A NOVEL CONTROL ALGORITHM FOR INTEGRATION OF ACTIVE AND PASSIVE VEHICLE SAFETY SYSTEMS IN FRONTAL COLLISIONS

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ABSTRACT

The present paper investigates an approach to integrate active and passive safety systems of passenger cars. Worldwide, the introduction of Integrated Safety Systems and Advanced Driver Assistance Systems (ADAS) is considered to continue the today's trend of reduction of traffic accidents and mitigating their severity and consequences. An algorithm is proposed in this paper where force levels and activation times of an adaptive restraint system are calculated based on the actual crash scenario.

The method takes into account the crash severity by a forecast of the acceleration behaviour of the passenger cell. This is calculated by a simplified multi body model of the impact, considering input data from an environment recognition system. The vehicle deformations are simulated using non-linear springs with hysteresis. The characteristics of the springs are derived from NHTSA's crash database. The occupant of the ego-vehicle is considered also by a simplified rigid body model, taking into account mass and seating position of the occupant. Optimal force levels and trigger times of the adaptive restraint system are calculated in order to minimise the acceleration of the occupant.

For demonstration, different configurations with different collision severity and occupant mass were investigated with numerical simulations. In almost every load case significant reductions up to 90 % of the acceleration experienced by the occupant were observed. Influences on the accuracy of the recognition of mass and stiffness of the opponent vehicle were analysed in order to derive requirements for environment recognition systems. The present study forms the basis of future work which includes a real-time application and demonstration in a vehicle.

Keywords: Frontal Impact, Integrated Safety, Pre-Crash, Adaptive Restraints, Collision Prediction

1. INTRODUCTION

Background

Active safety systems such as Electronic Stability Control, Emergency Brake Assist and Lane Keeping Support will contribute to avoid and mitigate collisions in future [3, 5, 6]. Passive safety systems currently are activated by electronic control units that for example evaluate accelerations, roll rate and door pressure during an accident. The adaption of passive safety systems to the accident is mainly limited to low and high crash severity. The integration of active and passive safety systems and the adaption of their functionality to the actual collision is considered as a significant step towards improved traffic safety [4, 7].

Objective

The present paper is based on previous work [9] and describes an approach to integrate active and passive safety systems by development of an algorithm where force levels and trigger times of the frontal restraint system are predefined based on the actual collision scenario. Reference values for these force levels are generated in order to minimise the acceleration of the occupant. These values are input for active and adaptive passive safety systems.

Important sources for the development of the algorithm are found in [1, 2, 8].

2. Methodology

The main idea of the algorithm is a prediction of the passenger cell acceleration pulse of the ego-vehicle. This is based on a forecast of collision speed, mass and stiffness of the colliding vehicles, which are the main input parameter of the algorithm.

The described approach consists of three separate models, the pre-collision model, the collision model and the occupant model. The pre-collision model, which is not presented in detail in this paper, serves to predict the impact energy and delivers the above mentioned input parameter for the collision model. It takes into account the vehicle dynamics of the ego-vehicle and uses the input of an environment recognition system (such as Radar, Video or Laser scanner) to predict the state vector (position and velocity) and mass of the collision opponent.

The collision model consists of two rigid bodes with a single degree of freedom for each in longitudinal direction (x_{opp} and x_{ego}), see Fig. 1. They represent the opponent vehicle (mass m_{opp}) and the ego vehicle (mass m_{ego}). The rigid bodies are linked together by force elements (nonlinear springs with hysteresis, F_C).

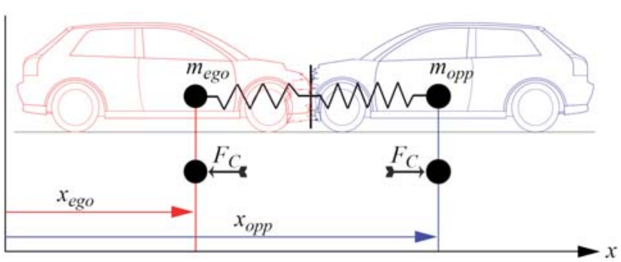

Figure 1: Scheme of collision model.

