CONTINUOUS RESTRAINT CONTROL SYSTEMS: SAFETY IMPROVEMENT FOR VARIOUS OCCUPANTS

Ewout van der Laan
Bram de Jager
Frans Veldpaus
Maarten Steinbuch
Technische Universiteit Eindhoven
Ellen van Nunen
Dehlia Willemsen
TNO Integrated Safety, Helmond
The Netherlands
Paper Number 09-0044

ABSTRACT

Occupant safety can be significantly improved by continuous restraint control systems. These restraint systems adjust their configuration during the impact according to the actual operating conditions, such as occupant size, weight, occupant position, belt usage and crash severity. In this study, the potential of a controlled restraint system is demonstrated. First, an overview is given of the problems concerning the sensors, actuators and control strategy of such a system, and solutions are given. Next, a numerical demonstrator is developed, which includes a dummy and vehicle model, and a realistic implementation of the components of the controlled restraint system. The demonstrator is subjected to different loading conditions, and the results are compared to a reference model. This reference model contains a conventional restraint system with optimized settings, and it has been validated against sled test experiments. Simulation results with the demonstrator indicate that significant injury reduction can be achieved with continuous restraint control systems.

INTRODUCTION

In high-speed vehicle crashes, the occupant is subjected to high forces, typically resulting in severe injuries. The forces depend on the actual loading condition, which reflects the severity and complexity of the impact, and the occupant's size, weight, behavior and posture. The seat belt and airbags, referred to as the restraint systems, are designed to reduce these forces. For the most effective reduction, the settings of the restraint systems should be geared towards the loading condition. Current restraint systems, however, have typically one level of operation, and this level is a compromise between several loading conditions. It implies that the benefits of current restraint systems may not be fully exploited (Holding et al., 2001). This fundamental shortcoming of current safety systems makes that not every vehicle occupant will be optimally protected under all possible conditions.

Nowadays, an increasing number of sensors and electronics is being integrated in vehicles, and this allows the use of advanced safety systems with adjustable components. An example is the adaptive restraint system, which can adjust its configuration during the crash, but typically only once. A large number of studies on adaptive passive safety focuses on the adjustment of the tension in the safety belt. Adaptive belt forces lower thoracic injury especially for occupants or collisions that deviate from the average (Iyota et al., 2003; Adomeit et al., 1997). For example, the dual-stage load limiter can significantly improve thoracic injury mitigation (Miller et al., 1996; Paulitz et al., 2006; Mertz et al., 1995; Clute et al., 2001).

Compared to adaptive restraint systems, a near optimal protection can be delivered when the seat belt force can be continuously adapted during impact. In two similar studies, by Crandall et al. in 2000 and by Kent et al. in 2007, a time-varying belt force is applied in open-loop. The optimal input is found through optimization using an elementary chest model. More robust solutions are presented in Habib et al., 2001; Cooper et al., 2004; Hesseling et al., 2006; van der Laan et al., 2009, where the belt force is applied in a feedback configuration, and optimal values are obtained by solving a control problem. These types of systems, in which restraint settings can be continuously adapted during the crash, are referred to as *Continuous Restraint Control (CRC)* systems. CRC systems will be the main focus of future restraint system development, and this paper contributes to the development.

Objective and Contributions

The aim of this paper is to demonstrate the potential of CRC systems to mitigate injuries in frontal impacts. This is achieved with a *numerical demonstrator*, which is a simulation model of an occupant, vehicle interior and a CRC system, subjected to various loading conditions. The outcome of the numerical demonstrator is compared with the results of a validated *reference model,* consisting of a conventional restraint system, albeit with optimized settings.

Previous studies have already shown the evident benefit of CRC systems (Hesseling et al., 2006; Shin et al., 2007; and references therein), but an idealized implementation of the system was assumed in those studies. In this study, the properties and limitations of the various components of the CRC system are shortly discussed, and their limitations and properties are explicitly incorporated in the numerical demonstrator. This leads to a model that closely resembles a CRC system that could be implemented in future vehicles.

The CRC system proposed in this paper controls the seat belt force to lower thoracic and head injury criteria, based on measurements of the vehicle and the occupant. In this study, the airbag settings are not adapted to the loading condition, as control of the belt force makes the forward movement of the occupant more predictable, which in turn may already improve the airbag performance.

This paper is structured as follows. In Section 2, a set of frontal MADYMO dummy models with a conventional restraint system is developed, and validated against experimental data from sled tests. Subsequently, the restraint settings are tuned to obtain a reference model that achieves optimal injury reduction with non-adaptive or fixed restraint systems. In Section 3, the four components of the proposed CRC system are shortly discussed. This includes (i) the control strategy, (ii) the state estimator, since sensors to directly measure injury related occupant responses are not available, (iii) a simple, low-order occupant model to be used in the controller and estimator, and (iv) the design and construction of the belt force actuator. The properties of these components are used in Section 4 to develop the numerical demonstrator. The result in injury criteria achieved by the conventional and the controlled restraint system are compared and evaluated for several loading conditions. Finally, in Section 5 conclusions and outlook are presented.

REFERENCE MODEL

In this section, the vehicle and occupant model will be described. It is developed in MADYMO (TNO, 2005), and it forms the baseline model in this study. It serves two purposes. Firstly, it is used as a reference model with conventional restraints. To show that this reference model has sufficient resemblance to the real world, it is validated against results from sled test experiments. Secondly, the baseline model is used in the numerical demonstrator, now with the CRC system, to demonstrate the benefit of the CRC system.

Validation

Several car models are developed representing averages of classes of cars during the European PRISM project (Bosch-Rekveldt et. al., 2005). This approximation of an "average" car consists of a multi-body belt, compartment model and hybrid III dummy model. The belt characteristics are obtained from an experimental test. This MADYMO model is validated against sled test experiments, performed at TNO, the Netherlands. The geometrical aspects (like distance to steering wheel) are adjusted so they coincided with the geometry of the car on the sled. Since the belt rollout will be used to estimate several dummy responses, a belt rollout sensor is added to the standard test setup. Additionally, belt forces are measured at three different locations (between shoulder and D-ring, between hip and buckle, and between hip and attachment point). The belt forces are used to estimate friction coefficients in the buckle and D-ring, which can then be implemented in the friction models.

