AIR BAG DEPLOYMENT CRITERIA

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ABSTRACT

Air bag control modules utilize complex algorithms to make air bag deployment decisions based on crash severity related to the change in vehicle speed or deceleration over time. Due to the proprietary nature of air bag deployment algorithms, the velocity, acceleration, or displacement thresholds for air bag deployment during a collision are not easily obtained; however, a range of frontal barrier impact speeds and corresponding deceleration and displacement threshold values for air bag deployment can be approximated using known vehicle stiffness-to-weight ratios.

KEY WORDS

air bag deployment, decision, event, data, sensor, trigger, threshold, algorithm, acceleration, accelerometer, crash pulse, wakeup, enable

LEARNING OBJECTIVES

1. Gain an understanding of the air bag system and components.
2. Gain an understanding of when an air bag should or should not deploy.

SCOPE OF PAPER

An introduction to air bag systems and inflation processes will be followed by a brief history of crash sensors. Variables used in air bag deployment algorithms will be described, and examples of several patented systems compared. A method to estimate the range of speed, deceleration, or displacement thresholds for air bag deployment will also be provided.

DEFINITION OF TERMS - See Appendix:Glossary

INTRODUCTION

The purpose of the air bag is to provide a cushion between the occupants and the vehicle's interior. For air bags to be effective they have to be fully inflated in a short amount of time, before the occupants make contact with them; however, this rapid inflation can potentially cause fatal injuries to certain people if they are in contact with the air bag during its inflation. Therefore, air bags must have a control system that can recognize a crash correctly, and early enough for the air bags to inflate safely.

THE INFLATION PROCESS

Air bags inflate after an electric current from the air bag control module is sent to a detonator. This ignition starts a chemical reaction producing nitrogen gas which rapidly inflates the nylon fabric air bag. The deployment and inflation process takes approximately 0.04 seconds [1]. After full deployment, as the occupant impacts and compresses the air bag, the nitrogen gas is released through small vent holes. The holes are specifically sized and spaced to reduce the volume of the bag at different rates, depending on the type of vehicle. The gas is released along with dust particles from material used to lubricate the bag (typically talcum powder and cornstarch).

CRASH SENSOR HISTORY

Early air bag deployment systems in older vehicles utilized mechanical sensors for crash detection, which were phased out of the US market around 1994 [10]. Early mechanical sensors, such as the "rolamite" by Sandia National Laboratories, relied on a metallic sphere that was stabilized at a standby position by a spring or a magnet (see Figure 1).

