummies' protection criteria from the MADYMO simulations are correlated with the injury risk from the accident material. All the occupant sizes and crash speeds are included in the correlation. The correlation implies, for example, that a certain HIC36 value in laboratory crashes is related to a certain head injury risk in a corresponding crash situation in traffic.

Prediction of Frequency of Injuries

The final stage in the Injury Prediction Model is then to determine an injury risk. With the known correlation between laboratory data and injury risk, an injury frequency can be predicted for a proposed new protection system, provided that crash test performance in some form is available for the new system.

The procedure is to multiply the statistically established joint distribution of accident crash speeds and occupant sizes by the injury risks from the simulated crash data. The result will be a predicted total injury frequency for the proposed protective system.

STUDY OF POSSIBLE SUB-OPTIMIZATION

Choice of Belt Systems

For our study of the sub-optimization we need to select some alternative variants of belt systems. The variants shall, taking into consideration that we are working with a demonstration example, have properties that are clearly different from the base system.

In order to find "good" variations of the belt system's technical design, a sensitivity analysis on the baseline belt system was carried out in the MADYMO model. Five system parameters were varied, namely the stiffness of the belt itself, mechanical features such as pre-tensioner and force limiter, different belt feeds using slack or belt locking. Two other parameters, the softness of the seat cushion and the car crash pulse, were also varied. Customary dummy responses in the computer-simulated crashes were determined for the driver as well as the passenger. A factorial design of experiments (11, 12) was utilised in order to systematically combine and vary the seven parameters without requiring too much work.

As a result of the sensitivity study, and taking into account the purpose of our investigation, three belt systems were chosen for further study.

* The first system, designated **STD**, is the baseline system. It corresponds to the standard three-point belt system in the Volvo 240, with belt elongation of 10%[4]. This was the system used in the laboratory crash tests.

* The second system, designated **FLM** (for Force Limiter), has a 4% belt elongation and 8 kN force limiter. This combination should, according to the sensitivity study, give good performance at crash speeds of around 35 mph.

* The third system, designated **PRT** (for Pretensioner), is a standard belt with 10% elongation, but modified by the addition of a pyrotechnical pretensioner. This combination should, according to the sensitivity study, give good performance for a wide spectrum of crash speeds.

[4] The elongation is determined at 10kN tensile force.

Study of Chosen Belt Systems

Simulated crash tests were performed in the MADYMO model for the two newly defined systems. The test parameters were the same as for the baseline system. The output was 48 groups of dummy responses: three dummy sizes, four crash speeds, two front seat positions and two belt systems. See Tables 1 and 2.

Table 1
Passenger Dummy Response Data for the Simulated Crashes with the Three Belt Systems

		Cr m/s^2			HIC_{36} $sg^{2.5}$		
Speed mph	Dummy size	STD	PPT	FLM	STD	PPT	FLM
15	M50	266	213	317	65	80	86
15	F5	255	172	240	98	76	100
15	M95	168	154	185	26	41	14
25	M50	299	246	355	116	146	159
25	F5	252	208	239	186	144	168
25	M95	221	189	238	320	96	213
35	M50	540	402	405	1159	377	369
35	F5	303	299	337	397	269	375
35	M95	347	304	328	912	733	859
40	M50	555	596	553	1817	1452	1727
40	F5	421	379	385	680	440	614
40	M95	440	358	406	1969	1264	1510

Table 2
Driver Dummy Response Data for the Simulated Crashes with the Three Belt Systems

Speed mph	Dummy size	Cr m/s² STD	Cr m/s² PPT	Cr m/s² FLM	HIC_{36} $sg^{2.5}$ STD	HIC_{36} $sg^{2.5}$ PPT	HIC_{36} $sg^{2.5}$ FLM
15	M50	265	213	317	151	118	151
15	F5	261	182	250	101	77	102
15	M95	168	154	186	72	67	53
25	M50	299	246	355	396	328	396
25	F5	276	217	257	295	164	252
25	M95	191	191	239	176	225	165
35	M50	441	471	442	692	679	563
35	F5	341	307	327	318	280	362
35	M95	376	378	378	1031	783	918
40	M50	573	583	528	1890	928	1383
40	F5	487	445	452	824	440	914
40	M95	424	400	419	1622	1400	1508

Some of the tabulated results from the simulations at 35 mph are presented in the bar chart in Fig. 4.