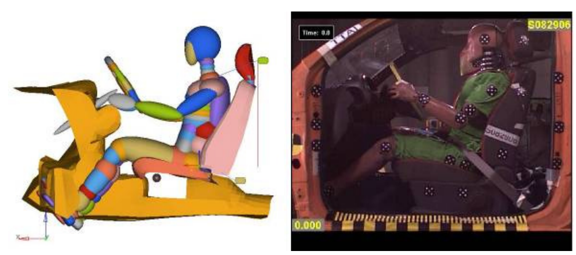

Figure 1. MADYMO simulation model (left) versus experimental setup (right).

The experimental sled test is based on a supermini car as shown in Figure 1. The acceleration pulse (in longitudinal direction) is shown in Figure 2. The experimental sled test does not include an airbag, since this reduces the number of unknown parameters like airbag frictions, flow rate, vent size, and volume. Of course, future research should include the airbag in the validation, since it is part of the baseline restraint configuration in today's consumer vehicles.

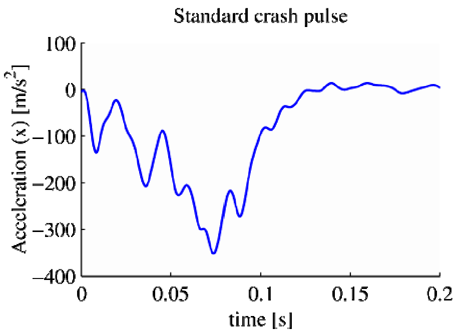

Figure 2. Vehicle acceleration (x) pulse used in the sled test (referred to as the standard pulse).

The following injury responses are obtained from the sled test dummy and from the simulations:

1. head acceleration in longitudinal (x) direction,
2. chest acceleration in longitudinal (x) direction,
3. chest deflection,
4. neck force in z direction (vertical compression),
5. neck torque in y direction (flexion/extension),
6. pelvis acceleration in longitudinal (x) direction.

The results of the validation are shown in Figure 3.

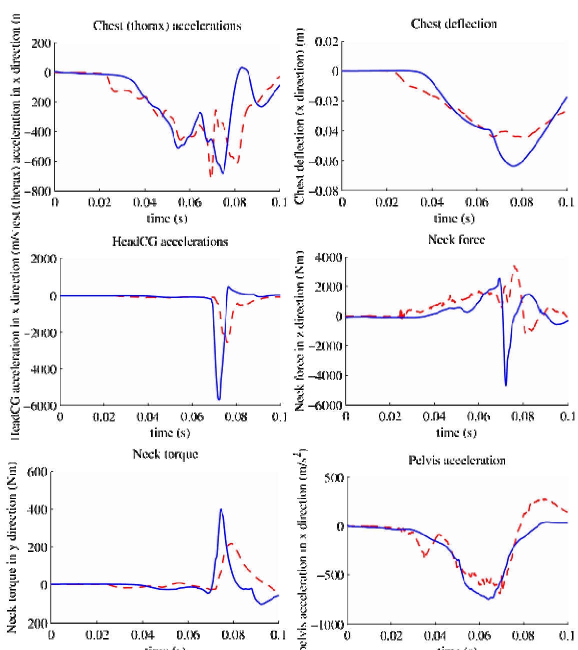

Figure 3. Injury responses MADYMO average car model simulation (blue solid line) versus sled test (red dotted line).

An objective rating is used, which is based on the weighted integrated factor method (WIF), global peak value (GPV), global peak time (GPT), and difference in area under curve (DUC) of these responses, see Twisk et al, 2007. The conclusion is that on average the derived MADYMO model mimics the sled test phenomena sufficiently, at least for the considered responses, as shown in Figure 3. When the neck injuries are not included in the simulation, the results are more accurate, as shown in Figure 4. The belt forces and rollout fit the measurement very accurate. The model can be further improved when the characteristics of the steering wheel, seat model and dashboard are known more precisely.

Avg score = 72.4983%	Avg score = 76.8499%
WIF = 40.7574 %	WIF = 52.3322 %
GPV = 71.0881 %	GPV = 75.0178 %
GPT = 92.984 %	GPT = 92.2278 %
DUC = 85.1635 %	DUC = 87.8219 %

Figure 4. Average score for relevant injury parameters (left) and average score for relevant injury parameters without neck parameters (right).

Optimization

The validated model is now used as a reference model in the comparison with the CRC system. It contains a pretensioner and load limiter for the belt system, and a conventional airbag is added to the model. To make a useful comparison, the reference model should mitigate injuries maximally. Therefore, the following three restraint parameters are optimized:

1. scaling of the airbag flow rate,
2. airbag timing,
3. load limiter value.

The optimization is based on a minimal total injury parameter. This total injury parameter is defined as a weighted sum of all relevant injury parameters. The 50th Hybrid III model, seated in the position as used for the sled test (according to EURONCAP norms) is used for this optimization. A full factorial optimization is done, using three different values for each parameter.

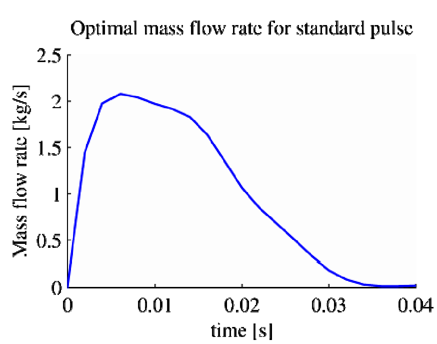

Figure 5. Optimal mass flow rate.

The airbag flow rate is found to be optimal when no additional scaling was applied with respect to the original flow rate, which is shown in Figure 5. The optimal airbag timing for the standard pulse is 25 ms and the optimal load limiter value is found to be 4.5 kN.

