

## COLLISION DETECTION ALGORITHMS IN THE ECALL SYSTEM

**Tomasz Kamiński, Michał Niezgoda, Mikołaj Kruszewski**

*Motor Transport Institute  
Transport Telematics and Management Centre  
Jagiellonska 80, 03-301 Warsaw, Poland  
tel.: +48 22 8113231, fax: +48 22 8113231  
e-mail: tomasz.kaminski@its.waw.pl, mikolaj.kruszewski@its.waw.pl  
michal.niezgoda@its.waw.pl, www.its.waw.pl*

**Rafał Grzeszczyk, Tomasz Drop**

*Automex Sp. z o.o.  
Marynarki Polskiej Street 55d, 80-557 Gdansk, Poland  
tel.: +48 58 5220620, fax: +48 58 5220621  
e-mail: rafalg@automex.pl, tomasz.drop@automex.pl*

**Przemysław Filipek**

*Technical University of Lublin  
Department of Mechanical Engineering  
Nadbystrzycka Street 36, 20-618 Lublin, Poland  
tel./fax.: +48 81 5384499  
e-mail: p.filipek@pollub.pl*

### **Abstract**

*The article describes some algorithms for collision detection used in modern cars airbag systems. While controlling the activation of airbags and other passive safety systems, installed in modern vehicles, the algorithms must operate in the early stage of accident, because for operating effectively it is necessary to run control systems early enough, for example filling airbags before the body of the driver or passenger reaches the zone of airbag. These algorithms could be applied into the on-board eCall modules, but they would require calibration. Detection of the collision that activates eCall system must be made on the basis of measurable signals or observable events, which intensity can be relatively clearly linked to the probability serious injury of the driver and the passengers' of the vehicle. A table summary presented in this article contains a description of the collision detection algorithm along with a brief description of the method of detection and description of the used methodology. A frequently used method is to evaluate the gradient of the change of speed - the parameter  $\Delta V$ , or its combinations with different parameters, such as the derivative of acceleration, displacement, and energy of the collision. Each of the algorithms has been briefly described. The whole of article is summarized with the conclusions arising from its content.*

**Keywords:** road transport, emergency response, eCall, 112, road safety

### **1. Introduction**

Only one described in the widely available literature, collision detection algorithm is the algorithms for triggering passive safety systems (called Supplementary Restraint System – SRS), such as airbag systems, air curtains, and seatbelt pretensioners. While collision detection for control SRS systems such as airbags and side curtains is a problem similar to the collision detection activating eCall system, one should also be aware of some differences and different purposes, due to which these systems are optimized.

While controlling the activation of airbags and other passive safety systems, installed in modern vehicles, the algorithms must operate in the early stage of accident (sometimes even with the use of proximity sensors to detect obstacles or approaching vehicle before collision, that is before occurrence of physical contact of the vehicle with another object), because for operating effectively it is necessary to run control systems early enough, for example filling airbags before the body of the driver or passenger reaches the zone of airbag. The design goal is to ensure complete filling of an airbag before it comes into contact with the passenger of the vehicle, when the bag begins to empty (the pressure in it decreases) - it is best to minimize injury to passengers. In the case of the lateral protection, these systems have to be activated in advance (in many cases certainly before the moment of collision), which is necessary for their effective operation, due to the short distance between passengers and exterior contour of the vehicle as well as the lack of crumple zones.

When it comes to trigger systems intended for eCall system, on the one hand the time of connection to the Public Service Answering Point (PSAP) can co-decide about the life of passengers and the effectiveness of help given to them by emergency services, and on the other hand it is rather difficult to accept (also for road safety reasons) the concept of connection initialization before or during the accident. Another aspect that should be considered when determining the guidelines for the implementation of eCall device for a vehicle is the device's damage resistance during the collision. With the passage of time, after the collision, the probability of activating the devices may decrease in case of power failure (breakage or disconnection of the battery, short circuit) - therefore in target models of these devices, it will be most likely to use independent systems to maintain power in eCall module after immobilization of the vehicle. In particular cases, the wreck of the vehicle may be (except destruction) overturned in such a position that the operation of GSM communication systems and positioning may be difficult or even impossible (natural obstacles or depressions, dense flora, water, infrastructure features of a compact construction). In case of using a navigation satellite system, this problem seems to be solved at the level of formal requirements and technical specifications for the on-board implementation of eCall systems, what requires to currently record the position of the vehicle obtained from continuously operating GNSS module on the on-board eCall module. Thus, the availability from MSD message regarding the position and current speed vector of vehicle seems to be assured. However, the efficiency of GSM communication module is a prerequisite for establishing a connection and to provide a PSAP with necessary information. In case of fire or damage of the vehicle's battery, as time passes the probability of preserving the functionality of on-board eCall device will be decreased as time passes.