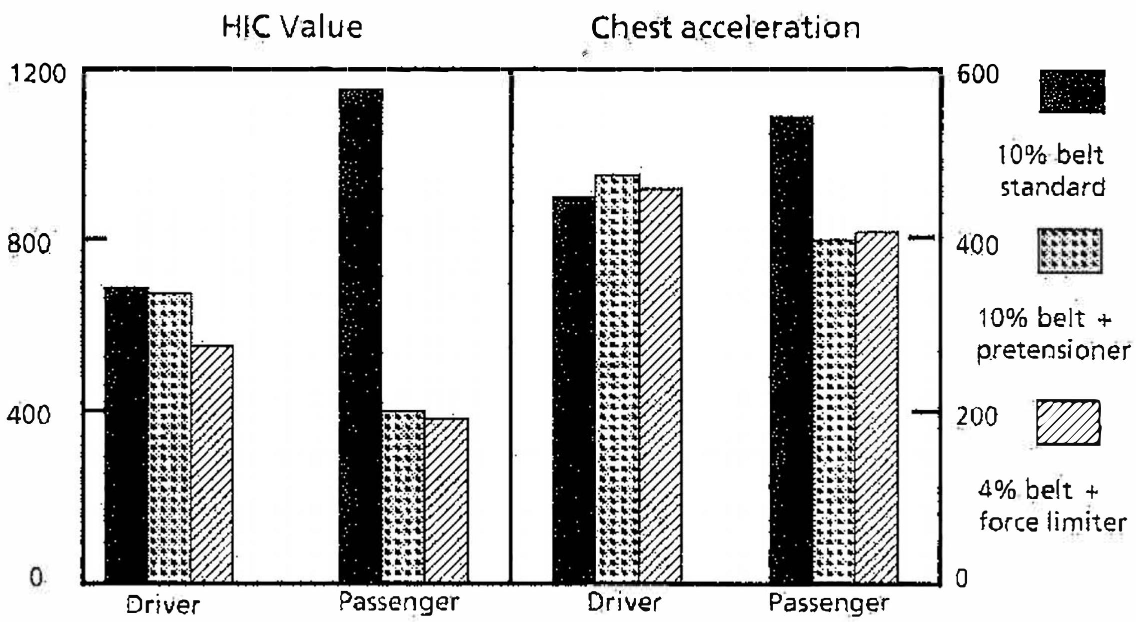

Figure 4. Simulated crash test results. HIC36 values and chest acceleration for analysed belt systems, 50th percentile dummy, driver and front seat passenger, 35 mph.

Looking at the driver's HIC36 values in Fig.4, we can see that there has been a reduction for the **PRT** and **FLM** systems compared with the **STD** system.

For the passenger, the **STD** version's HIC36 value is high (due to an adverse impact against the dashboard) whilst the two alternative belt systems have considerably reduced HIC36 values. With regards to the chest acceleration for the driver, the change from the base version is marginal (slight increase), whilst we can see a clear improvement in the values for the passenger.

Analysis of Performance at 35 mph. The conventional evaluation of a safety system is a single crash test and analysis of the performance at the legally prescribed 30 mph. Some presume that meeting the requirement at an increased crash speed implies an increased occupant protection. Such an evaluation of the data from the three simulated belt systems is possible from Fig. 4. It indicates that both the pretensioner **PRT** and the stiff belt **FLM** could contribute towards an increased level of safety. If we had to choose between these two systems, the **FLM** alternative has slightly lower dummy responses throughout.

The **FLM** system is probably also, from a technical point of view, a simpler design solution. These factors can be arguments for choosing the **FLM** system before the **PRT** system.

Analysis of Injury Outcome. As an alternative to the conventional test at 35 mph we can, thanks to the Injury Prediction Model, evaluate the belt systems in terms of predicted injuries in accidents. Using the correlation between dummy response numbers and injury risk for the baseline **STD** belt system, the dummy responses for the alternative belt systems **FLM** and **PRT** can likewise be translated to injury risk for these systems. The result is a predicted total injury frequency for each of the alternative belt systems. This is presented in the bar chart in Fig. 5.

