PRINCIPLES OF THE ACTIVE COLLISION MITIGATION SYSTEM FOR VEHICLES INVOLVED IN LIGHT IMPACT

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ABSTRACT

The paper presents a collision mitigation method in which the aim is to stabilize the motion of the vehicle after a light impact has occurred. A yaw rate servo control based on the bicycle model is applied for control purposes. The collision is assumed to have been detected by a passive safety system, e.g., airbag sensors. The control system is activated by the monitoring signal. After the collision has occurred the motion of the vehicle and the operation of the control system are illustrated through CarSim simulation examples. Two control solutions are analyzed: in the first case active steering is used while in the second case steering is combined with differential braking. With the knowledge of certain vehicle parameters and the impact force and direction, post impact vehicle states (yaw rate, velocities, roll rate) can be analyzed. A sensitivity analysis is carried out to determine the validity range of the vehicle model in the presence of uncertainties and different kinds of impact forces. Several software packages are used for the design and analysis of the controlled system. The control design is performed by using the Matlab/Simulink software and the verification of the designed controller is performed by using the CarSim software.

Keywords: collision mitigation, yaw control, bicycle model, integrated control

1. INTRODUCTION

In the past decades vehicle safety has become one of the key issues in the automotive industry. Together with the effective organization of the traffic flow, the engineers' goal is to decrease the number and seriousness of vehicle accidents. In the developed countries with the grown motorization rate road capacity is nearly at it's maximum, hence the number of conflict situations among vehicles increased. Accordingly vehicles participating in traffic need to meet constantly higher safety standards. Safety features can be rated to two major categories: passive safety equipment (seat belts, safety cabin, airbags, etc.) mitigate the severity of accidents already occurred, while active safety tools are responsible for the prevention of dangerous traffic situations (ABS,ESP, ACC, etc.). Statistics show that in the developed countries the number of fatal accidents decreased in the past few decade despite the dramatic growth of the traffic. The main factor contributing in this result besides the advanced traffic engineering is the higher safety standards of the vehicles.

However to approach the goal of a road traffic without fatal accidents defined by government agencies, various type of hazards must be eliminated. Several statistics [1] shown that a vehicle involved in a light impact may experience a severe secondary crash, and 1/3 of all ac-

cidents with severe injuries are due to multiple events. Thus the task of controlling a vehicle in an accident is an important issue studied by relatively few researchers.

One of the first study on collision control was reported by Chan [2], in which a post-impact steering control was investigated. The controller used information about the vehicle position in the lane and the heading angle, which can be realized with technically complex and expensive tools (marker sensors, computer vision, etc...). In addition, steering control alone without braking is probably not capable to deal with a severe collision with bigger impact angles.

Bosch, a German company, released a prototype of a Secondary Collision Mitigation (SCM) system. Here the active and passive safety systems of the car are combined. The airbag sensors detect the collision event by measuring the vehicle's acceleration (passive), and after the detection phase automatic braking is applied (active). Accordingly the kinetic energy and the distance traveled after the collision is reduced for the subject vehicle, thus the risk and/or the severity of a secondary accident is mitigated.

One may think that an electronic stability control (ESC) is capable of stabilizing a vehicle after an impact, but research conducted by Thor [3] has shown the limitations of such systems. Since the disturbance and the control source of such control system are both from the tire force variations, an exogenous impact induced vehicle motion is likely to be beyond the operation range of the ESC.

A four-DOF collision vehicle model was proposed by Jianbo Lu et al. [4] for collision control. With the knowledge of certain vehicle parameters and the impact force and direction (or the bullet vehicle's velocity and heading angle), the post impact vehicle states (yaw rate, velocities, roll rate) were determined. The results were compared with the results calculated with the three-DOF momentum-conservation-based model and was validated by the calculations of CarSim. One of the major achievement of this four-DOF model was the capability to consider tire forces and roll rate variations. This model was the base for the collision detection and control developed later with a sliding surface method and model predictive supervisory control [5] [6].

The motivation of this is paper is to propose the design of a control method dealing with the stabilization of the vehicle after a light collision has occurred. The control goal is to track the desired yaw rate set by the driver with the use of active steering and differential braking. The design method is then validated with the use of simulation software Carsim, where control strategies using different actuators are compared to each other along with the uncontrolled collision case.

The paper is organized as follows: in Section 2 a vehicle model used for collision control is introduced. The description of the collision is discussed in Section 3. In Section 4 a yaw rate tracking linear quadratic design method is presented. The simulation results are discussed in Section 5. Finally, conclusions are presented in Section 6.