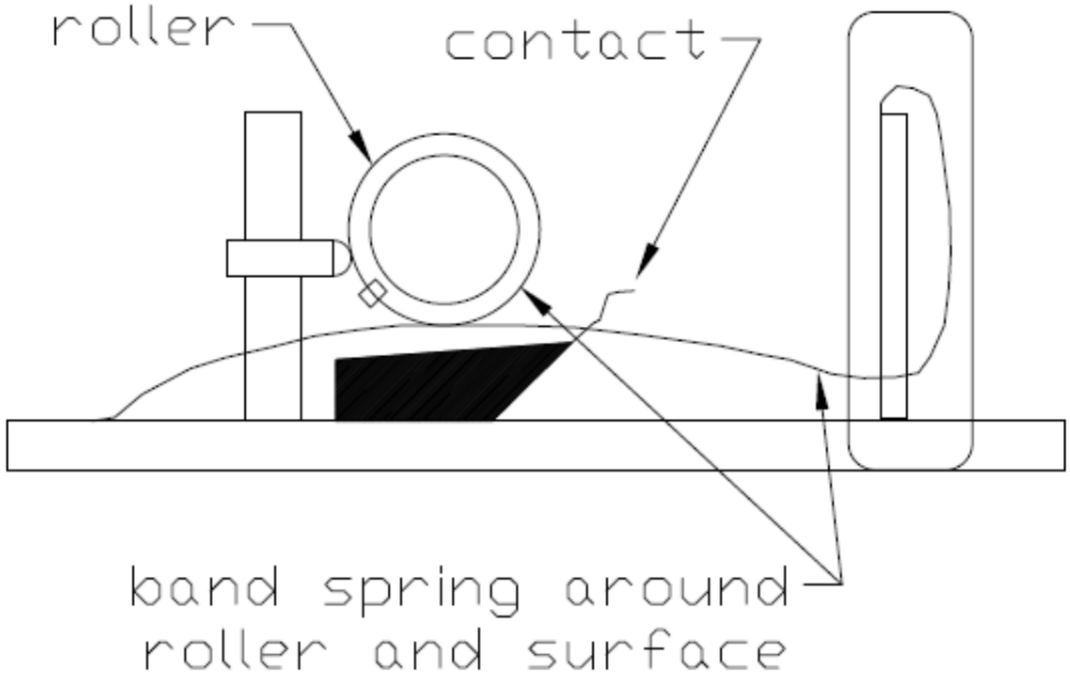


Figure 1. Mechanical Air Bag Sensor [10]

When the sensor was subjected to a force beyond a designed threshold, the spring or magnet could no longer keep the metallic mass in place. The mass moved and made contact with an electrode, sending an electrical signal to the air bag control module, which then sent a signal to the air bag control module. Systems with mechanical sensors were generally inaccurate at interpreting minor collisions. Movement within mechanical sensors can be underrepresented with frontal collisions, and the acceleration the sensor experiences are sometimes slightly delayed. As an improvement, modern air bag deployment now relies on microelectromechanical system (MEMS) components.

NEW CRASH SENSING SYSTEMS

New MEMS crash sensors measure acceleration with an accelerometer that sends a continuous stream of data to the air bag control module. Accelerometers are typically piezoelectric or variable capacitance sensors. The most common MEMS accelerometer in use today is the ADXL-50 by Analog Devices (see Figure 2 below).

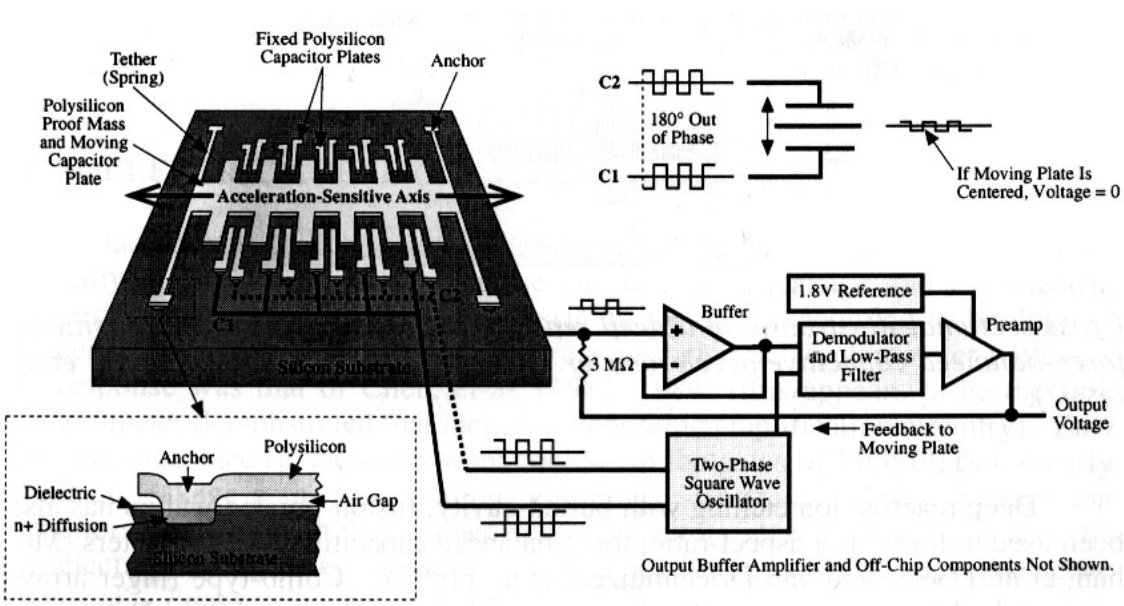


Figure 2. Microelectromechanical Sensor (MEMS) [Source: Analog Devices, Inc.]