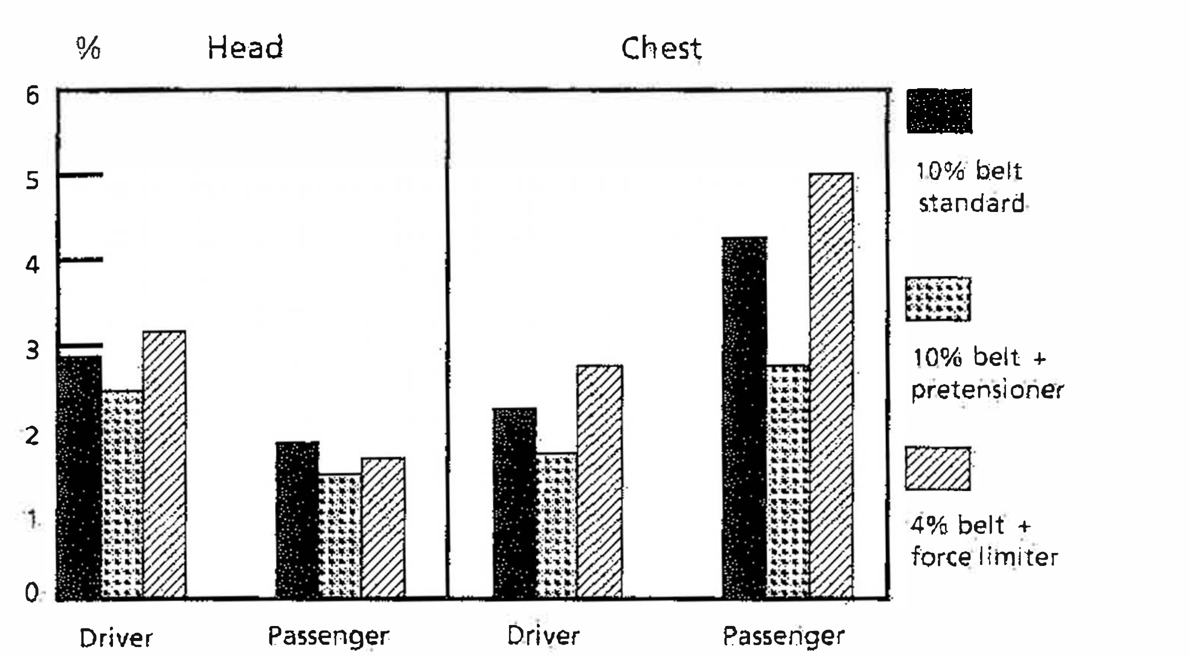

Figure 5. Predicted head and chest injury frequencies for standard and modified belt systems, driver and front seat passenger, all speeds, all occupant heights.

We can see from Fig 5 that the alternative pretensioner PRT has a lower injury frequency in relation to the base version STD for both head and chest injuries (AIS 2+) for the driver and front seat passenger. The stiff belt FLM alternative, however, has resulted (except for the passenger's head injury frequency) in an increase in the risk of injury. The alternative which, from the simulated crash test results involving a 50 percentile dummy at 35 mph, appeared to be the best solution, has, when we take into consideration the distribution of crash severity and occupant height, a much higher injury frequency for head and chest than the base version STD and the pretensioner alternative PRT.

The relative increase and reduction of the injury frequency for the two alternative belt systems is evident from Fig. 6.