By numerical integration of the equations of motion of this model, Eq. (1), the acceleration of the passenger compartment of the ego-vehicle is calculated.

$$
\begin{aligned}
&m_{opp} \cdot \ddot{x}_{opp} + F_C = 0 \\
&m_{ego} \cdot \ddot{x}_{ego} + F_C = 0 \\
&F_C = c_{def} \cdot (x_{opp} - x_{ego}) \\
&c_{def} = f(x_{ego}, x_{opp})
\end{aligned}
\qquad (1)
$$

The spring characteristics of the force elements which describe the deformation behaviour of the vehicles in a full overlapped frontal crash are derived from crash tests published by NHTSA [1]. A total number of 39 vehicles were analysed, for an example see Fig. 2. The filtered data forms the basis for further analysis. In case of a hang-on collision with full overlap, a method [9] was developed to combine the individual stiffness's of the opponents to one single spring F_c with discrete non-linear force-deflection characteristics c_{def}, Fig. 3 and Eq. (1).

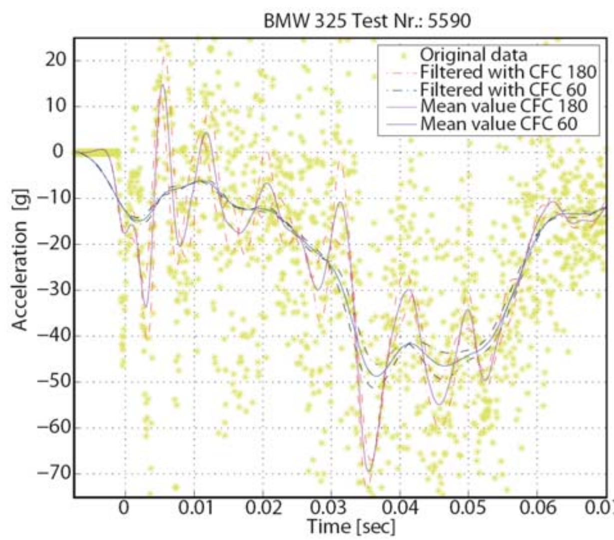

Figure 2: Example of a deformation spring.

The occupant of the ego-vehicle is also considered by a simple rigid body model, taking into account its mass and seating position (see Fig. 4). The equation of motion for the occupant model is:

$$
m_{occ} \cdot \ddot{x}_{occ} = F_{Air} + F_{Belt} + F_{Steer} + F_{Seat} \qquad (2)
$$

m_{occ} denotes the mass of the occupant, x_{occ} the position of the occupant, F_{Air}, F_{Belt}, F_{Steer} and F_{Seat} the forces of the restraint system acting on the occupant, see Fig. 4.

An optimisation algorithm determines suitable force levels and trigger times of the adaptive restraint system, based on the criterion of minimising the maximum and average acceleration while avoiding bottoming-out of the restraint components. Within this study, genetic as well as gradient based optimisation algorithms were investigated.

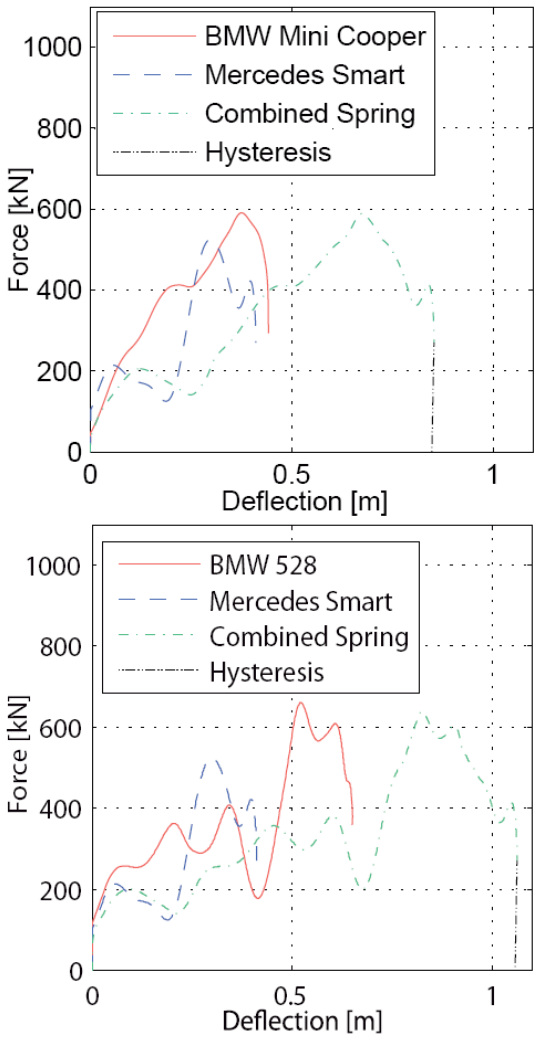

Figure 3: Two examples of the combined deformation spring, the solid (red) and dashed (blue) line correspond to two different vehicles, the dot and dash line (green) represents the combination of them.