2. VEHICLE MODEL FOR COLLISION CONTROL

For modeling of the vehicle motion a commonly used simplification, the so called bicycle model is used. This single track bicycle model with 3-DOF as shown in Fig. 1 is unable to capture certain aspects of the vehicle motion, such as the roll and the pitch dynamics. In this work these motions are not included, since the main task of the con-

troller is to maintain the vehicle's directional stability, thus the modeling of the yawing motion is sufficient. In later work the model can be modified to incorporate other aspects of the vehicle dynamics in order to avoid such treats as a turnover.

The left and right wheels at the back and at the front of the vehicle are represented by one wheel in the bicycle model. The major assumption of this model is that the wheels velocity vector is in the same direction as the wheels orientation angle, which is only true for small velocities. The state variables are the yaw rate $\dot{\psi}$ and the vehicle body side slip angle β. The vehicle velocity v is considered as a changing parameter in the model. The control input may vary depending on the control strategy.

In the state equation below two controller inputs are considered: the steering angle of the front tires δ (considered equal for both sides of the vehicle) and the moment applied on the vehicle vertical axis M_f generated by differential braking of the rear wheels. The impulse of the collision is formalized as a disturbance acting on the input, where F_y is the lateral force applied at the center of gravity of the vehicle, M_z is the impact moment applied at the vehicle vertical axis.
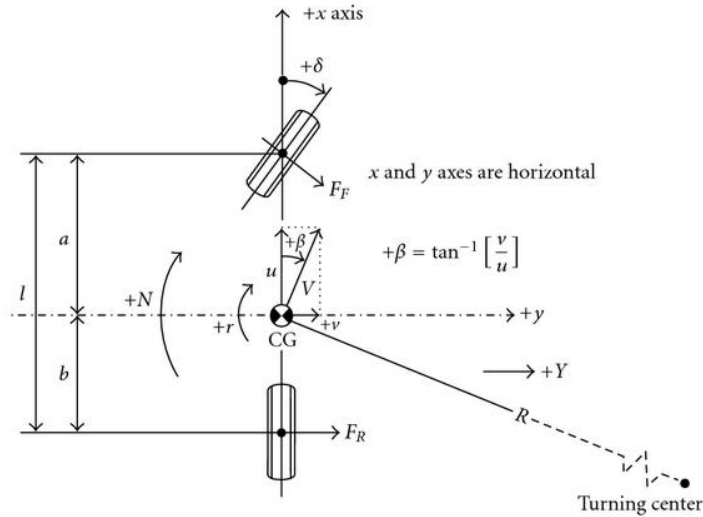

Fig. 1 Single track bicycle model

The state equation is as follows:

$$\dot{x} = \begin{bmatrix} -\dfrac{c_1 l_1^2 + c_2 l_2^2}{Jv} & \dfrac{c_2 l_2 - c_1 l_1}{J} \\ \dfrac{c_2 l_2 - c_1 l_1}{mv^2} - 1 & -\dfrac{c_1 + c_2}{mv} \end{bmatrix} x + \begin{bmatrix} \dfrac{c_1 l_1}{J} & \dfrac{1}{J} \\ \dfrac{c_1}{mv} & 0 \end{bmatrix} u + \begin{bmatrix} 0 & \dfrac{1}{J} \\ \dfrac{1}{mv} & 0 \end{bmatrix} d, \tag{1}$$

where $\quad x = \begin{bmatrix} \dot{\psi} & \beta \end{bmatrix}^T, \quad u = \begin{bmatrix} \delta & M_f \end{bmatrix}^T, \quad d = \begin{bmatrix} F_y & M_z \end{bmatrix}^T, \quad \delta_{\min} \leq \delta \leq \delta_{\max},$ $M_{f\min} \leq M \leq M_{f\max}.$

The steering angle δ of the front tires is constrained by the construction of the steering system, while the moment applied on the vehicle M_f is constrained by the principle

of limiting the friction. This maximum moment can be calculated with the following equation: $M_{f\,\text{max}} = -M_{f\,\text{min}} = \mu F_{zr} d$, where μ is the friction coefficient, d is the half length of the rear axle and F_{zr} is the normal load of the rear axle given by:

$$F_{zr} = mg\,\frac{a}{a+b} \tag{2}$$

The moment applied at the vehicle center is given by differential braking of the rear wheel (see Fig. 2). The relation between this moment and the braking force is given as:

$$M_f = (F_{xr,L} - F_{xr,R})b \tag{3}$$

where a and b are the distances of the front and rear axle from the center of gravity (see Fig. 1), m is the vehicle mass, g is the gravity constant, $F_{xr,L}$ and $F_{xr,R}$ is the longitudinal wheel force.
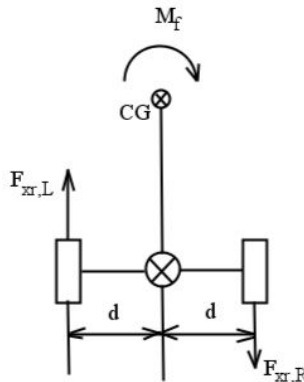