As an anchored mass moves relative to the sensor's body due to acceleration, a plate attached to the anchored mass moves closer to a stationary plate. The change in distance between the plates affects the capacitance of the sensor, or the ability to hold an electrical charge. This change in capacitance is easily measured and is then converted to a change in voltage. The voltage change is directly correlated to force due to acceleration, and the readings are interpreted as acceleration by the air bag control module. Using an algorithm, the control module can determine if air bag deployment is necessary based on the pattern of the acceleration pulses over time.

THE DECISION PROCESS

The air bag control module (ACM) receives a continuous signal from each MEMS sensor and records the data for a fixed period after a specific event. With a central processing unit (CPU), it performs algorithmic computations and controls the "fire" or "no-fire" command for air bag deployment. The triggering algorithms determine crash severity by evaluating one or more of the kinematic variables (derivatives/integrals of acceleration) shown in Table 1. Examples of algorithm decision flow charts are shown in the following Figures 3, 4, and 5.

Variable	**Expression**	**Units**
Acceleration	$a = \frac{dv}{dt}$	ft/s^2
Velocity (Δv)	$v = \int adt = \frac{dx}{dt}$	ft/s
Displacement	$x = \int vdt = \iint adtdt$	ft
Jerk	$j = \frac{da}{dt}$	ft/s^3
Energy Density	$e = \int_{x_0}^{x} adx = \int_{v_0}^{v} vdv = \frac{1}{2}\,(v^2 - v_0^2)$	(ft/s)^2
Energy	$E = \frac{1}{2}\,m(v^2 - v_0^2), \qquad m: mass$	ft-lb
Power	$\bar{p} = \frac{dE}{dt} = mva$	ft-lb/s
Power Density	$p = \frac{\bar{p}}{m} = va$	ft^2/s^3
Power Rate Density	$p' = \frac{dp}{dt} = vj + a^2$	(ft/s^2)^2

