

## Real-Time Optimal Control of Seat-Belt Systems

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**Abstract:** This work presents a real-time implementable, computationally light algorithm for semi-active seat-belt systems. It consists of a linear feedback loop on the belt force that is cascaded by an algebraic reference governor. The governor is based on the explicit solution to a widely used optimization problem regarding optimal control of seat-belts. The algorithm is applied to a prototype semi-active hydraulic seat-belt actuator and is demonstrated on an experimental setup simulating frontal collisions. In comparison to an uncontrolled experiment, the controlled one managed to reduce the injury criterion with 15%, without increasing the occupant travel. When twice the travel was allowed, the criterion was reduced by 51%, showing the effect of variable settings to occupant/vehicle dimensions. However, the injury criteria were still 2.0 – 2.5 times the optimal injury criterion, as calculated with perfect future knowledge of the crash event.

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### 1. INTRODUCTION

According to World Health Organization (2015), 1.25 million people died in road traffic accidents in 2013 worldwide. Car occupants account for approximately one third of these fatalities and in Europe this was even half. In September 2015, the United Nations adopted the sustainable development target to halve this number by 2020. Among other approaches, technological advances in the automotive industry could contribute to achieving this target. In conclusion, the World Health Organization states the following: “Wearing a seat-belt reduces the risk of fatality among drivers and front-seat passengers by 45 – 50%, and the risk of minor and serious injuries by 20 – 45% respectively”.

Nowadays, standard automotive seat-belt systems consist of a three point seat-belt, a load limiter and a pre-tensioner. The pre-tensioner is a pyrotechnical device which removes slack from the seat-belt at the moment a crash is detected. Kent et al. (2007b) study the effect of belt-slack extensively and show that there is still much room for improvement in current technology. The load limiter mechanically upper-bounds the seat-belt force by either intended ripping of sews in the belt or by a dedicated mechanical device. Although load limiters show good results on barrier crash tests, Brumbelow et al. (2007) show that the increased motion of the occupant results in an increase in the fatality rate for real world high speed frontal collisions. This while Hoffenson et al. (2013) show that current barrier tests are too harsh as 98% of real world crashes are less severe. As current safety features are non-adaptive, these kind of trade-offs are inherent to the problem.

Applying control technology to occupant restraint systems allows for a more tailored solution for different crash scenarios. This possibility was first investigated in the end of the 20<sup>th</sup> century by Miller (1995), Bernat (1995) and Johannessen and MacKay (1995). The general idea is to continuously vary the seat-belt force such that injuries are minimized for given occupant, vehicle and crash specifics. Hesseling (2004) develops control design oriented models and extensively performs numerical simulations. Griotto et al. (2007) present real-time control

strategies which are numerically analyzed on multi-body occupant models. Kent et al. (2007a) and Van der Laan et al. (2010) pose the seat-belt control problem as an optimal control problem. However, these strategies are not experimentally demonstrated.

The 1-DOF controlled seat-belt optimization problem was solved explicitly by Kent et al. (2007b) and Mott et al. (2013) for a Dirac and half-sine vehicle crash pulse respectively. This study shows that the shape of the crash pulse is irrelevant and that therefore the presented solution holds for general crashes. In addition, experimental work has been performed in continuation of Van der Laan (2009), where a control strategy and prototype seat-belt actuator was developed. The strategy consists of a linear tracking problem for the hydraulic pressure in a semi-active actuator, cascaded by a reference governor based on optimal control theory. In order to validate this algorithm, an experimental setup has been built. Due to implementation challenges, the full control algorithm had not been experimentally validated. One of the major challenges was the formidable computational effort required to numerically solve the optimization problem in real-time. This challenge is overcome in the present study by replacing the optimization problem by its explicit solution. In addition to reducing the required computational effort, the solution provides clear insights in the potential of seat-belt control. However, the solution is non-causal since it depends on future crash events, therefore a causal approximate solution is used for real-time implementation.

The novel contributions of this study are deriving the explicit optimal control solution for general crashes, introducing an implementable approximation of this solution and experimental demonstration of the potential of seat-belt control to reduce injuries in frontal crashes.

The paper is organized as follows. Section 2 poses the generally accepted 1-DOF control problem and derives its solution using the equations of motion governing the crash. Section 3 implements and demonstrates the optimal controller on the experimental setup. Conclusions are provided in Section 4.

## 2. CONTROL PROBLEM AND SOLUTION

Controlled seat-belt systems continuously vary the belt force such that the motion of the occupant follows an optimal trajectory. However, before the occupant motion can be controlled, the optimal occupant motion, resulting in the least amount of injury, should be known. In this section, the optimal occupant motion is derived by using the equations of motion governing a 1-DOF frontal crash. Fig. 1 shows this crash situation where an occupied vehicle collides with an object with unknown mass, velocity and shape.

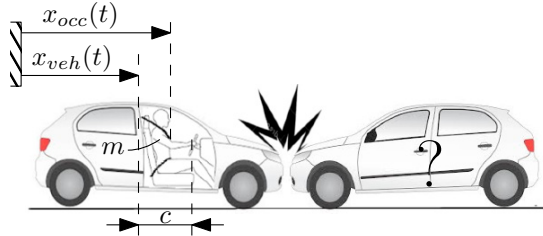


Fig. 1. Schematic representation of a frontal crash of a vehicle with occupant and an unknown object.