COMPONENTS OF THE CONTINUOUS RESTRAINT CONTROL SYSTEM

In the previous section, a MADYMO model for the 50th percentile HIII dummy was developed and validated with experimental data from a sled test. The objective of this paper was previously formulated as to demonstrate the potential of realistic CRC systems, which aim at reducing neck and thoracic injuries of this numerical dummy model by control of the seat belt force. In this section, the components of this CRC are discussed.

1. Semi-active belt force actuator in an experimental setup

The requirements for a restraint actuator that can effectively be used in a controlled seat belt system are very challenging. Numerical simulations performed previously, (van der Laan et. al, 2009), indicated that peak belt forces of 7-10 kN are required for optimal injury reduction. The bandwidth of the local control system of the actuator has to be around 300 Hz. Finally, the dimensions of the actuator are limited, as it ultimately has to be fitted in a vehicle's B-style. Up until today, no devices exist that can deliver these high belt forces during a crash, and can actually be used in a commercial vehicle.

This has led to the decision to design and develop such an actuator at the Eindhoven University of Technology. The concept of the actuator is based on a semi-active hydraulic damper, where semi-active refers to the fact that the velocity and force vectors have opposite directions, so the actuator does not have to deliver energy to the system. Due to the desired forces and displacements, fully active systems would require a large amount of energy storage. , which is for non-chemical sources difficult to realize in commercial vehicles.

The hydraulic damper consists of a custom-made cylinder, piston and valve. The belt is attached to the piston, and the cylinder is mounted to the vehicle. During frontal impact, the relative forward movement of the occupant makes the piston to extent from the cylinder, thereby inducing flow through the valve. By restricting the valve orifice, the cylinder pressure and hence the belt force increases.

The valve design is fundamentally different from most conventional hydraulic servo-valves. The latter have typically too low a bandwidth for this application. In conventional servo-valves, the motion of the spool valve is perpendicular to the hydraulic pressure, such that the force needed to close the valve does not have to counteract the (large) hydraulic force. The valve developed in this study is deliberately designed to counteract this force.

The advantage is that the force needed to prevent the spool body from accelerating equals the force from the hydraulic pressure. If these forces are not equal, the spool body starts to move, thereby changing the restriction, until there is a force balance. Hence, the nonlinear relations for flow through an orifice do not play a part in the control law, which is advantageous from a control point of view. The constructed valve is shown in the left part of Figure 6. Fluid from the cylinder enters the valve through the opening on top, and it is led to a container via the tubes on the side. The hydraulic cylinder with the valve is shown on the right side.

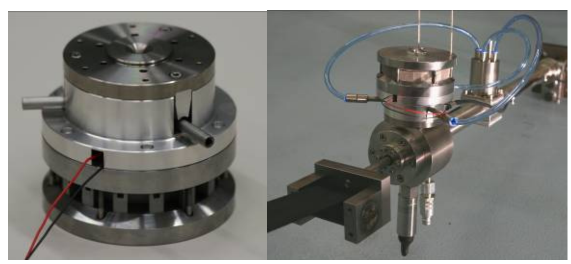

Figure 6. The hydraulic valve (left) of the semi-active hydraulic damper (right), which is used to control belt forces during the crash. The device is developed at the Eindhoven University of Technology.

The belt actuator is tested in the sled setup, which shown in Figure 7. The sled is accelerated up till 10 m/s, and it impacts then against a deformable crumple bar (not shown). During this impact, the actuator is used to control the acceleration of a sliding mass of 30 kg, representing the torso of a human body.

The results of the experiments with the sled test setup have provided information on the performance of this specific actuator, such as semi-active behavior, force limits, bandwidth and delay. This information is used in the numerical demonstrator, such that the actuator model reflects an actual device.

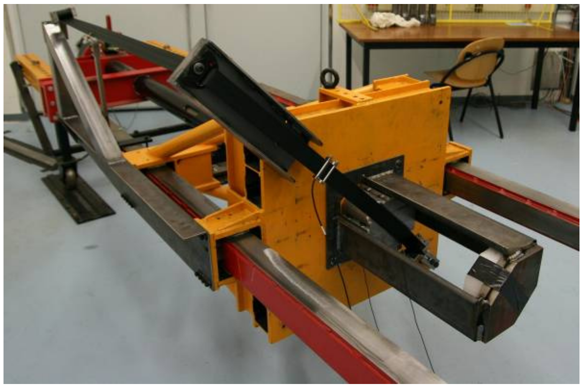

Figure 7. Sled crash setup used to test the belt force actuator during impact.

2. Design Model

In the development of CRC systems, it is essential to have manageable, low-order models of the occupant. Most of the relevant occupant responses, for instance the chest compression, cannot be measured directly with current sensors, for instance the chest compression. An accurate, but low-order model of the occupant may be used to estimate this compression in real-time, given some measurable signals and the loading conditions. Additionally, in the design of the control algorithms of the CRC system, it is convenient to have knowledge on the input-output behavior of the system. A low-order model for this behavior is therefore very useful.

The low-order models, referred to as design models, have been developed in a previous study. More details on theses models can be found in (van der Laan, 2009). The knowledge obtained from a sensitivity analysis on MADYMO Hybrid III dummies has been used to construct and parameterize the design model. The analysis has resulted in a 2D model of the dummy, with 11 rigid bodies and 14 degrees of freedom, see Figure 8. The model parameters such as masses, dimensions, initial conditions, are directly linked to parameters in the MADYMO model, which makes scaling of the design model very straightforward.

Outputs of this model are biomechanical responses that are used to assess injury risk to thoracic and neck regions. These are chest acceleration, chest compression and its time derivative, neck bending moment and neck axial and shear forces. Additionally, the belt rollout is added as a model output, as a belt rollout sensor will be used to estimate injury responses later on.