Table 1. *Kinematic variables used in air bag triggering algorithms.*

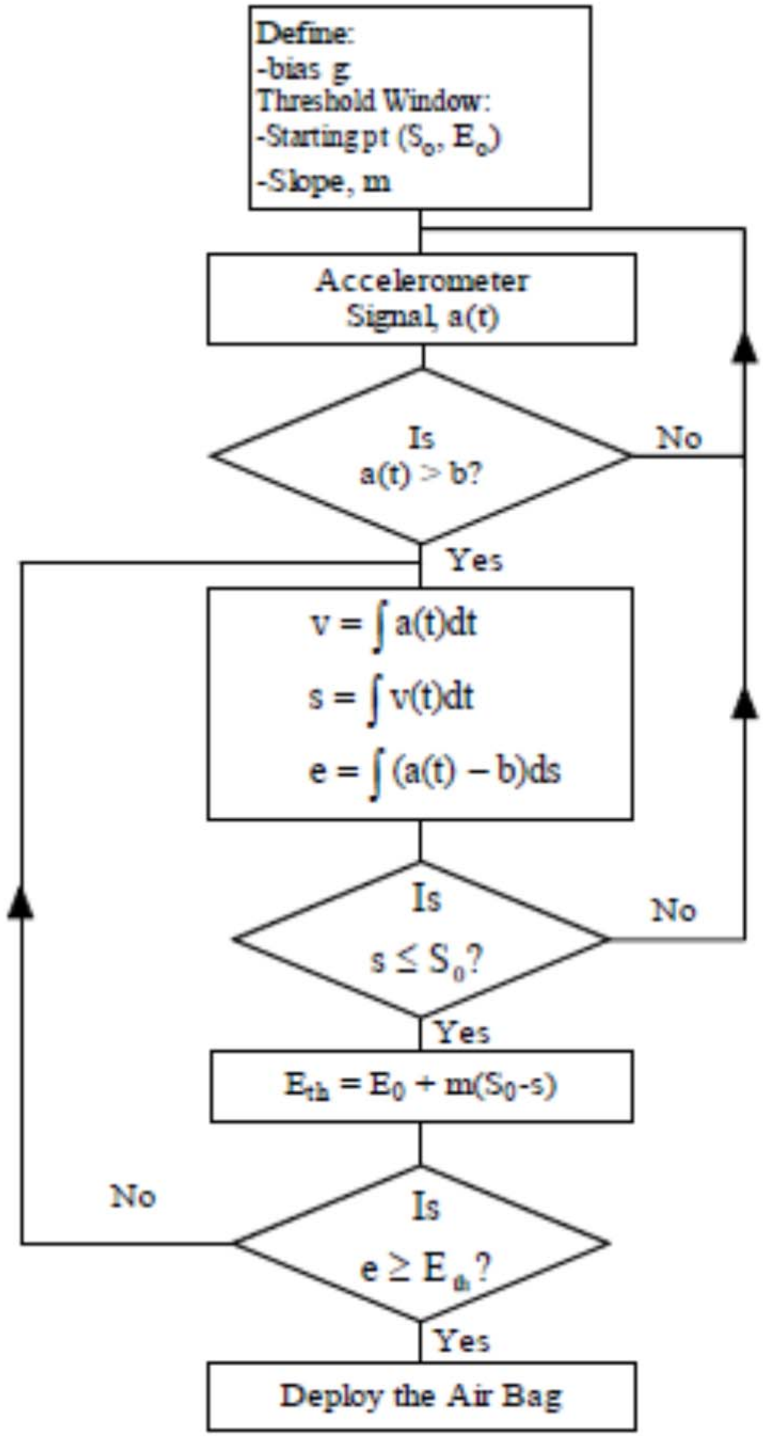
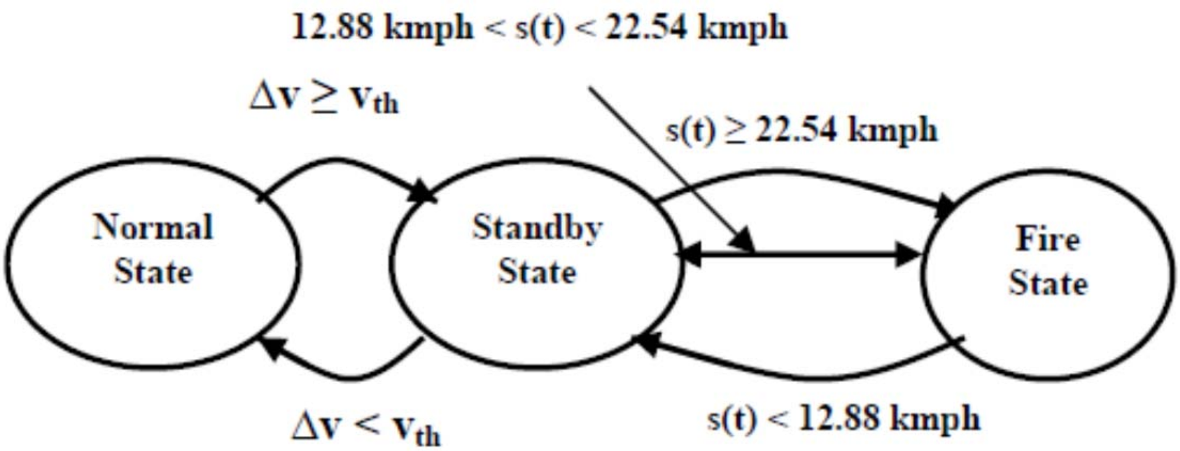