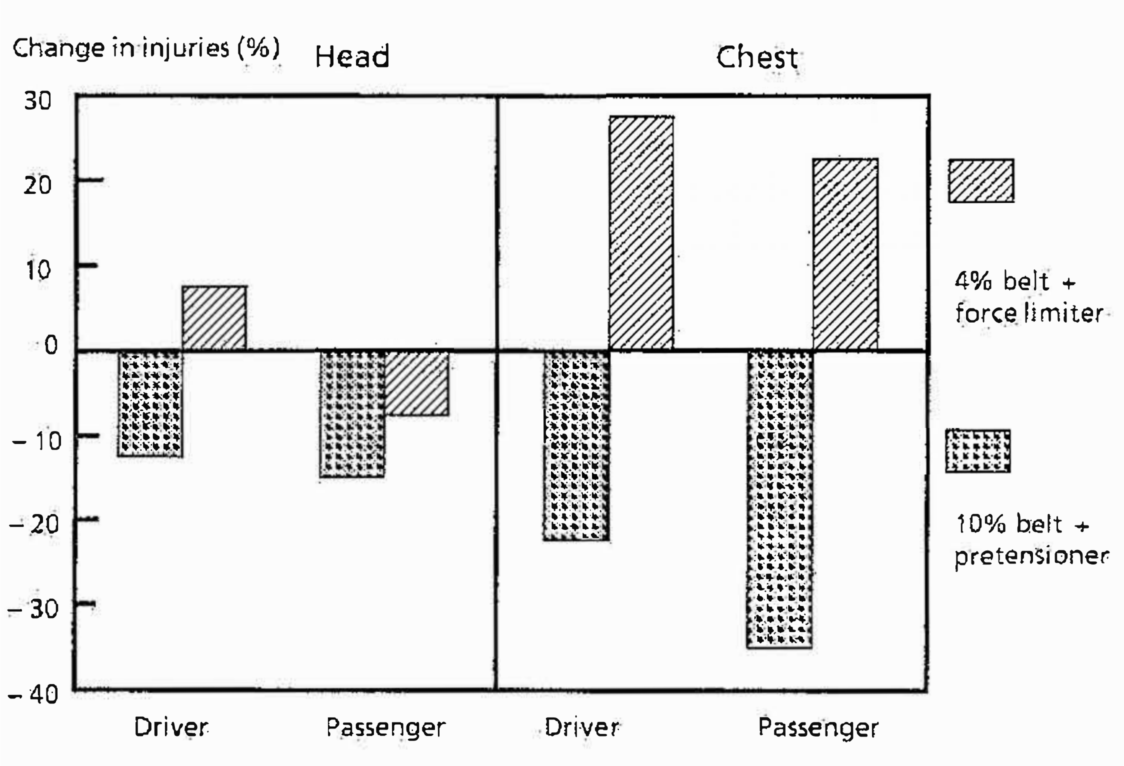

Figure 6. Percent changes in predicted head and chest injuries between the STD belt system and the alternative systems.

Compared with the **STD** belt,we can see that the **PRT** reduces the head injuries by approximately 12% for the driver and 14% for the front seat passenger. Corresponding reductions for the chest injuries are approximately 22% and 36% respectively.

For the alternative **FLM** versus **STD**, however, we can see an increase in the head injuries for the driver of approximately 8% and for the passenger there is a reduction of 8%. Regarding the risk of chest injuries, there is a marked increase for both the driver and front seat passenger of 26% and 23% respectively.

<u>Tests at One Speed versus Tests in Several Scenarios.</u> It can be seen clearly from the above analyses that a test strategy confined to laboratory testing at the standardized 35 mph will give quite a different picture of the relative merits of the three belt systems than that obtained from tests performed at several speeds and with several occupant sizes. This fact should affect future test strategies for occupant protection systems.

DISCUSSIONS AND CONCLUSIONS

Optimized performance

We have shown that tests carried out at only one speed mean a risk of sub-optimizing the car's safety properties. Fig. 7 shows clearly that a system (FLM) can be designed which has good performance at high speeds, but not at low speeds. It is also evident that it is possible to design a system (PRT) which produces improvements within a large range of speeds. Corresponding effects can be achieved for all occupant heights.