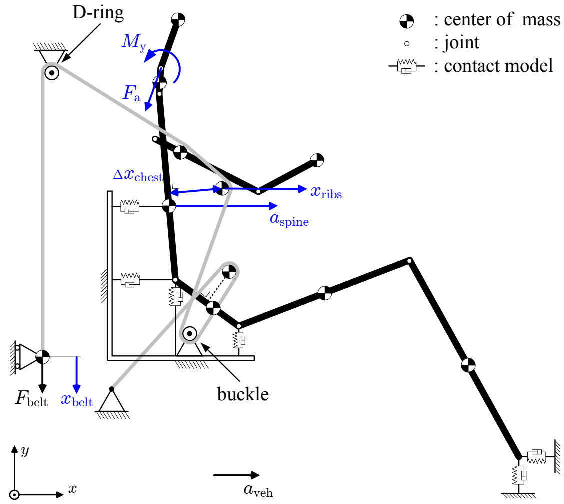

Figure 8. Representation of the multi-body design model of a 50th %-ile Hybrid III dummy.

Simulations show that the design model generates the biomechanical responses related to injury predictors for the chest and neck region remarkably well. The models are validated for a broad range of frontal crash scenarios, and for three different adult Hybrid III dummies. For all these tests, it was shown that the low-order model includes all relevant dynamics of the reference model. An example of the results is shown in Figure 9.

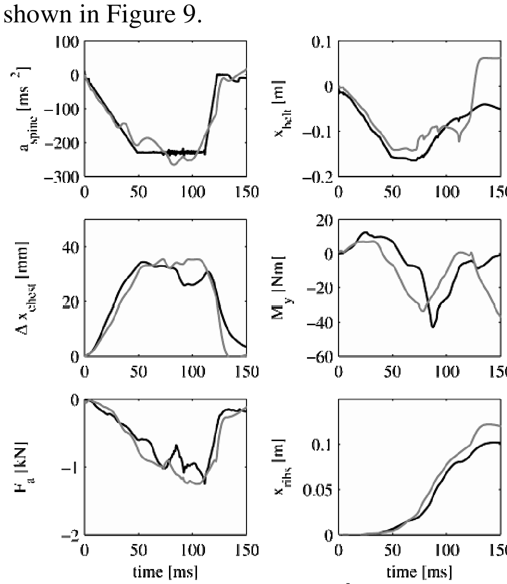

Figure 9. Responses of the 50th %-ile MADYMO reference model (grey) and design model (black) in a 40% ODB frontal impact at 64 km/h.

The linearized version of the presented design model is used in the design of the CRC controller and of the state estimator. These topics are discussed in the remainder of this section.

3. Reference Governor

A control strategy has been developed to solve the control problem formulated at the beginning of this section. In previous studies on controlled belt restraint systems (Hesseling et al., 2006), the control problem was formulated as a tracking problem, where biomechanical responses of the occupant are measured and forced to follow a predefined reference trajectory. This trajectory results in a minimum risk of injury, while satisfying certain constraints. However, the reference trajectories are constructed assuming full a priori knowledge of the crash pulse, constraints and occupant characteristics, which is in practice clearly not realistic.

To harvest the advantages of using CRC systems, these limitations have to be overcome. This indicates the compelling need for the development of a control algorithm that - based on the available measurements from the sensors - computes the optimal control signals for the belt restraint actuator. This includes the incorporation of the following requirements:

1. the algorithm must be computationally feasible in order to meet the real-time requirements,
2. a priori knowledge of the crash pulse is not available, and
3. the algorithm must be based on on-line measurement data.

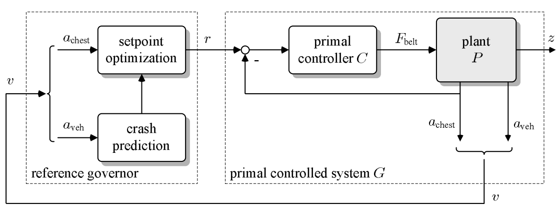

Figure 10. Control strategy based on Reference Governors. On the left, the modified RG, on the right a primal controlled loop.

A novel control strategy has been proposed to this challenging design problem (van der Laan et al., 2008; 2009a). The control method consists of a combination of a primal controlled system, which achieves good tracking properties, and a modified reference governor (RG), (Bemporad et al., 1998). The layout of the method is graphically shown in Figure 10, where *r* indicates the setpoint, *v* the measurements, and *z* injuries. The RG finds an optimal setpoint for the spinal acceleration, while satisfying constraints and without having a priori knowledge of the upcoming crash. It includes a crash prediction procedure of the vehicle motion to provide good estimates of its position during the crash.

The setpoint optimization problem is robustified with respect to the estimation errors. Moreover, the whole design procedure is generic in nature. For instance, multiple injury criteria can be easily included in the design process. In addition, different primal controllers and plant dynamics can be accounted for. This enables the incorporating of various additions, such as future improvements in the actuator and sensor technologies.

An example of the results obtained with the RG is given in Figure 11. It shows a reduction of 45% of the 3ms acceleration criterion with respect to conventional restraint systems (EuroNCAP pulse), while still meeting the real-time computational requirements.

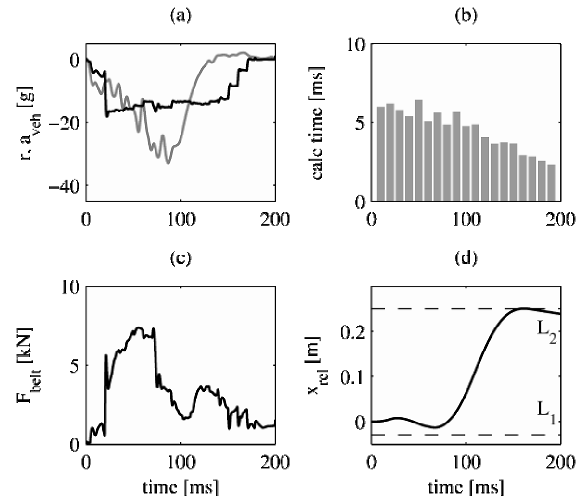

Figure 11. (a) Optimal setpoint for the chest acceleration (black), without a priori knowledge of the crash pulse (grey); (b) calculation times per optimization step; (c) required belt force in the primal controlled loop; and (d) constraint on the relative chest position with respect to the vehicle.