All these factors make the choice of the algorithms (and their decision-making parameters) used to activate eCall system while detecting a collision quite challenging and requiring consideration of multiple, conflicting requirements.

Detection of the collision that activates eCall system must be made on the basis of measurable signals or observable events, which intensity can be relatively clearly linked to the probability serious injury of the driver and the passengers' of the vehicle.

Accelerometers are most commonly signal sources used for this task. These elements are located at different points of the vehicle. Because during the collision the mass of the vehicle is more or less deformed, the signals recorded by sensors mounted at different locations have different course and characteristic features. Algorithms analyzing acceleration waveforms that would activate eCall module may not consider the maximum values of acceleration (acceleration above an arbitrarily set level of any signal value) when making decisions. Large values of instantaneous acceleration can appear for reasons other than serious road collision, such as hitting (accidental or intentional) in the area near the sensor (e.g., falling hammer in the workshop) or, in extreme cases, the pulses could originate from the road profile. For this reason, although it is expected that the average value of acceleration at more dangerous (more intense and serious in its consequences), road accidents is higher, it is necessary to use more complex algorithms to detect

road accidents, that would take the parameters of recorded signals and their characteristics other than the maximum value of acceleration into account.

In search of methods (selection of algorithms and signal processing), useful for the detection of an accident, disparate examples are given in the literature [2].

Currently, the most common practice is to analyze the value of the vehicle's speed change studying if this could be a parameter well correlated with the probability of injury by the traffic accident participants. Then the source of signal is electronic (formerly electrical or mechanical) sensors sensitive to changes in speed (acceleration).

In another case, the degree of potential danger to the driver and the passengers of the vehicle are estimated as a function of deformation of a vehicle, being the result of a collision. The source of signal is a sensor (or sensors) mounted in a specific location of the vehicle's structure. Change of this point's location to the crumple zone of the vehicle causes triggering of the sensor and activating the system. There are no known instances of use (in the serial produced solutions), in the second of these methods, to detect a frontal collision and to trigger the front airbags. Currently, this solution is used by some manufacturers to run the side airbags SRS systems - air curtains and active reinforcements mounted in the door of the vehicles.

Another solution of the problem concerning detecting a collision is the use of acoustic sensors, attached to the vehicle's construction in such a way that they can capture and process the acoustic vibration signals associated with the deformation (crushing) of vehicle's metal structure. To process these signals band-pass filters with the range of 200-300kHz are used, then the envelope of registered and filtered signals is analyzed. If it exceeds the preset levels for a certain period of time, e.g. at least 5ms, the airbags are activated.

Another kind of collision detection sensor may be a pressure sensor detecting changes in pressure of a closed car body profile. Other solutions are built using magnetostrictive sensors that is components or sensors operating with Villari effect (magnetostrictive inverse effect) or changes in magnetic properties of the material in terms of being subjected to the action of mechanical tension. The sensor must be mounted in such a location of vehicle's design structure that could be subjected to mechanical tension in case of a collision.

## **2. Study of collision sensors**

All types of sensors and collision detection modules require testing and research to determine and verify the design process and later, also a production process, their characteristic parameters and to ensure their quality and reliability.

In the literature below, characteristics of the methods and test equipment used in these studies are given. In case of testing, the sensors are subjected to test stimulation with different waveforms (characteristics shape as a function of time), the values and durations, for example have sine waveform, half-sine waveform, square waveform, triangle waveform (saw-shaped). Some devices can generate (display) specific test waveforms, for example the ones recorded during crash tests. Testing often consists of iteratively repeated attempts, where artificially generated waveforms changing from test to test both with the amplitudes and duration time are used. When testing the activation border of sensors, the amplitude of a collision signal is changing, while keeping constant duration of the accident, until the moment of reaching assumed  $\Delta V$ . Then, tests are carried out again for other values in scope of stimulation's duration, in order to conduct full characteristics of the sensor. In tests concerning performance of the SRS system trigger sensors (in the case of tests with pulses greater than the border values), the sensor response time (the release time) is tested.

