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Antilock Brake System Review

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- 1. Scope**—This SAE Information Report provides information applicable to production Original Equipment Manufacturer antilock braking systems found on some past and current passenger cars and light trucks. It is intended for readers with a technical background.

It does not include information about aftermarket devices or future antilock brake systems.

Information in this document reflects that which was available to the committee at the time of publication.

2. References

- 2.1 Applicable Publications**—The following publications form a part of the specification to the extent specified herein. Unless otherwise indicated the latest revision of SAE publications shall apply.

1. Zellner, John W., "An Analytical Approach to Antilock Brake System Design," SAE Paper 840249, 1984.
2. Leiber, Heinz., Czinczel, Armin., and Anlauf, Juergen., "Antiskid System (ABS) for Passenger Cars," Bosch Technische Berichte (English Special Edition), Feb. 1982.
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4. Ellis, J. R., "Vehicle Dynamics," London Business Books, 1969.
5. Flaim, T. A., "Vehicle Brake Balance Using Objective Brake Factors," SAE Paper 890804, February, 1989.
6. Rowell, J. Martin., Gritt, Paul S., editors, "Antilock Braking Systems for Passenger Cars and Light Trucks—A Preview (PT-29)," SAE, 1987.
7. Ward Automotive Reports; Ward's Communications
 - January 25, 1988
 - January 16, 1989
 - February 5, 1990
 - January 28, 1991
 - February 25, 1991
 - July 8, 1991
 - August 19, 1991
8. Lowery, Joseph., "Jensen—Ferguson: 2+2 = 4;" February, 1966; p.u.
9. "Ward's Automotive Antilock Braking Systems In The 1990s," p. 2; Lamm, Michael., Ward's Communications, 1990.
10. ISO 611-1980 "Road vehicles—Braking of automotive vehicles and their trailers—Vocabulary"
11. ECE R13.05, Annex 13 "Requirements Applicable to Tests for Vehicles Equipped with Anti-Lock Devices"
12. SAE J670—Vehicle Dynamics Terminology

3. Definitions

- 3.1 ABS (Acronym for Antilock Brake Systems)**—A device which automatically controls the level of slip in the direction of rotation of the wheel on one or more wheels during braking (see ISO 611).
- 3.2 Accumulator—Low Pressure (Sump)**—A low pressure brake fluid storage device not intended as an energy source.
- 3.3 Accumulator—High Pressure**—An energy storage device using pressurized brake fluid as the storage medium.
- 3.4 Actuation Principle—Pump Back**—An ABS system configuration where during modulation control, low pressure brake fluid is restored to high pressure by a pump and made available for a subsequent build cycle. The total amount of fluid available for modulation control for a given stop is limited to the amount of fluid provided by the master cylinder for that particular stop.
- 3.5 Actuation Principle—Replenishment**—An ABS system configuration employing an external source of high pressure fluid in addition to displaced master cylinder fluid for modulation control. This type of system has virtually an unlimited supply of high pressure fluid available during modulation control.
- 3.6 Add-On ABS System**—An ABS configuration in which both the ABS power supply and modulation control functions are independent from the base brake actuation system. The components of this system may be packaged together or separately.
- 3.7 Control Channel**—A portion of the hydraulic brake circuit which can be operated independently from other portions of the hydraulic brake circuit. In ABS braking, it is a hydraulic brake circuit that controls a wheel or wheels independently of other wheels.
- 3.8 Controller**—A component of the antilock braking system which interprets input signals from the sensor(s) and transmits the controlling output signals to the modulator(s) (see SAE J670e).
- 3.9 Diagonal Split Brake System**—A brake system in which separate hydraulic circuits actuate the service brakes for one front wheel and one rear wheel on the opposite side.
- 3.10 Directly Controlled Wheel**—A wheel whose braking force is modulated according to data provided at least by its own sensor (see ECE Regulation 13).
- 3.11 G-Switch/Accelerometer G-Sensor/(Lateral and Longitudinal)**—A device by which acceleration or a change in acceleration of the vehicle is detected or confirmed.
- 3.12 Indirectly Controlled Wheel**—A wheel whose braking force is modulated according to data provided by the sensor(s) of other wheel(s) (see ECE Regulation 13).
- 3.13 Integrated ABS System**—An ABS configuration in which some ABS and base brake actuation functions are shared. Most commonly, both systems may share a hydraulic power supply.
- 3.14 Lateral Force Coefficient**—The ratio of the lateral force to the vertical load (see SAE J670e).
- 3.15 Longitudinal Force Coefficient**—The ratio of the longitudinal force to the vertical load (see SAE J670e).
- 3.16 Modulation Control**—The systematic regulation of braking force resulting from the build, decay, and/or hold of pressure to a given control channel.