Figure 3. *Algorithm Flow Chart for US Patent 5948032 [Huang]*

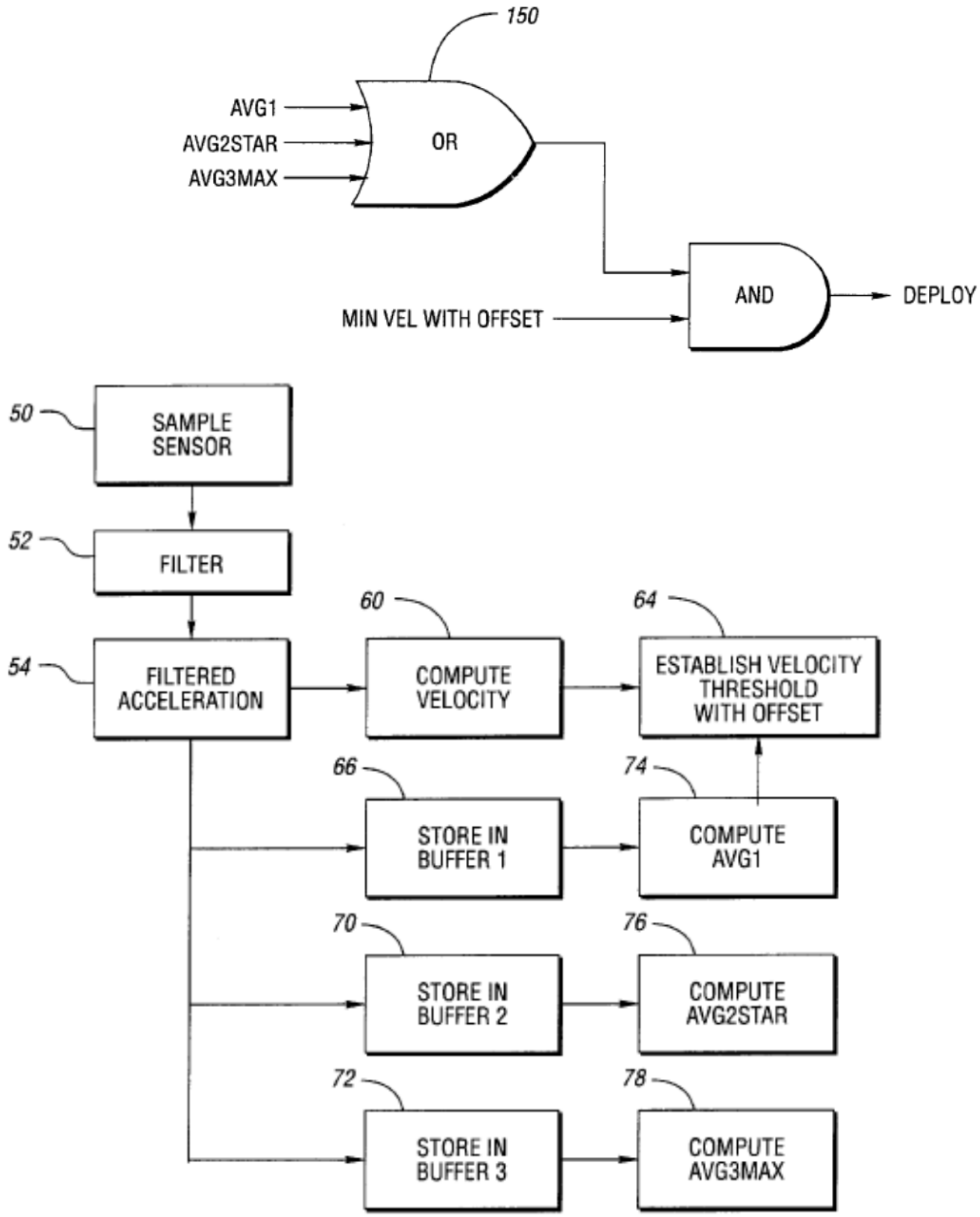


$$\Delta v = \int_0^T a_s(t)dt$$

s(t) = vehicle speed at time (t)

v_{th} = 5 m/s ~ 11 mph

Figure 4. *Algorithm Flow Chart from [13] Hussain.*



AVG1 = average acceleration over 4 ms, $\bar{a}_4$

AVG2 = average acceleration over 8 ms, $\bar{a}_8$

AVG3MAX = average acceleration over 24 ms, $\bar{a}_{24}$

Figure 5. *Algorithm Flow Chart from US Patent 6236921 [McConnell]*

ALGORITHM VARIATIONS

Crash sensing schemes vary greatly between patents. A majority of systems patented after 1995 utilize *delta-V*, *acceleration*, or *jerk*, as variables in the system wakeup command, and for triggering the air bag. Recent systems also include *occupant sensing* and analysis of the *distance* from the occupant [13]. Table 2 outlines the approaches used between 1995 and 2008 by several inventors. The differences are considerable and widely varied; however, the basis for deployment relies on one or more of the basic kinematic expressions previously described.