Fig. 2 Rear axle geometry

The tire side force constants c_1 and c_2 are identified at constant speed. The vehicle velocity v is a dynamic parameter considered to be constant (v=104 km/h). Note, that this vehicle model is nonlinear with the quadratic parameter v and the tire side slip forces c_1 and c_2, thus for a global solution for the above equation a gain scheduling or LPV controller must be designed.

Measuring vehicle state β is rather difficult and expensive, thus it is practical to estimate it. Vehicle side slip estimation has been introduced by several authors. The side slip angle can be estimated by using GPS measurements in conjunction with other vehicle sensors as shown by Bevly *et. al.* or can be estimated using observers [7,8]. In this paper for the estimation of the state variables an observer was designed.

3. COLLISION DESCRIPTION

There are several types of collisions which can occur on the roads with different severity. In this paper, some assumptions need to be made in order to design an effective post impact control strategy. First of all, after the collision impact the steering and brake system must function properly for at least a short period of time. This assumption probably means that the velocity differential between the vehicles is less than 40-55 km/h for rear-end collisions.

The resultant impulse vector of the collision is assumed to have a specific point of application on the target vehicle's periphery. This application point together with the force vector amplitude and angle can be calculated by the measures of the airbag sensor.
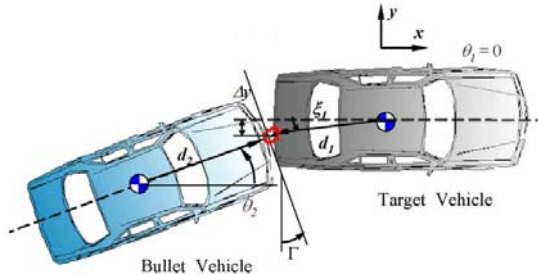

Fig. 3 The scheme of the collision impact

Typical time duration of a collision is around 0.1-0.2second. Hereinafter the time duration assumed to be 0.15s. The impact force is assumed to build up in a spike form. The collision scene is shown in Fig.3, where the bullet vehicle is hitting the target vehicle which is controlled after the impact. Note that this rear end collision is with a certain angle, thus the impact force has components on both the *x* and *y* axis.

4. YAW RATE SERVO CONTROLLER DESIGN

Control objectives can differ depending on the collision event, the traffic situation and technical facilities. Stopping the vehicle after the impact as soon as possible may be a logical control objective. However, this can still result in dangerous situations like a suddenly stopping vehicle on motorway. Thus, in this paper the control goal is to maintain the target vehicle directional stability.

For this purpose a yaw rate tracking controller was designed with a servo structure (see Fig.4). In this scheme the state feedback is combined with an output feedback with integrating property. The vehicles states $\dot\psi$ and β were used for state feedback and the system output $\dot\psi$ is tracked. The reference signal is the calculated yaw rate, which is set by the driver with the use of the steering wheel:

$$r = \dot\psi_r = \frac{v\cos(\beta)}{a+b}(\tan(\delta_1) - \tan(\delta_2))$$ (4)

where δ_1 and δ_2 are the front and rear wheels cornering angle.
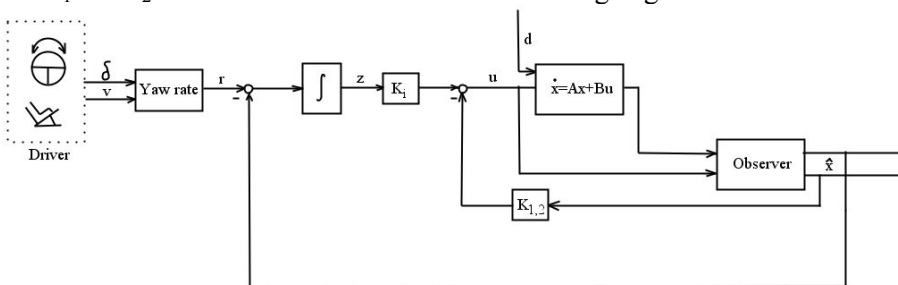