- 3.17 Modulator**—The component responsible for modulating the force developed by the brake actuators as a function of the order received from the controller (see ISO 611).
- 3.18 Nonuniform/Nonhomogeneous Coefficient of Friction**—A braking tractive surface in which variable surface conditions exist.
- 3.19 Pedal Feedback**—A tactile sensation felt by the driver's foot on the brake pedal during modulation control.
- 3.20 Pump Motor**—A mechanical pump driven by an electric motor used to pressurize or move brake fluid.
- 3.21 Select High**—Multi-wheel control where the signal of that wheel which is the last to tend to lock controls the system for all the wheels of the group (see ISO 611).
- 3.22 Select Low**—Multi-wheel control where the signal of that wheel which is the first to tend to lock controls the system for all the wheels of the group (see ISO 611).
- 3.23 Slip**—The difference between the angular velocity of a freely rolling wheel (ω) and the angular velocity of the braked wheel (ω_B) divided by the angular velocity of the freely rolling wheel (ω), expressed as a percentage.
- $$\% \text{ SLIP} = \frac{\omega - \omega_B}{\omega} \quad (\text{Eq. 1})$$
- 3.24 Slip Angle**—The angle between the wheel plane and the direction of travel of the center of the tire contact (see SAE J670e).
- 3.25 Solenoid**—An electromagnetic device in which an electrically energized magnet moves an armature to open or close a hydraulic flow path (see ISO 611).
- 3.26 Split Coefficient (Split μ)**—A braking tractive surface in which two significantly differing coefficients of friction exist at the left and right side of the vehicle.
- 3.27 Transition Coefficient (Transition μ)**—A braking tractive surface in which two significantly differing coefficients of friction exist in the direction of travel of the vehicle.
- 3.28 Uniform/Homogeneous Coefficient of Friction**—A braking tractive surface in which no significantly differing coefficient of friction exist throughout the surface.
- 3.29 Vertical Split Brake System**—A brake system in which separate hydraulic circuits actuate the service brakes, one for both front wheels and one for both rear wheels.
- 3.30 Wheel Speed Sensor**—The component responsible for sensing the condition of rotation of the wheel(s) and for transmitting this information to the controller.
- 3.31 Yaw Rate (r)**—The angular velocity about the (vehicle's) vertical axis (see Figure 1).