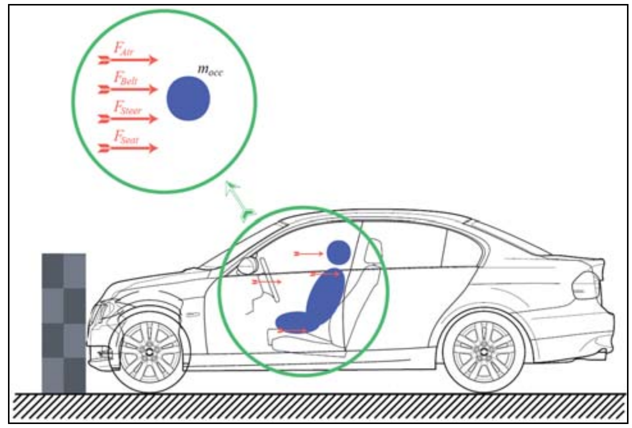

Figure 4: Simplified rigid body model of the occupant. F_{Air} describes the forces by the frontal airbag, F_{Belt} is the resulting force in lateral direction of shoulder and lap belt, F_{Steer} depicts the forces of the steering column and F_{Seat} stands for the frictional force of the seat, [9].

3. Limitations

As a first step only straight hang-on collisions with full overlap are considered, but basically the method can be enhanced for other impact scenarios such as rear-end collision, lateral or oblique impact. Another shortcoming is the simplification of the model in order to achieve real-time performance for a full vehicle application. Especially, it is assumed that a minimisation of occupant acceleration lowers the injury risk. Detailed injury responses such as the Head Injury Criterion (HIC) cannot be assessed. Therefore the performance of the algorithm has to be demonstrated with more complex models. The application in a vehicle and verification of the real time performance and functionality of the algorithm is part of future work.

4. Results and discussion

Different configurations with different collision severity and occupant mass were investigated. The collision severity ranges from a collision speed of 20 kph up to 56 kph. Different masses of the opponent vehicle ranging from A-segment vehicles (700 kg) up to luxury class cars (3000 kg) were used. For the passenger weight, a range from 30 kg up to 125 kg was chosen in order to represent most occupants except from children. A standard restraint system optimised for FMVSS 208 requirements was compared to a restraint system, controlled by the presented algorithm.

In almost every configuration significant improvements up to 90 % were observed, see Fig. 5. For collisions close to the standard FMVSS 208 requirements (e.g. 54 kph closing speed and 75 kg occupant mass) the improvements are small because the non adaptive restraint system is already optimised for that. The main improvements occur at lower severity and especially occupant masses outside of the 50th percentile, which demonstrates the effectiveness of the integrated safety approach in real traffic conditions.

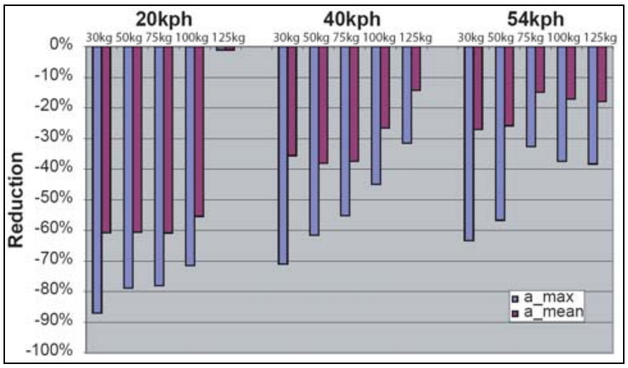

Figure 5: Reduction of the occupant maximum and mean acceleration with respect to different collision speeds and occupant masses.

Since the present study assumes that make and model of the collision opponent are known, the influence of the accuracy of mass and stiffness of the opponent vehicle were analysed. Even when knowing make and model based on video recognition and estimating the mass of the opponent, there is a lack of knowledge about the actual payload.

According to statistics of vehicle registrations in Austria [8], the NHTSA database was searched for these most likely collision opponents. But through the restrictive database it was not possible to retrieve all vehicle models. After all, the 39 vehicles found in the NHTSA database are grouped into six mass classes, as Table 1 shows.