US Patent No.	Year	Inventor	Assignee	Title	Description
5394326	1995	Liu	Delco Electronic Corporation	Air bag deployment control system and method	ΔV + acceleration
5430649	1995	Cashler	Delco Electronic Corporation	SIR deployment method based on occupant displacement and crash severity	ΔV + jerk + displacement + acceleration
5587906	1996	McIver	TRW Inc.	Method and apparatus for sensing a vehicle crash condition using velocity enhanced acceleration crash metrics	ΔV + acceleration
5668720	1997	Takahashi	Toyoda Gosei Co., Ltd.	Air bag controlling apparatus	ΔV + jerk + acceleration
5777225	1998	Sada	Sensor Technology Co.	Crash sensor	ΔV + jerk + displacement + acceleration
5835007	1998	Kosiak	Delco Electronic Corporation	Method and apparatus for crash sensing using anticipatory sensor inputs	ΔV + acceleration
5948032	1999	Huang	Ford Global Technologies	Polynomial windowing algorithm for impact responsive activation	ΔV + jerk + displacement + energy
5999871	1999	Liu	Delphi Technologies	Control method for variable level airbag inflation	ΔV + jerk
6236921	2001	McConnell	Visteon Global Technologies	Three Speed Algorithm for Airbag Sensor Activation	ΔV + jerk + displacement
7424354	2008	Shen	Delphi Technologies	Supplemental restraint deployment method using dynamic crash classification	ΔV + jerk + displacement

Table 2. *Algorithm patents and criteria.*

WHEN AIR BAGS DEPLOY

According to the National Highway Traffic Safety Administration [6], "Air bags are typically designed to deploy in frontal and near-frontal collisions, which are comparable to hitting a solid barrier at approximately 8 to 14 mph." Specific thresholds are calibrated by each manufacturer according to vehicle size and stiffness. In frontal collisions, the system 'wake-up' or 'algorithm-enable' command is used to distinguish between events such as hitting a pothole and a collision with an automobile. It is generally initiated when two consecutive acceleration pulses less than (approximately ≈) -1.0 g for smaller vehicles or less than (approximately ≈) -2.0 g for larger vehicles, occur within a short period of time (10 milliseconds) [3]. After system wake-up from a pulse exceeding the deceleration threshold (stand-by mode), a decision is made to either fire the air bag or return to normal state.

Due to the proprietary nature of air bag deployment algorithms, the velocity, acceleration, or displacement thresholds for air bag deployment during a collision are not easily obtained; however, using the NHTSA guideline for an air bag to deploy in frontal barrier collisions within impact speeds of 8 to 14 mph, a range of threshold values can be estimated using known vehicle stiffness-to-weight ratios.

THRESHOLD ESTIMATES

In a collision, the amount of crush (C, in inches) at a given impact speed (V, in mph) is related to the ratio of the stiffness of a vehicle (k, in lb./in) and the vehicle weight (w, in lb.) by the following equation [14]:

$$\frac{C}{V} = 0.9\sqrt{\frac{w}{k}}$$

The time from the beginning of the impact to the time of the maximum crash pulse is:

$$t_m = 56.8\frac{C}{0.64V}$$

By substituting for C/V, the time (t_m) can be calculated using the weight-to-stiffness ratio as follows:

$$t_m = 56.8\frac{0.9\sqrt{\frac{w}{k}}}{0.64}$$

Vehicle stiffness, (k) can be determined from collision test results, which report mass (m) , crush (c), and impact velocity (v) for vehicles subjected to frontal rigid barrier collision testing. Vehicle stiffness is calculated as:

$$k = \frac{mv^2}{2c^2}$$

Table 3 shows the corresponding range of decelerations and displacements in frontal barrier collisions, at which air bags are designed to deploy, given the calculated time to maximum crash pulse and different vehicle stiffness-to-weight ratios.