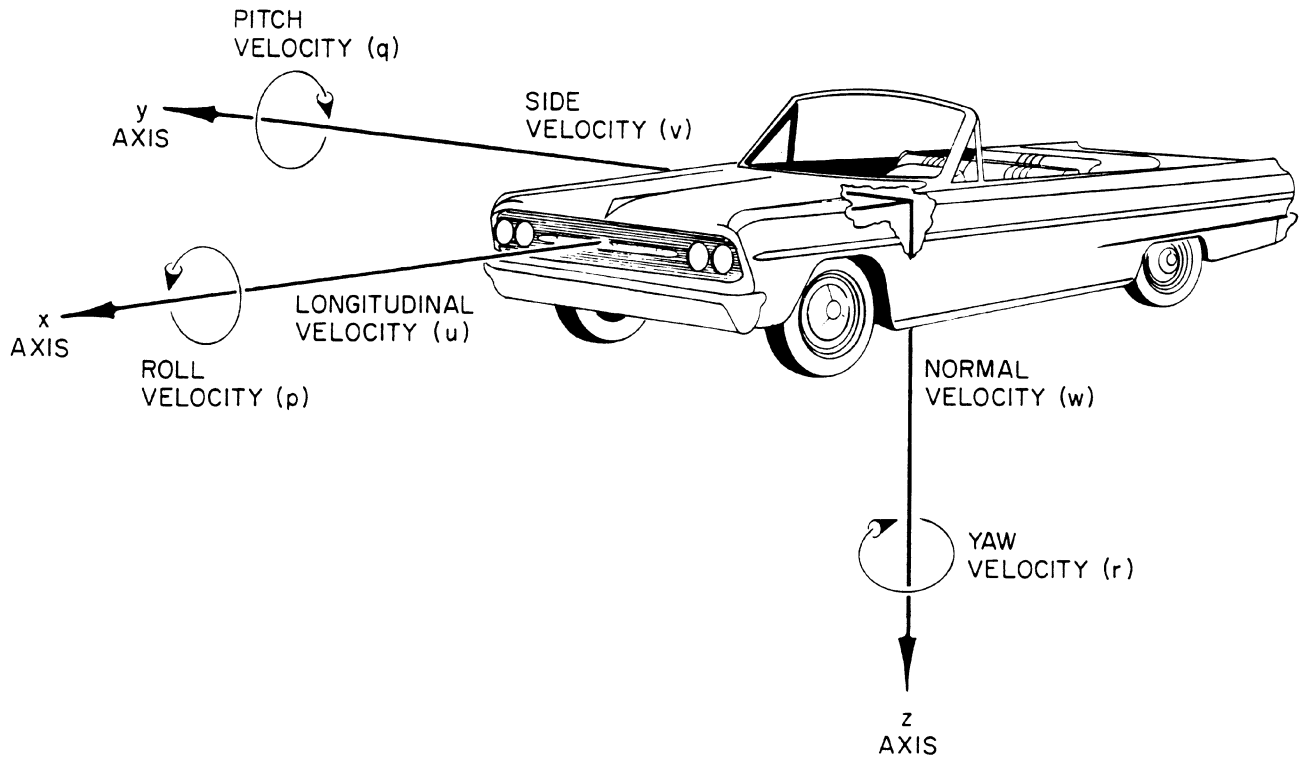


FIGURE 1—DIRECTIONAL CONTROL AXIS SYSTEM

4. Nomenclature

a_x — Acceleration along the x (longitudinal) axis of the vehicle
 e — Base of Napierian logarithmic system, (2.7182....)
 G — Brake specific torque
 g — Acceleration due to gravity
 J — Wheel inertia
 M — Vehicle mass
 P — Brake pressure
 P_0 — Initial brake pressure
 P_1 — Rate of change of brake pressure
 R — Radius of tire
 S — Stopping distance
 s — Slip
 s_0 — Initial slip
 T — Torque
 t — Continuous time
 u — Vehicle velocity along its x (longitudinal) axis
 V — Peripheral velocity of free straight rolling tire
 X — Longitudinal force
 Z — Vertical force
 μ — Longitudinal force coefficient
 α — Slip angle
 γ — Slope of longitudinal force coefficient curve
 τ — Lumped time constant

ω —Angular velocity

4.1 Subscripts

B Brake
H High limit
i Initial
L Low limit
p Peak
R Road
s Slide

5. **Introduction**—ABS may represent the single greatest advancement in automotive braking since the development of hydraulic brakes. Given the significance, this document has been written to provide the reader with the following;

- a. Historical Review of ABS
- b. Basic ABS Theory
- c. Profile of Current Antilock Brake Systems

This information is intended to provide the reader with an understanding of the fundamentals of ABS and its development. With this knowledge, the reader should have a better understanding of the present, and may have the tools to help understand future ABS developments.

6. Historical Review

- 6.1 **The Evolution Of Passenger Car and Light Truck Antilock Brake Systems**—The current hydraulic antilock brake systems were conceived from systems developed for trains in the early 1900's. The development of passenger car and light truck ABS appears to have started around 1936, when Bosch received its first patent for an antilock brake system using electromagnetic wheel speed sensors. When the sensors detected a locked wheel, an electric motor controlled orifice at each brake line was activated, thus regulating the brake pressure.

Several ABS development projects began in the 1950's. The first project began in 1954 at Ford when a Lincoln sedan was fitted with an antilock brake system from a French aircraft. In 1957 Kelsey-Hayes began an "automatic" braking system exploratory development program. The program concluded that the system should prevent the loss of vehicle control and reduce the vehicle's stopping distance. 1957 also saw Chrysler begin research on a "skid control" brake system, however, it was not until 1966 that Chrysler began developing antilock brake systems that were intended for production.