The RG control strategy is believed to be an important step towards real-time implementation of controlled passive safety systems. The strategy is used to evaluate the performance of CRC in the numerical demonstrator, presented in the next section.

4. State Estimator

The primal feedback controller from the previous section has to ensure that the spinal acceleration tracks the setpoint generated by reference governor. Obviously, the acceleration of the human spinal cord cannot be obtained directly as a measurement signal from the occupant. Furthermore, it is considered to be cumbersome to develop such a type of sensor, as it should be robust, ‘foolproof‘ (each driver must be able to use it, preferably without his or her awareness), cheap and crash safe. Hence, it is proposed to employ a set of more conventional sensors, and then estimate the state of the system using a model of the system.

Many types of occupant sensors are available in today’s cars, both contact as well as non-contact, see e.g. (Fleming, 2008). Non-contact sensors are not preferable, since the “line-of-sensing” may be easily blocked during an impact, e.g. by the airbags. Since the occupant typically has uninterrupted contact with the seat belt during an impact, it is chosen to attach sensors to the belt: one acceleration sensor to the shoulder belt in the center of the torso, and one displacement sensor to measure the belt rollout where usually the load limiter is placed. As mentioned in Section 2, this belt rollout sensor has also been attached to the belt in the sled experiments, in order to validate the belt displacement signal from the reference model. The acceleration sensor measures the absolute acceleration of the sternum in forward direction; the accuracy of this sensor could however not be checked with sled test measurements.

Since a manageable design model is available, as well as inputs and measurements, it is obvious to choose a model-based recursive estimation method. Besides that, much experience is already gained with recursive estimation methods in other automotive applications. More specifically, the Kalman filter approach was chosen as a candidate to set up an estimator for the chest acceleration. Since the proposed estimator estimates all states of the (human) model, it is referred to as “human state estimator”.

The behavior of the occupant, which is subject to belt forces and a vehicle acceleration pulse, can be approximated by the following linear state-space system:

$$\begin{aligned} x_k &= Ax_{k-1} + Bu_{k-1} + w_{k-1} \\ z_k &= Hx_k + v_k \end{aligned} \quad (1).$$

In Equation 1, u is the input vector consisting of the vehicle deceleration in forward direction, and the seat belt force. The measurement vector z consists of the sternum acceleration, a_{ribs}, and the belt rollout, x_{belt}. The vectors w, v are the (uncorrelated) measurement and process noise, respectively.

The Kalman filter setup is shown in Figure 12. The gain for the filter correction K is calculated from the measurement noise covariance R, the process noise covariance Q, and the linearized system matrices A and H, see for example (Gelb, 1974).

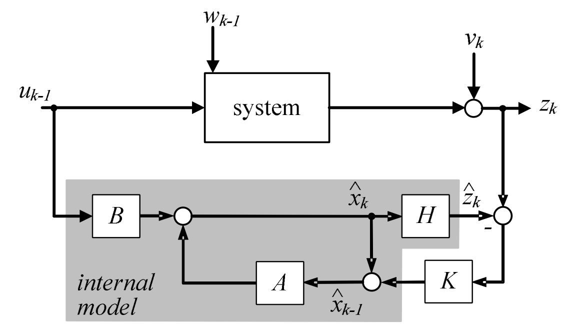

Figure 12. Kalman filter setup.

First, a fully linear approach was set up and tested against MADYMO results. However, this linear approach did not give satisfactory results under all conditions, whereas the non-linear model fits the MADYMO results very well. So the linear internal model in the Kalman filter was replaced by the non-linear design model whereas the gain calculation K is still based on the linear system. This approach resembles the Extended Kalman Filter, albeit that the A and H matrices are constant. Measurement data from the reference model are used to estimate a number of occupant responses. In Figure 13, the estimated responses are compared with true responses from the reference model.

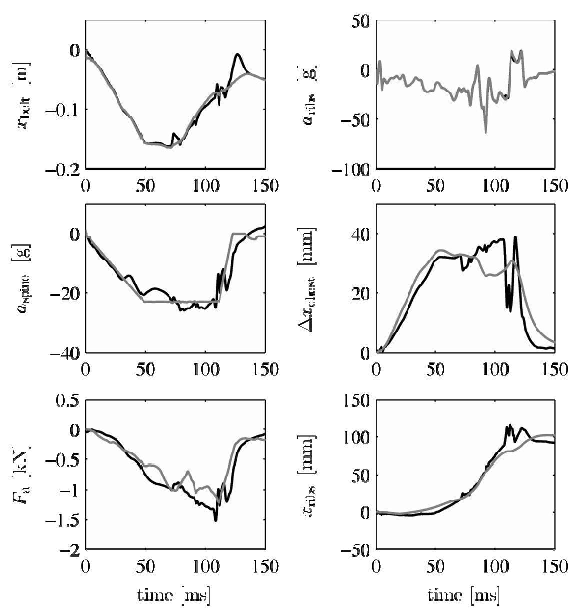

Figure 13. Results of the human state estimator (black) applied to the reference model (gray), with both measurements in the top figures.

NUMERICAL DEMONSTRATOR

This section shows the benefit of the CRC system above the conventional system by means of a simulation study. Note that the conventional restraint system is optimized as described on page 3. Several cases are investigated, which are shown in Table 1. Original seat angle and original D-ring height represent the settings that are obtained from the model validation with the sled test results. Variation is applied in these settings and in the size of the dummy model. Three crash pulses are simulated: One standard crash pulse (obtained from the sled test, see page 3) and two non-standard crashes, based on an offset frontal collision between two cars, as shown in Figure 14. For the two non-standard crash pulses, the reference model is also optimized (italics in Table 1), using the same method as described on page 3.