Vehicle Year	Vehicle Model	Vehicle Class	Vehicle Weight, w	Vehicle Stiffness, k	Ratio k/w	Time to max. pulse, t_m	Δv Delta-v range		a Deceleration Range		x Displacement Range	
			(lbs)	(lbs/in)	(lb/in/lb)	(ms)	(mph)	(mph)	(g's)	(g's)	(in)	(in)
2010	Ford Fusion	midsize	3640	3839	1.055	78	8.0	14.0	4.7	8.2	7.0	12.3
2010	Lexus RX350	SUV	4747	5690	1.199	73	8.0	14.0	5.0	8.7	6.6	11.5
2009	Ford Escape	SUV	4198	5070	1.208	73	8.0	14.0	5.0	8.8	6.6	11.5
2010	Honda Insight	compact	3115	3917	1.257	71	8.0	14.0	5.1	9.0	6.4	11.2
2010	Toyota Prius	midsize	3499	5672	1.621	63	8.0	14.0	5.8	10.2	5.7	9.9
2007	Chevrolet Corvette	sportscar	3132	5526	1.764	60	8.0	14.0	6.1	10.6	5.4	9.5
2007	Chevrolet Equinox	SUV	3172	8647	2.726	48	8.0	14.0	7.5	13.2	4.4	7.6

Table 3. *Air bag deployment ranges (based on vehicle front impact with a rigid barrier).*

There is no significant correlation between vehicle weight and stiffness. Two vehicles of similar weight may have very different stiffness values, as seen when comparing the 2010 Ford Fusion to a 2010 Toyota Prius. Both vehicles have approximately the same vehicle weight, yet the front-end stiffness of the Toyota Prius is substantially greater than the Ford Fusion. Since both the amount of displacement and the duration of impact for a Ford Fusion are greater, an air bag would need to deploy in the Ford Fusion within a range of deceleration values lower than those required for the Toyota Prius.

Comparing values

Real-world crashes are often not identical to solid barrier crashes, and care should be taken when comparing ranges of tested and calculated values. Impact duration does not vary significantly with impact velocity, but varies greatly with the type of collision. Air bags might not deploy where there are extreme deformations, such as a collision with a telephone pole where only one portion of the car is deformed. Air bags sometimes do not deploy when the impact is gradual, over a longer period time as when a vehicle rides under or over another object. Air bags might not deploy in collisions in which the relative stiffness are vastly different, such as the front of a vehicle impacting the side of another vehicle. Additionally, collisions that occur at oblique angles do not always result in air bag deployment, when significant deceleration does not occur in a direction concurrent with the sensing device.

Case study: Air bag non-deployment

An example of an impact where there was a significant change in velocity, but the driver or front passenger air bags did not deploy, involved a 2007 Chevrolet Equinox colliding with an oncoming Harley-Davidson motorcycle. The air bag control module in the Equinox reported a maximum ΔV of 9.27 mph. This value was within the 8.0 to 14.0 mph range where deployment (for frontal impact with a solid barrier) is expected; however, the maximum deceleration recorded for the subject collision was only 3.27 g's. The deceleration of the Equinox in this accident was well below the estimated deployment range (7.5 to 13.2 g's) as shown in Table 3. Therefore, the driver and passenger air bags rightfully did not deploy.

Figure 6. *Collision damage resulting in non-deployment of front passenger/driver air bags.*

Case study: Air bag deployment

An example of an impact that did not result in a significant change in velocity, but yet the air bag deployed, involved a 2007 Chevrolet Corvette that struck several small signs, trees, and a utility pole off road at a very high rate of speed. As the vehicle struck the first object at over 60 mph, the air bag control module reported a maximum ΔV of 4.96 mph, which is well below the 8.0 to 14.0 mph range where deployment (for frontal impact with a solid barrier) is expected. Fortunately, the maximum deceleration recorded at the same time during impact was 11.3 g's, which is above the estimated threshold range (6.1 to 10.6 g's) shown in Table 3. As a result, the air bags deployed and saved the lives of both the passenger and driver.