Class	Make	Model	Mass
1	Mercedes	Smart	963 kg
1	VW	Polo	1100 kg
2	Toyota	Yaris	1245 kg
2	Kia	Rio	1352 kg
2	Mini	Cooper	1371 kg
2	Dodge	Neon	1379 kg
2	Toyota	Corolla	1379 kg
2	Ford	Focus	1394 kg
2	Honda	Civic	1394 kg
2	Ford	Focus	1398 kg
3	Toyota	Prius	1515 kg
3	Subaru	Impreza	1585 kg
3	BMW	Z4 Roadster	1630 kg
3	Honda	Accord	1673 kg
3	Saab	9-3	1705 kg
3	Subaru	Forester	1708 kg
3	VW	Jetta	1719 kg
3	Nissan	350Z	1729 kg
3	Volvo	S60	1732 kg
4	VW	Passat	1765 kg
4	Ford	Taurus	1785 kg
4	BMW	325l	1806 kg
4	Audi	A4	1820 kg
4	Volvo	S80	1820 kg
4	Saturn	Aura	1828 kg
4	Nissan	350Z	1855 kg
4	Mercedes	C300	1864 kg
4	Chrysler	Sebring	1915 kg
4	BMW	528l	1924 kg
5	Dodge	Journey	2136 kg
5	Volvo	XC90	2389 kg
5	Hummer	H3	2404 kg
5	Mercedes	ML350	2431 kg
5	BMW	X5	2458 kg
6	Audi	Q7	2582 kg
6	VW	Touareg	2600 kg
6	Toyota	Sequoia	2816 kg
6	Toyota	Tundra	2884 kg
6	Ford	F250 Pickup	3054 kg

Table 1: Investigated cars and defined mass classes.

Table 2 presents the results of the investigation of the mass influence for two different vehicles (FORD Taurus and MERCEDES C300). An occupant with 75 kg is taken into account. The collision speed is 106 kph. The parameter $s_{disp,occ}$, $a_{max,occ}$ and $a_{mean,occ}$ present the resulting loading to the occupant. $s_{disp,occ}$ is the relative displacement, $a_{max,occ}$ the maximum acceleration and $a_{mean,occ}$ the mean acceleration of the occupant respectively. The average acceleration $a_{mean,occ}$ of an occupant sitting in a MERCEDES C class is almost doubled when it is impacted from an 3000 kg vehicle compared to a 800 kg vehicle. When increasing the mass of the vehicle in steps of 200 kg, the average acceleration increases by approximately 1.5 g. The typical payload of a passenger car is around 300 kg [2], so the accuracy of the results are in the range of about 2 g, which has to be taken into account by the algorithm.

There where no results in the simulation of the first investigated vehicle (FORD Taurus) when colliding against a vehicle with a mass higher than 2600kg (marked with "-" in Table 2). The reason for that is that the maximum force levels of the restraint system are limited. At high impact energy levels, the occupant strikes through the airbag and contacts the dashboard.

m_2	Ford Taurus $s_{disp,occ}$ [mm]	$a_{max,occ}$ [g]	$a_{mean,occ}$ [g]	Mercedes C300 $s_{disp,occ}$ [mm]	$a_{max,occ}$ [g]	$a_{mean,occ}$ [g]
800 kg	24.1	23.17	14.90	30.3	29.43	16.70
1000 kg	40.7	23.54	16.00	52.1	30.74	18.33
1200 kg	63.2	29.13	17.22	70.0	38.02	20.25
1400 kg	74.1	32.93	18.46	87.4	45.14	21.67
1600 kg	87.5	32.93	19.37	105.5	52.49	23.61
1800 kg	87.5	32.93	20.30	116.5	57.00	24.67
2000 kg	130.3	32.93	21.12	125.8	57.40	25.93
2200 kg	158.0	32.93	21.62	133.8	57.40	27.30
2400 kg	187.8	32.93	21.98	141.4	57.40	28.02
2600 kg	221.8	32.93	22.28	149.4	57.40	28.86
2800 kg	-	-	-	161.4	57.40	29.55
3000 kg	-	-	-	173.3	57.40	30.22

Table 2: Influence of collision opponent mass on the loading of the occupant.

For investigation of the influence of the crush zone stiffness the following approach has been chosen: All studied vehicles were classified according to their mass. Next the stiffness springs of these vehicles were compared and combined to an average force-deflection curve (thick line in Fig. 6).

It can be seen, that according to the mass classes, the deformation characteristics of different vehicles are similar. The reason for that is that vehicles structures are designed to fulfil requirements of standard laboratory crash tests. There, only the vehicle mass has an influence on the energy that has to be absorbed by the crush zone. Restraint systems are designed to meet injury criteria of dummy responses in these specific tests.