In case of collision sensors' tests, devices with different technical capabilities and with varying degrees of sophistication are used. All systems should be equipped with reference measurement systems necessary to evaluate the response of a tested device. The devices can operate in manual, semi-automatic or automatic mode. The most commonly used are:

- pendulum – the tested module is attached to a pendulum and striking in the bumper with it provides a rapid stop at the lowest point of trajectory of the pendulum. The amplitude of impact is adjusted for the pendulum release angle, and the characteristics of the pulse depend on the properties of the material used for making the bumper. It is a simple device that does not provide high precision,
- pneumatic devices – are powered by compressed air energy. Impact signal amplitude depends on the speed before the collision with the bumper, and a collision signal is shaped by selection of the appropriate material of the bumper,
- devices powered by electric actuators – used in practice, in mass production. They consist of an electrically controlled platform that is moving horizontally. The amplitude and shape of the generated waveforms are controlled by the electric actuators control system, which are powering the platform during the experiment.

### 3. Test waveforms

In practice, the most commonly used test functions are haversine functions and a half-sine functions (sine(x) for values of  $x$  in range  $(0, \pi)$ ).

Haversine function is described by formula:

$$A(t) = \frac{\Delta V}{T} \left( 1 - \cos \frac{2\pi t}{T} \right), 0 \leq t \leq T, \quad (1)$$

where  $T$  is the period of the pulse, and  $\Delta V$  is a change in velocity or area under the curve.

Half-sine function (sin(x)) for values of  $x$  in range  $(0, \pi)$ :

$$A(t) = \frac{\pi \Delta V}{2T} \left( \sin \frac{\pi t}{T} \right), 0 \leq t \leq T, \quad (2)$$

where  $T$  is the period of the pulse, and  $\Delta V$  is a change in velocity or area under the curve.

### 4. Crash detection algorithms

Implemented in modules (controllers) the collision detection algorithms decide about their physical properties. For the purpose of collision detection, the acceleration signal recorded in the modules determines the following parameters that are then included in the decision-making algorithms, in order to verify the conditions for system activation:

- derivative of acceleration (called jerk),
- speed (after integration of acceleration signal),
- displacement, squeeze, deformation (double integration),
- the signal energy (acceleration or velocity),
- signal power (acceleration or velocity).

Below there is a summary of selected collision detection algorithms along with a brief description.

The main assumptions of collision detection algorithms included in the table are described below.

#### **Diller (TRW)**

The algorithm developed by R. W. Diller (TRW) team analyzes the energy distributed during an accident. The analysis is carried out in time domain to avoid the need for hardware implementation of FFT (Fast Fourier Transformation). The algorithm calculates and monitors the amount of energy determined in subsequent time intervals (the width of the window duration is 12 ms with 2 ms needed for update). The basic principle of the algorithm is based on the assumption that the energy dissipated in an accident (and indirectly recorded by the accelerometers) is divided between a general deceleration of the vehicle (signals with a frequency of 3 Hz and below) and energy dispersed in the

Tab. 1. The selected collision detection algorithms [2]

No.	Solution author/ company	Method / Properties	Description
1.	Diller et al./TRW	Energy: the total and partial	The energy in the time domain
2.	Allen/ASL	Signal power	Energy + derivative of acceleration + acceleration + $\Delta V$
3.	Gioutsos/ASL	Waveform recognition	Derivative of acceleration
4.	Watanabe, Umezawa	Optimizing of SRS system releasing time	Predicting the displacement, acceleration, a derivative of acceleration, energy
5.	Mattes et al./ Robert Bosch GmbH	Adjustable speed border	$\Delta V$
6.	Diller/TRW	Expert system	$\Delta V$ + derivative of acceleration + displacement
7.	Eigler, Weber/Siemens	Multicircuited evaluation and the variable time interval of analysis	Identification of acceleration + speed + displacement
8.	Tohbaru/Honda Blackburn/TRW Blackburn, Gentry/TRW	Acceleration signal power in the frequency domain	$\Delta V$ + energy in the frequency domain
9.	Cashler, Kelly/ Delco Electronics	Displacement of passenger and evaluation of the accident effects	Derivative of acceleration + acceleration + $\Delta V$ + displacement
10.	McIver et al./TRW	Estimation of speed and identification of the waveform	$\Delta V$ + acceleration + identification of the waveform
11.	Sada, Moriyama/STC	Velocity estimation based on physical parameters	Derivative of acceleration + acceleration + $\Delta V$ + displacement
12.	Kosiak/Delco Electronics	Detection of an accident using overtaking sensors	Scaling of acceleration using overtaking sensors