Figure 7. *Collision damage resulting in air bag deployment.*

SUMMARY

Air bags must have a control system that can recognize a crash correctly, and early enough for air bags to inflate safely. Deployment systems generally use electronic sensors that continuously report a vehicle's acceleration to an air bag control module. The modules utilize complex algorithms to make air bag deployment decisions based on one or more kinematic variables. Due to the proprietary nature of air bag deployment algorithms, the velocity, acceleration, or displacement thresholds for air bag deployment during a collision are not easily obtained. Instead, a range of impact velocity, deceleration, or displacement threshold values can be calculated (based on vehicle stiffness-to-weight ratios) and used to estimate when an air bag should or should not deploy in a collision.

APPENDIX GLOSSARY OF TERMS

Acceleration:	A vector quantity specifying the rate of change of velocity.
Accelerometer:	A device which converts mechanical motion into an electrical signal proportional to the acceleration value of the motion; it measures inertial acceleration or gravitational force.
ACM:	Air bag Control Module – the control module for air bags and related restraint systems.
Algorithm:	A series of steps designed to accomplish a specific task.
Algorithm enable:	"AE" – A programmed threshold for a specific ACM at which the ACM begins the deployment decision making algorithm.
Control Module:	An electronic device that makes decisions and controls other devices.
Crash Pulse:	The period of time defined by the moment when two vehicles come into contact until the point where they separate at the centroid of damage and the exchange of momentum between the vehicles ends. As "crash duration," it is defined by time.
Delta-V:	The vector change of speed of a vehicle involved in an "event" described by a magnitude and direction.
Deployment (Event):	Acceleration observed along one of the car's axes sufficient to cause the control module's crash sensing algorithm to "enable" or "wake up" and which is sufficient to warrant a commanded deployment.
Enabled:	When a threshold has been met satisfying one of the criteria necessary to begin a process or deploy a device.
Event:	The occurrence of some level of acceleration which causes an ACM to evaluate available data and decide whether or not to deploy restraint devices(s). A crash or other physical occurrence that causes a module's trigger threshold to be met or exceeded.
Frontal Air Bag:	The primary inflatable occupant restraint device that is designed to deploy in a frontal crash to protect the front seat occupants. It requires no action by vehicle occupants and is used to meet the applicable frontal crash protection requirements of FMVSS No. 208.
Jerk:	The rate of change of acceleration.
Millisecond:	A millisecond is 0.001 seconds.

Non Deployment (event):	Acceleration observed along one of the car's axes sufficient to cause the module's crash sensing algorithm to "enable" or "wake up" but which does not warrant a commanded deployment.
Wake-up:	A programmed threshold for a specific ACM at which the ACM begins the deployment decision making algorithm. See also algorithm enable.

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(Definitions taken from: Collision Safety Institute)

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Mr. Jesse Kendall, P.E., obtained a Bachelor of Science degree in Civil Engineering from the University of Vermont in Burlington, Vermont. He completed his engineering internship in Denver, Colorado, working for civil engineering consulting firms before becoming a licensed professional engineer in six states. With over fifteen years of civil engineering experience, Mr. Kendall now lives and works in California for the Institute of Risk and Safety Analysis, specializing in forensic engineering and accident reconstruction.

Dr. Solomon obtained a Bachelor of Science, Master of Science and Doctorate in Engineering, as well as a Post-doctorate in Risk Benefit Assessment from UCLA. Dr. Solomon also holds a Professional Engineering License. Dr. Solomon's studies are limited primarily to accident reconstruction, biomechanics, and risk-benefit assessment as demonstrated by his 39 years of independent research; his more than 200 internationally distributed publications, reports, and presentations; his thirteen book co-authorship; and his journal guest editorships. In December of 1998 and after over 22 years of service, he retired as Senior Scientist with the RAND Corporation. He was on the faculty at the RAND Graduate School for eighteen years, and has taught as an Adjunct Faculty at UCLA, USC, Naval Post-Graduate School, and George Mason University. Dr. Solomon has published studies in Transportation Accidents (automotive, trucks, motorcycles, bicycles); Industrial & Recreational Accidents (pressure vessels, rotating machinery, forklifts and cranes, exercise, gym, & recreational equipment, swimming pools, manufacturing and punch presses); Slip- or Trip-and-Fall Accidents; and Adequacy of Warnings.