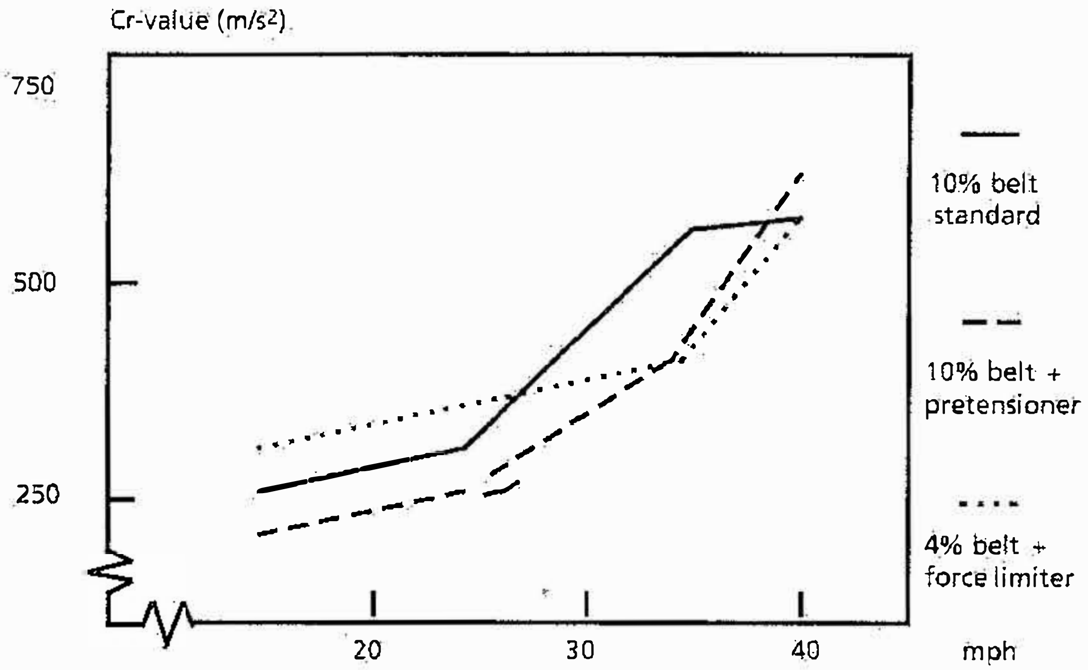

Figure 7. Chest acceleration as a function of crash speed for the three different systems, 50th percentile passenger dummy.

If crash safety properties at several speeds are not taken into consideration during development work, there is a risk of investing large resources into incorrect measures, and instead of achieving a reduction in injuries, the result is an increase in the number of injuries out in the real traffic environment.

Using the method described in this paper it is, however, possible to study the effect of future design and legislative proposals, through which it is possible to concentrate on correct measures at an early stage.

With an accuracy which up until now has not been possible, our example shows the magnitude of the sub-optimization which crash tests at only one speed can lead to.

There are, admittedly, several approximations and uncertainties in the data and the models used. However, many of these errors are probably of a systematic nature. So if, for instance, the calculated chest injury frequencies in Fig. 5 have a systematic error making them 20% too high, the difference between the calculated injury frequencies should to a large extent be free from such errors. And it is the differences, which are plotted in Fig. 6, that we use for judging the relative merits of the three analyzed belt systems.

Other shortcomings and errors in the models and the data are more difficult to determine. As described in the next section, work is underway to improve the quality in these areas.

Even if it is difficult today to give an accurate assessment of the magnitude of the errors involved, an engineer's reflection on Fig. 7 leads to a conviction that there are actual differences between the belt systems. The relationship between their performance data is presumably a reality which has consequences for car manufacturers as well as for motorists.

Development of the model

The Injury Prediction Model has now become a tool at Volvo in the evaluation and design of new occupant protection systems.

The method is also applicable for comparison of more different types of protection systems, e.g. airbag versus belt. It can also be applied for different types of accidents, e.g. side collisions and rear end collisions. Design parameters which can then be analyzed are, for example, the stiffness of the padding and the structure.

It is therefore important that corresponding methods are developed for other types of accidents, e.g. side collisions (2), and that the way of thinking becomes generally used by car manufacturers and legislators.

The method's usability means that there is a need for better computer programs for the simulation of accidents.

More accurate accident data needs to be collected, e.g. better parameters for crash severity and injury mechanisms should be developed and put into use.

It could also be of great value to simplify the described method so that a rough estimate of the injury reduction for a given design proposal is obtained quickly by using a relatively simple mathematical expression. This assumes that the system's performance at various speeds is known. This can be very useful, for example, for manufacturers who do not have access to their own databases regarding speed and occupant size distribution, etc. Here, the authorities can play a crucial role by developing the neccessary basic information and spreading the acquired knowledge.

When discussing laboratory tests for new safety systems, the MADYMO simulations and the Injury Prediction Model are also helpful aids in the selection of test parameters and testing matrixes. They also form a complement to crash tests which cannot be performed in the laboratory for capacity reasons.

For the readers to consider

There is a tendency to consider any opposition from the automotive industry to high crash speeds in the safety standards and safety ratings as an unwillingness to cooperate towards improving traffic safety. This is generally not true. It is in the interests of all parties that the level of occupant safety is raised. That must be a top priority.

Volvo is deeply committed to safety. We therefore feel under obligation to optimize the occupant protection systems in our cars towards real world crashes and their effect on occupants. For this reason, we perform crash tests at a range of speeds in order to find the optimum safety design properties of the vehicles. Publicity-wise, this attitude may not be very rewarding, since it will not necessarily give the best results in rating tests. But it is what we believe in.

The purpose of this paper is to spread the knowledge about the importance of a well-optimized crash protection system for the whole range of crash speeds. We urge the readers to consider the facts presented in this paper in future discussions about crash ratings, safety standards, etc.

ACKNOWLEDGEMENTS

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