To evaluate the influence of the stiffness a certain crash scenario (fully overlapped car to car frontal collision, masses of each vehicle 1785 kg, collision speed 108 kph, mass of occupant 75 kg) is calculated using the algorithm. The only investigated parameter is a variation of the stiffness of the crush zone according to the six classes described above. The average acceleration of the occupant scatters by approx 1 g (mean value 20.4 g). The results are shown in Table 3.

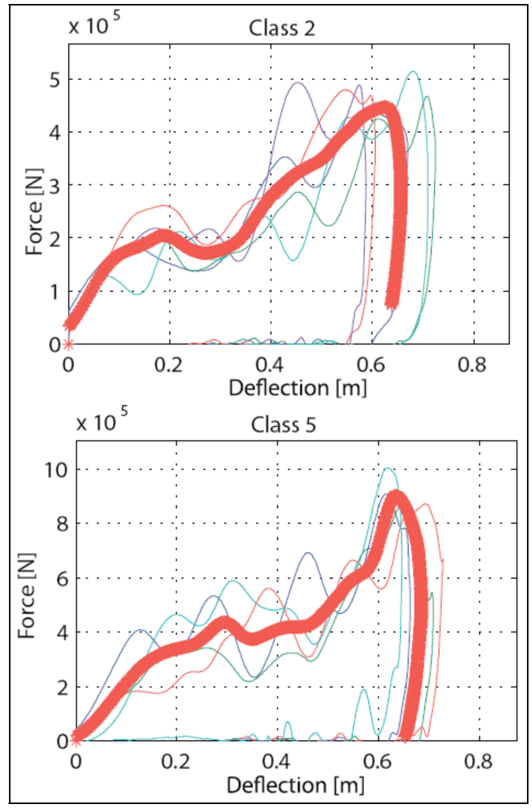

Figure 6: Examples for deformation springs with respect to different mass classes. Mass class 2 represents vehicles from 1200 to 1400 kg, mass class 5 from 2000 to 2500 kg. The thick line is the combination of the different deformation springs.

$s_{disp,veh}$ denotes the displacement of the vehicle, which is the deformation of the vehicle front in this load case. Analogue to Table 3, $a_{max,veh}$ and $a_{mean,veh}$ represent the maximum and mean acceleration of the vehicle under consideration.

	Occupant $s_{disp,occ}$ [mm]	$a_{max,occ}$ [g]	$a_{mean,occ}$ [g]	Vehicle $s_{disp,veh}$ [mm]	$a_{max,veh}$ [g]	$a_{mean,veh}$ [g]
Class 1	162.2	32.93	21.28	579.30	40.06	21.59
Class 2	100.4	32.93	20.23	665.50	33.64	19.88
Class 3	101.6	32.93	20.16	663.40	34.50	19.85
Class 4	108.7	32.93	20.41	653.90	39.24	20.00
Class 5	94.6	32.93	19.87	677.70	38.25	19.56
Class 6	120.4	32.93	20.52	649.90	44.74	20.22
Class 1-6	103.5	32.93	20.21	662.00	37.64	19.89

Table 3: Influence of crush zone stiffness; A standard frontal crash scenario was investigated, only the stiffness of the collision opponent varies.

The small influence of the stiffness shows that it is sufficient to estimate roughly the mass of the opponent vehicle and to use the stiffness characteristics derived in the corresponding mass class introduced in this paper.

5. Conclusions

An algorithm prepared for a real-time application in a passenger car was developed. It generates reference values for an adaptive restraint system by calculating force levels of the different restraint components, such as belt and airbag. These force levels were optimised with respect to maximum and mean acceleration of the occupant. The method consists of three separate models (pre-collision model, collision model and occupant model), which are working together. Simplified models were used in order to maintain a future real-time application.

The basic functionality of the algorithm was demonstrated in simulations of fully overlapped frontal collision considering different input parameters:

a) Mass of colliding vehicles

b) Crush zones stiffness of colliding vehicles

c) Collision speed

d) Occupant mass of ego-vehicle

e) Seating position of occupant

These input parameters were supposed to be known, since the development of the pre-collision model is still under progress.

Significant improvements up to 90 % with respect to maximum and average acceleration of the occupant could be demonstrated in different crash scenarios. The influence of mass and stiffness were investigated in order to derive requirements for the environment recognition system.

Further studies will investigate whether the algorithm is accurate enough when comparing it to detailed simulations of vehicle deformation and dummy responses using numerical crash simulation methods. Additionally the model will be enhanced for application a real vehicle to demonstrate a real-time application.

6. References

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