Fig. 4 The scheme of the yaw rate tracking control

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Then a new state is defined as follows:

$$z = \int_0^t (\dot{\psi}_r - \dot{\psi})dt \tag{5}$$

Let the augmented state vector be defined as follows: $\tilde{x} = [x \quad z]^T$, where $\hat{x}$ is the estimated state vector. The state equation is modified containing the above error signal:

$$\dot{\tilde{x}} = \begin{bmatrix} -\dfrac{c_1 l_1^2 + c_2 l_2^2}{Jv} & \dfrac{c_2 l_2 - c_1 l_1}{J} & 0 \\ \dfrac{c_2 l_2 - c_1 l_1}{mv^2} - 1 & -\dfrac{c_1 + c_2}{mv} & 0 \\ -1 & 0 & 0 \end{bmatrix} \tilde{x} + \begin{bmatrix} \dfrac{c_1 l_1}{J} & \dfrac{1}{J} \\ \dfrac{c_1}{mv} & 0 \\ 0 & 0 \end{bmatrix} u + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} r + \begin{bmatrix} 0 & \dfrac{1}{J} \\ \dfrac{1}{mv} & 0 \\ 0 & 0 \end{bmatrix} d, \tag{6}$$

The input signal is then as follows:

$$u(t) = -K_{1,2}\hat{x}(t) + K_i z(t) \tag{9}$$

where K^T is the gain of the states, while K_i is the gain of the augmented state z defined as an error signal. The control goal is to follow the desired yaw rate by the intervention of the steering angle and the brake torque. The design of control gains is based on different robust control design methods such as LQ or Hinf.

5. SIMULATION RESULTS

The post impact design method has been validated with simulation performed in CarSim. The impact of the collision was given as exterior force acting on the vehicle. The vehicle speed was set to constant 104 km/h before the collision, and after the impact no driver intervention was assumed. In the simulation a full size SUV was used with the parameters given in Table 1.
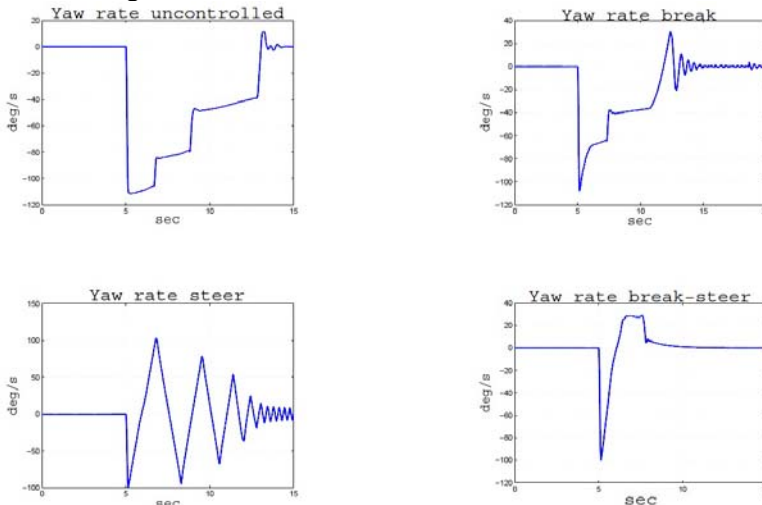

Fig. 5 Post impact yaw rate tracking with different methods

Variable	Value	Unit		Variable	Value	Unit
m	2210	kg		d	0.975	m
I_z	4946	$kg.m^2$		$\delta_{max}=-\delta_{min}$	45	deg
a	1.105	m		g	9.81	m/s^2
b	1.745	m		μ	0.7	-

Table 1 Vehicle data

The impact of the collision was simulated by applying a force vector on the vehicle with longitudinal (F_x) and lateral (F_y) components. The performances of the designed controllers are shown in Fig.5, where the yaw rate tracking ability of the vehicle is analyzed.

6. CONCLUSIONS

A yaw-rate servo control method has been introduced to avoid stability loss in the case of a light impact collision. The simulation results have shown that by applying both differential braking and active steering the vehicle's yaw rate set by the driver can be tracked much faster than by applying solely the break or the steering input or without any control action. The vehicle's directional stability can be preserved with the proposed method without significant deviation in the lateral position of the vehicle or without the spinning out of the lane.

Future work must consider the problem of collision detection and validation to avoid any control action taken based on false sensor information or sensor error. A sensitivity analysis must be carried out to describe the margins of such post impact control systems and to describe collision situations where the control action may be ineffective or harmful. A three dimensional vehicle model should also be applied to capture roll and pitch dynamics of the vehicle in order to avoid a possible rollover.

7. ACKNOWLEDGEMENT

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