Table 1.
Investigated cases

Seat Angle	D-ring height	Seize	Crashpulse
orig	*orig*	*50%*	*standard*
orig+10deg	orig	50%	standard
orig	orig	95%	standard
orig	orig	5%	standard
orig+10deg	orig	95%	standard
orig	orig-10cm	5%	standard
orig+10deg	orig-10cm	50%	standard
orig	orig-10cm	50%	standard
orig	*orig*	*50%*	*nonstandard1*
orig+10deg	orig	95%	nonstandard1
orig	orig-10cm	5%	nonstandard1
orig+10deg	orig-10cm	50%	nonstandard1
orig	orig-10cm	50%	nonstandard1
orig	orig	5%	nonstandard1
orig	*orig*	*50%*	*nonstandard2*
orig	orig	95%	nonstandard2
orig	orig	5%	nonstandard2
orig+10deg	orig	50%	nonstandard2

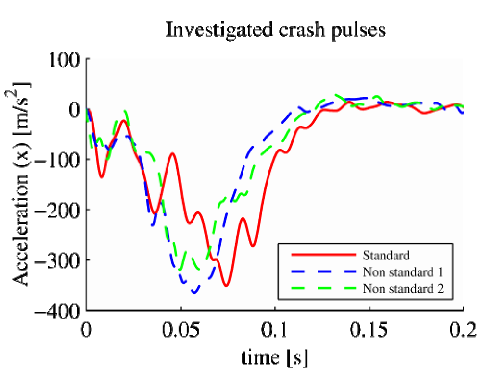

Figure 14. Investigated crash pulses.

Figure 15 shows that the chest acceleration tracks the setpoint from the reference governor sufficiently well. Hence, the control system is robust against disturbances from the crash pulse and the airbag, and has good tracking performance. It should be noted that the state estimator as described op page 7 is not included at this point.

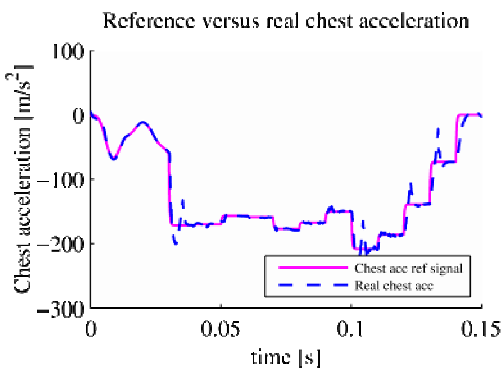

Figure 15. Reference chest acceleration (solid) versus simulated chest acceleration (dashed).

The results are shown in Figure 16 and Figure 17 for two following cases:

- original seat angle, original D-ring height, 50% dummy, standard crash pulse,
- original seat angle, original D-ring height, 5% dummy, nonstandard crash pulse 2.

Figure 16 and Figure 17 present three different curves:

- The red solid line describes the result for the conventional restraint,
- The dotted blue line shows the CRC with an ideal actuator. The optimization done by the RG is based on chest acceleration only,
- The dotted green line shows the CRC result with a realistic actuator.

The properties of the realistic actuator, which are implemented in the demonstrator, are:

- Maximum belt force: 8kN
- Rate limit: 10^6 N/s
- Time delay: 0.2 ms

Note that the actuator is semi-active, in a sense that the actuator does not have to deliver energy to the system. This is indeed the case after a short period of pretension.

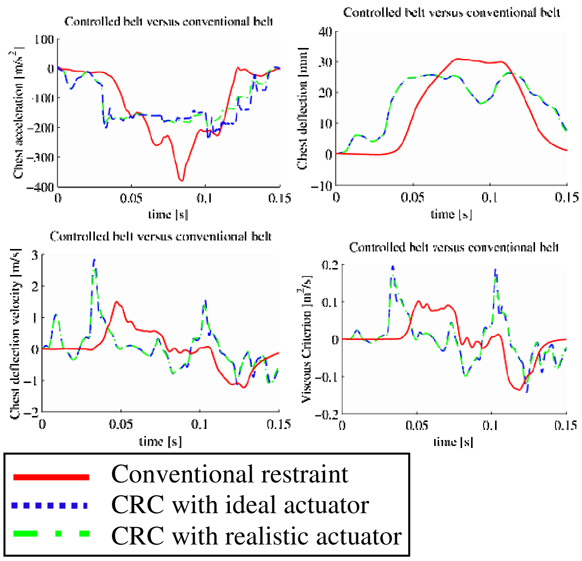

Figure 16. Results for several injury parameters for 50% dummy, standard crash pulse.

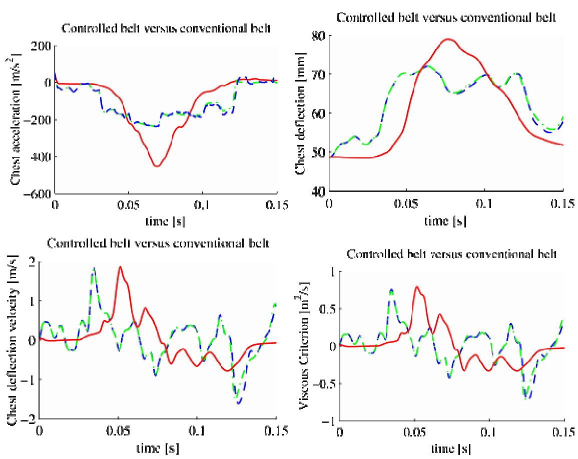

Figure 17. Results for several injury parameters for 5% dummy, non-standard crash pulse 2.

Injury Limits

Within the EURONCAP protocols (EuroNCAP, 2003), injury limits are determined for several injury criteria. Two limits are specified, i.e. a lower performance limit (limit2) and a higher performance limit (limit1). The injury criteria and limits are shown in Table 2, but only for the head, neck and chest criteria. The results for the reference system are shown in Table 3. The results for the controlled belt with realistic actuator are shown in Table 4. In these tables, three color codes are applied:

- green: the injury value is below limit1
- orange: the injury value is between limit1 and limit2
- red: the injury value is above limit2.