structure of the vehicle (bending, vibration, strain, braking that are associated with the individual components of total energy). The total energy associated with the accident is calculated as the square root of the absolute value of the acceleration signal. Partial energy is determined by subtracting the average signal value (constant component). The algorithm determines the activation if there is a detection of exceeding border values for both total energy and partial energies in a fixed period of time. The results of the algorithm could also be corrected in some implementations by using feedback from  $\Delta V$  that in this case acts as a traditional mechanical protection used in many designs with electronic triggers of SRS systems (extra, in addition to semiconductor accelerometers, mechanical sensor mounted in series circuit of the SRS system release, which main function is to protect against accidental release of short-term electromagnetic interference or a signal conditioning circuits fault and electronic components. This sensor provides a physical opening of a circuit in conditions of lack of delay of sufficient value and duration, which are distinctive for the collision). This prevents against the occurrence of undesirable activation in case of registering high values of instantaneous acceleration from sensor, which are not accompanied by respectively significant change in velocity, i.e. in a collision with a small animal, or accelerations caused by running into potholes of the road.

### **Allen (ASL)**

In the method developed by J. L. Allen (ASL), first derivative of the designated course of signal power is analyzed. To determine the intensity of the accident it uses measurements of acceleration, velocity and acceleration derivative. The factors used to determine signal parameters in the algorithm are as follows:

– energy:

$$E = \frac{1}{2} m v^2, \quad (3)$$

– power:

$$P = \frac{dE}{dt} = m v \frac{dv}{dt} = m v a, \quad (4)$$

– variation of power (power derivative):

$$\dot{P} = \frac{dP}{dt} = m \left( v \frac{da}{dt} + \frac{dv}{dt} a \right) = m (v j + a^2). \quad (5)$$

In the equation describing the variation of power, the dominant component is a product of  $v(t) \cdot j(t)$  equation during the 0-40 ms from the beginning of the collision. Power variation method takes into account both the value of speed change and acceleration variability (derivative), what has some advantages, such as allowing proper detection of accidents at lower speeds, where  $\Delta V$  does not have to be the best indicator of risk measurement, during the angle collisions and the collisions with fixed obstacles. Taking into account the factor  $v(t)$  ensures proper operation of the algorithm in a long term, while protecting against false activations resulting from potholes in the roads that generate large values of  $j(t)$  (the variability of acceleration). However, they are accompanied by small values of  $v(t)$  which compensate all value of  $v(t) \cdot j(t)$  member. The algorithm assumes that the power variation calculated from the acceleration signal is proportional to the power variation effects on the passengers of the vehicle. Measurement data from the acceleration sensor are averaged using a sliding “window” and the data stream from this “outstretched average” process is used to determine the variability of acceleration. The aim of averaging is to smooth the course of recorded signals and as a result eliminating the problems caused by roads potholes.

### ***Gioutsos (ASL)***

Prediction algorithm developed by T. Gioutsos (ASL) identifies the type and intensity of the collision by identifying the forehead of acceleration signal waveform according to the relation:

$$c(t) = f\{n(t), ah(t)\}, \quad (6)$$

where:  $c(t)$  is estimated waveform at time  $t$ ,  $n(t)$  is value of the noise at time  $t$ ,  $a$  is the slope of the rising edge of the ramp signal, and  $h(t)$  is a registered course at time  $t$ .

It is assumed that the major consequences of accidents are accompanied with higher value of a parameter, i.e. the increase of slope is steeper. In this method, sliding measurements window is not applied. The main parameter of the signal used to activate airbags is the acceleration’s volatility value – i.e. rising rate of signal front edge.

### ***Watanabe, Umezawa***

K. Watanabe and Y. Umezawa developed algorithm, in which the emphasis is placed on optimizing the time of release of the SRS system, with the predicted displacement of the vehicle passenger. The algorithm uses Kalman filtering to estimate the speed and its variability over time, estimation of velocity and displacement of the passenger, predicting velocity and displacement of the passenger after the collision, in order to determine the optimal timing of release of SRS system. Trigger borders of algorithm are achieved by the predefined limit of the estimated acceleration or its derivative, or by the expected velocity of the passenger, or by displacement value of the passenger's body obtained in predicting way.