The relative position of the occupant with respect to the vehicle  $\Delta x(t)$  is defined as the difference between the position of the vehicle  $x_{veh}(t)$  and the position of the occupant  $x_{occ}(t)$ , given by:

$$\Delta x(t) := x_{occ}(t) - x_{veh}(t). \quad (1)$$

In the coming analysis, the following quantities are assumed to be known as they can be obtained in a real world scenario. The initial velocity of the vehicle  $\dot{x}_{veh}(0)$  follows from the vehicle speedometer. The initial position of the occupant with respect to the vehicle  $\Delta x(0)$  can be obtained using belt roll-out measurements. Using seat pressure sensors, the mass of the occupant  $m$  can be estimated. The available space in the interior of the vehicle  $c$  can be deduced from seat position information.

The amount of injury sustained by the occupant is quantified by using Injury Criteria (IC). For real-time optimal seat-belt control, the following IC is generally used:

$$IC := \max |\ddot{x}_{occ}(t)|. \quad (2)$$

Although for certified crash tests this IC has been replaced by more elaborate ones, Berthet and Vezin (2006) show that (2) is still of much value. The goal of seat-belt control is to minimize the IC by controlling the relative motion of the occupant such that no collision with the interior of the car occurs, formally:

$$\min_{\Delta x(t)} IC \text{ s.t. } \Delta x(t) \leq c. \quad (3)$$

Figure 2 provides a qualitative example of the speed profile of a vehicle during a frontal crash together with the solution to (3). At  $t = 0$  an accident occurs and the position of the seat of the vehicle is set to zero:

$$x_{veh}(0) = 0, \quad (4)$$

this effectively creates a frame of reference. At this moment, the occupant has no velocity relative to the vehicle:

$$\Delta \dot{x}(0) = 0 \rightarrow \dot{x}_{occ}(0) = \dot{x}_{veh}(0). \quad (5)$$

If a collision between the occupant and the vehicle has to be avoided, there must be a time  $t_{end}$ , for which holds that:

$$\Delta \dot{x}(t_{end}) = 0 \rightarrow \dot{x}_{occ}(t_{end}) = \dot{x}_{veh}(t_{end}). \quad (6)$$

For normal frontal crashes, the optimal velocity profile is characterized by full use of the available space:

$$\Delta x(t_{end}) = c, \quad (7)$$

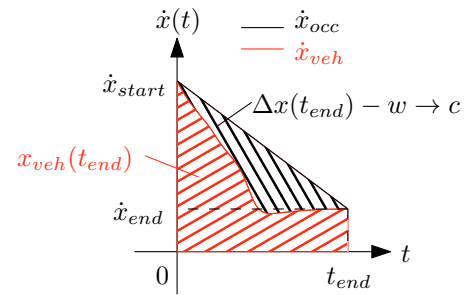


Fig. 2. Qualitative example of the velocity of a vehicle during a crash and the optimal occupant velocity profile.

and a constant deceleration:

$$\ddot{x}_{occ}(t) = -OIC, \quad (8)$$

where OIC is the Optimal Injury Criterion. Therefore, the velocity of the occupant  $\dot{x}_{occ}(t)$  is given by:

$$\dot{x}_{occ}(t) = -OIC t + \dot{x}_{veh}(0), \quad (9)$$

where (5) has been used. The motion of the occupant  $x_{occ}(t)$  becomes:

$$x_{occ}(t) = -\frac{1}{2}OIC t^2 + \dot{x}_{veh}(0)t + \Delta x(0), \quad (10)$$

where (4) has been used. The time  $t_{end}$  can be obtained using (6) and (9) for  $t = t_{end}$ :

$$t_{end} = \frac{\dot{x}_{veh}(0) - \dot{x}_{veh}(t_{end})}{OIC}. \quad (11)$$

Substituting (11) and (7) into (10) results in:

$$OIC = \frac{\dot{x}_{veh}^2(0) - \dot{x}_{veh}^2(t_{end})}{2(x_{veh}(t_{end}) + c - \Delta x(0))}. \quad (12)$$

The OIC can only be used in retrospect since both  $\dot{x}_{veh}(t_{end})$  and  $x_{veh}(t_{end})$  are unknown during the crash and will vary greatly from scenario to scenario. The dependency of the optimal solution on future knowledge is not a product of solving (3) but rather a fundamental limitation of applying optimal control to seat-belt systems. Van der Laan et al. (2010), Ziegahn et al. (2004) and Moritz (2000) provide solutions for the prediction of the future of the crash. Furthermore, since seat-belt systems are only a part of the vehicle safety system, a high level decision making process, see Musiol et al. (1997), must be performed. However, these two challenges regarding seat-belt control are beyond the scope of this study.

As (12) implies the solution to (3), the need to solve (3) numerically is omitted. This significantly reduces the computational effort of controllers based on it. In addition, (12) provides some useful insights into controlled seat-belt systems. First, the optimal occupant motion is independent of the shape of the deceleration profile of the vehicle as long as the inequality  $\dot{x}_{occ}(t) > \dot{x}_{veh}(t)$  for semi-passivity of the actuator is respected. Second, the OIC scales quadratically with the crash velocity  $\dot{x}_{veh}(0)$ . Third, seat-belt control in general becomes effective when the available space for the occupant in the vehicle  $c - \Delta x(0)$  is large compared to the amount of travel of the vehicle  $x_{veh}(t_{end})$ . Finally, the OIC is rather insensitive to the end velocity  $\dot{x}_{veh}(t_{end})$  since it is generally much smaller than the initial velocity. The following section provides an implementation example of (12) for crashes where the conditions for effectiveness of seat-belt control are clearly present.

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