Table 2. Investigated injury parameters and limits

	limit1	limit2
HIC36	650	1000
Headacc3ms	72	88
Neck shear force	1900	3100
Neck tension force	2700	3300
Neck extension moment	42	57
Chest compression	22	50
VC	0.5	1

Table 3. Results for investigated cases: reference system

Simnr	HIC36	Headacc3ms	FX_shear	FZ_tension	NMY_ext	Chest_c	VC
1	423	54	363	1177	34	31	0.10
2	755	69	356	1302	24	31	0.10
3	776	71	1391	1779	94	50	0.24
4	218	36	288	602	16	31	0.17
5	2358	150	2604	1874	122	47	0.28
6	201	32	355	641	19	30	0.17
7	734	72	419	1072	31	30	0.09
8	420	55	364	1155	34	31	0.10
9	486	56	589	1357	46	38	0.18
10	3051	189	3390	3034	237	56	0.47
11	265	39	400	666	29	36	0.24
12	845	76	411	1800	32	34	0.15
13	491	58	620	1305	49	36	0.16
14	256	40	422	668	31	36	0.26
15	581	65	314	1339	25	31	0.15
16	450	54	361	1483	32	42	0.14
17	233	39	253	702	22	34	0.20
18	355	52	456	1099	35	34	0.14

Based on the results presented in these two tables, it can be concluded that the CRC system effectively reduces the criteria values of HIC36, Headacc3ms, neck shear force, neck tension force, and neck extension moment. The chest deflection is most of the times reduced as well, but the chest deflection velocity increases in some cases. In most cases, the VC does still not exceed limit1. Only for three cases, it slightly exceeds this limit. Overall, the CRC system improves injury mitigation in most cases.

Table 4. Results for investigated cases: controlled belt with realistic actuator

Simnr	HIC36	Headacc3ms	FX_shear	FZ_tension	NMY_ext	Chest_c	VC
1	177	38	523	711	29	27	0.19
2	163	35	589	553	24	32	0.52
3	161	33	611	784	29	36	0.34
4	111	32	417	542	22	32	0.35
5	191	34	526	770	26	42	0.64
6	142	42	413	585	16	33	0.34
7	142	32	727	773	38	31	0.32
8	198	39	506	706	26	27	0.18
9	272	47	451	826	34	30	0.17
10	276	40	552	1070	27	44	0.63
11	138	39	410	558	16	32	0.34
12	317	49	555	724	26	32	0.30
13	302	49	448	793	31	28	0.15
14	163	32	387	546	24	29	0.23
15	179	35	478	620	22	29	0.33
16	117	31	792	950	73	45	0.45
17	79	26	325	455	18	25	0.16
18	168	38	483	625	34	27	0.12

Previous results were obtained without the state estimator, since at the time of writing of this paper not all simulations were finished. For the 50% dummy with standard crash pulse, the results with the demonstrator including the estimator, the reference governor and a realistic actuator are shown in Figure 18 and Figure 19. The performance decrease caused by the estimator is only minor, which indicates that the estimator is quite accurate (compare Figure 16 and Figure 19).

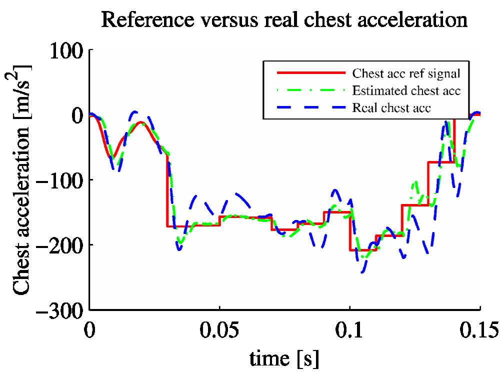

Figure 18. Estimator results for chest acceleration for 50% dummy, standard crash pulse.

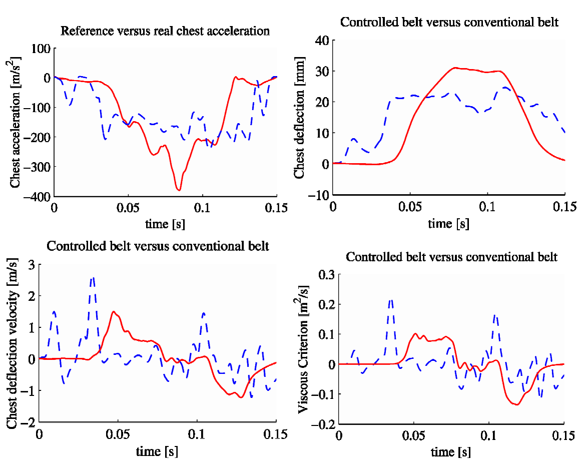

Figure 19. The red (solid) line represents the conventional restraint system, the blue (dotted) line represents the CRC with reference governor, realistic actuator and state estimator.

CONCLUSION AND OUTLOOK

In this paper, advancements are shown in the area of continuous restraint control (CRC) systems. More specifically, a system is described where the belt force is continuously manipulated as a function of measurements of the vehicle and occupant. The proposed CRC system aims at minimizing head, neck and thoracic injuries. The problems concerning the sensors, actuator and control strategy are discussed, and solutions are proposed.

Moreover, a numerical demonstrator is developed that incorporates the aforementioned CRC elements. The numerical demonstrator is based on a MADYMO model with conventional restraint systems. This model is validated with sled test experiments. Subsequently, the settings of this model are tuned to yield optimal protection for the occupant in the given scenarios, and this optimized model is referred to as the reference model.

The numerical demonstrator is tested in 18 different scenarios, including different dummy types, crash pulses, seating angles and D-ring positions. For these scenarios, the performance of the CRC system is evaluated by using performance limit values on 7 injury criteria. The resulting 126 performance values are compared to the values of the reference model for the same scenarios. Whereas the reference model has a poor performance in 9 cases and sufficient performance in 28 cases, the CRC system performs poorly in just 1 case and sufficiently in 21 cases.