### ***Mattes (Robert Bosch GmbH)***

The team of B. Mattes (Robert Bosch GmbH) developed an algorithm that initially integrates acceleration signal in the time domain, and then the resulting waveform of velocity is used to

activate the system. The limit parameter value used for the activation is variable depending on the type of identified collision, and the situation or condition of the vehicle. It depends for example on the trend (direction change) of speed. This method is also known as the method based on the concept of a variable trigger border for tracking  $\Delta V$  value.

#### ***Diller/TRW***

Multicriterial algorithm using an expert system is based on a patented solution by R. W. Diller. The algorithm independently analyzes many different signal parameters. Some are treated as the essential criteria (e.g. speed), the other as an additional / supportive - such as displacement or a derivative of acceleration. Each of the independent decision circuit with a specific weight affects the total result of the decision algorithm concerning system releasing. In addition, the analysis aimed at identifying the type of collision is made. Output signals from the expert model, which are consistent with the characteristic pattern associated with the detected type of collision are added together and included in the final verdict of the algorithm. Precision tuning of the algorithm is the selection of appropriate weights for individual components of the total index compared with specified border value.

#### ***Eigler, Weber (Siemens)***

Multicriterial algorithm using the windows was developed by J. Eigler and R. Weber. In this method at the same time different criteria are used to evaluate the accident, thus the acceleration signal is analyzed in the time domain and different methods and limit values are used. The different types of accidents are also detected, for example, there is a distinction between front impact collision and collision with obstacles (e.g. a pole). Then, depending on the fixed type of collision, different decision-making levels are set.

#### ***Tohbaru (Honda), Blackburn, Gentry (TRW)***

The basis for the release of SRS system concerning the algorithms developed by S. Tohbaru, BK Blackburn and SB Gentry is the signal power spectrum analysis of the acceleration in the frequency domain. To implement this algorithm, integral of acceleration signal is calculated to determine the velocity of a passenger. Signal power in band of 100-200 Hz is also calculated. Airbag launch happens in case of exceeding certain limit by any of these parameters.

#### ***Cashler, Kelly (Delco Electronics)***

Displacement of passengers and estimated scale of damage of collision participants are essential characteristics of an algorithm developed by the R.J. Cashler and J. P. Kelley. Based on analysis of signal variability parameters such as the derivative of acceleration, acceleration, velocity and estimated displacement are evaluated. On their basis, airbags can be activated.

#### ***McIver (TRW)***

G. C. McIver's team developed an algorithm, which sets velocity based on the acceleration signal. There are also determined, in particular work conditions, the appropriate reference levels (release signals). Shape of the acceleration course is also compared with stored patterns. Signal processing implements the following operations: low-pass filtering of acceleration signal, calculating the square of the acceleration signal, summing the squares of the acceleration values in the given time window, comparing the signal with the stored patterns of waveforms shapes.

#### ***Sada, Moriyama (STC)***

Algorithm by H. Sada and H. Moriyama designed for the system activation sets parameters such as velocity, acceleration, acceleration derivative and displacement, but these values are compared with border values set by a separate module of the algorithm. Triggering occurs after crossing the limit value.

### ***Kosiak (Delco Electronics)***

Solution by W. K. Kosiak (Delco Electronics) uses sensors to detect approaching the obstacles before the physical contact happens, in order to arm the system and prepare it for rapid activation. The use of two sensors mounted at the front of vehicle allows specifying whether the frontal or angle collision occurs.

## **5. Summary**

Due to the lack of guidelines for the construction of a collision detection module of on-board eCall device, the best solution seems to be taking assumption that the device should call assistance in case acceleration of the body of the vehicle occurs, a similar one to those caused by running airbags. Therefore, the evaluation criteria, algorithms and values of specific parameters related to the collision can be modelled on the vehicle SRS systems.

The article describes some collision detection algorithms for systems used in airbags. However, an unresolved problem, consisting of adjusting the parameters of collision detection algorithm for the car model, in which the eCall device will be installed, still remains. Depending on the mounting location, stiffness of elements linking the device with the vehicle body, weight and stiffness of the vehicle itself, correction of the value of these mentioned parameters will be required. There has been no specific recommendation on this case so far, which is a serious problem for the proper functioning of eCall as an entirety.

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