Concluding, the potential for injury reduction with CRC systems has been made evident with the numerical demonstrator, in which a realistic sensor, actuator and control strategy have been implemented.

Future research will focus on evaluation of the numerical demonstrator for a larger number of crash scenarios. Furthermore, effort has to be directed in making the control and estimator algorithms run in real-time, such that they can be tested in real-world experiments.

REFERENCES

H. Adomeit, E. Wils, and A. Heym, “Adaptive Airbag Belt Restraints - An Analysis of Biomechanical Benefits”, in Proceedings of the SAE International Congress and Exposition, 24-27 Feb 1997, Detroit, Michigan, USA, paper no. 970776, pp. 163-177.

A. Bemporad, E. Mosca, “Fulfilling Hard Constraints in Uncertain Linear Systems by Reference Managing”, Automatica, 34(4), 1998, pp. 451-461.

M. Bosch-Rekveldt, J. Brandse, G. Couper, R. Morris, and M. Neale, “Development and application of generic restraint numerical models for parametric investigations of selected impact scenarios”, Technical Report R6 and R7, PRISM, 2005, [online] http://www.prismproject.com.

G. Clute, “Potentials of adaptive load limitation presentation and system validation of the adaptive load limiter”, in Proceedings of the 17th International Technical Conference on the Enhanced Safety of Vehicles (ESV), 4-7 Jun 2001, NHTSA, Amsterdam, the Netherlands, pp. 113-134.

J. Cooper, P. Lemmen, and C. van Schie, “Effectiveness of real time control for active restraint systems in frontal crashes”, in Proceedings of Airbag 2004, 29 Nov. - 1 Dec. 2004, Fraunhofer-Institut für Chemische Technologie (ICT), Karlsruhe, Germany, pp. 1-7.

J.R. Crandall, Z. Cheng, W.D. Pilkey, “Limiting performance of seat belt systems for the prevention of thoracic injuries”, Journal of Automobile Engineering, 214(2), 2000, pp. 127-139.

European New Car Assessment Protocol (EuroNCAP), “Assessment Protocol and Biomechanical Limits”, v4.0, Jan. 2003, Euro NCAP, Brussels, Belgium.

W.J. Fleming, “New Automotive Sensors — A Review”, IEEE Sensors Journal 8(11), 2008, pp. 1900-1921.

A. Gelb, “Applied Optimal Estimation”, MIT Press, Cambridge, MA, USA, 1974.

M.S. Habib, “Active control of vehicle occupant's motion in front- and rearend collisions”, in Proceedings of the Automotive and Transportation Technology Congress and Exhibition, 1-3 Oct 2001, Barcelona, Spain, paper 2001-01-3430, pp. 1-9.

R.J. Hesseling, M. Steinbuch, F.E. Veldpaus, and T. Klisch, “Feedback control of occupant motion during a crash”, International Journal of Crashworthiness 11(1) (2006), pp. 81-96.

P. Holding, B. Chinn, and J. Happian-Smith, “An evaluation of the benefits of active restraint systems in frontal impacts through computer modelling and dynamic testing”, in Proceedings of the 17th International Technical Conference on the Enhanced Safety of Vehicles (ESV), NHTSA, June 4-7 2001, Amsterdam, the Netherlands, Paper 328, pp. 1-9.

T. Iyota, T. Ishikawa, “The Effect of Occupant Protection by Controlling Airbag and Seatbelt”, in Proceedings of the 18th International Technical Conference on the Enhanced Safety of Vehicles (ESV), NHTSA, 19-22 May 2003, Nagoya, Japan, paper no. 198, pp. 1-10.

R.W. Kent, D.V. Balandin, N.N. Bolotnik, W.D. Pilkey, S.V. Purtsezov, “Optimal control of restraint forces in an automobile impact”, Journal of Dynamic Systems Measurement and Control - Transactions of the ASM, 129(4), 2007, pp. 415-424.

E.P. van der Laan, F.E. Veldpaus, and M. Steinbuch, “Control-oriented modelling of occupants in frontal impacts”, International Journal of Crashworthiness, (in press), 2009.

E.P. van der Laan, H.J.C. Luijten, F.E. Veldpaus, W.P.M.H. Heemels, and M. Steinbuch, “Reference governors for controlled belt restraint systems”, in Proceedings of the IEEE International Conference on Vehicular Electronics and Safety (ICVES), Columbus, OH, 22–24 Sep 2008, pp. 114–119.

E.P. van der Laan, W.P.M.H. Heemels, H.J.C. Luijten, F.E. Veldpaus, and M. Steinbuch, “Reference governors for controlled belt restraint systems”, Vehicle System Dynamics, (submitted) 2009a.

H.J. Mertz, J.E. Williamson, and D.A. van der Lugt, “The effect of limiting shoulder belt load with airbag restraint”, in Proceedings of the SAE International Congress and Exposition, 27 Feb - 2 Mar 1995, Detroit, Michigan, USA, pp. 185-192.

H.J. Miller, “Restraint Force Optimization for a Smart Restraint System”, in Proceedings of the SAE International Congress and Exposition, 26-29 Feb 1996, Detroit, USA, paper no. 960662, pp. 79-84.

T.J. Paulitz, D.M. Blackketter, and K.K. Rink, “Constant Force Restraints For Frontal Collisions”, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 220 (2006), pp. 1177-1189.

H.S. Shin, T.J. Yeo, W.P. Ha, “The numerical study for the adaptive restraint system”, in Proceedings of the SAE 2007 World Congress, 16-19 Apr 2007, Detroit, Michigan, USA, paper no. 2007-01-1500.

TNO MADYMO B.V., “MADYMO Manual”, Version 6.3, TNO Road-Vehicles Research Institute, Delft, the Netherlands, 2005.

D. Twisk, H.H. Spit, M. Beebe, P. Depinet, “Effect of Dummy repeatability on numerical model accuracy”, JSAE Paper no. 20071415, 2007.