The late 1960's saw the first antilock brake system enter production. Kelsey-Hayes completed development of a rear wheel ABS in 1968. The single channel vacuum powered system was first offered by Ford on its 1969 Thunderbird and Lincoln Continental Mark III, under the trade name "Sure-Track".

Chrysler introduced four-wheel ABS on the 1971 Imperial. The system, developed with Bendix was a 3-channel, 4-wheel vacuum actuated system marketed under the trade name "Sure-Brake".

Jensen Motors became the first automobile manufacturer to offer ABS in conjunction with a viscous coupled 4-wheel drive system. In 1972 the Jensen Interceptor was made available with the Dunlop "Maxaret" antilock brake system. The system used a prop-shaft mounted speed sensor to operate a solenoid, which in turn operated air valves to reduce the brake vacuum servo output force.

Bosch began supplying a hydraulically actuated antilock brake system to Mercedes-Benz in October of 1978. The 3-channel, 4-wheel, add-on system was the first to employ a digital electronic control system to replace the analog electronics.

The use of ABS increased dramatically during the 1980's. In 1984, Teves began volume production of the first "integrated" ABS, in which the hydraulic brake booster, master cylinder, and antilock actuator were combined into a single component. The system, designated MK II, was also the first microprocessor based ABS and was first used on the 1985 Lincoln Mark VII.

Lucas Girling began supplying Ford of Europe with a mechanical ABS called Stop Control System (SCS) in 1986, a derivative of one developed in the early 1980's for motorcycles. The system used two mechanical wheel speed sensors on the front wheels. The rear wheels were valved to prevent lock up.

In 1986 Kelsey-Hayes introduced a single channel rear-wheel ABS on light trucks. The system saw widespread usage in the late 1980s, beginning with Ford in the 1987 model year.

Delco Moraine NDH began production of its ABS VI system in 1990. The system is unique in that the pistons used to control brake pressures are driven by electric motors via gear boxes and ball screws.

A summary of the previous information is shown in Figure 2.

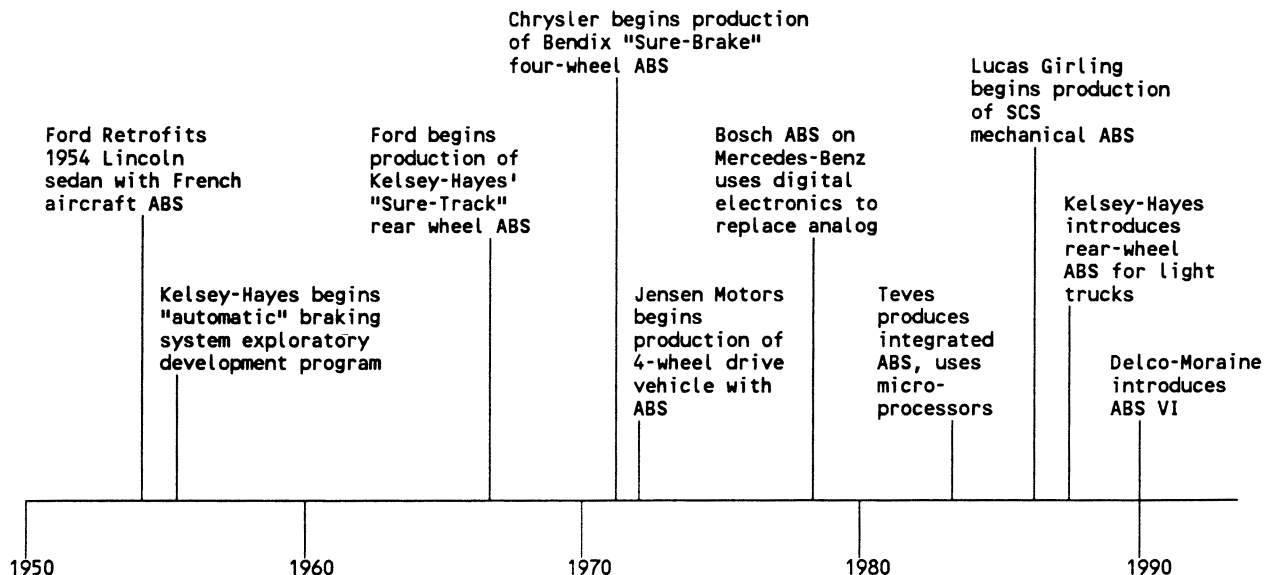
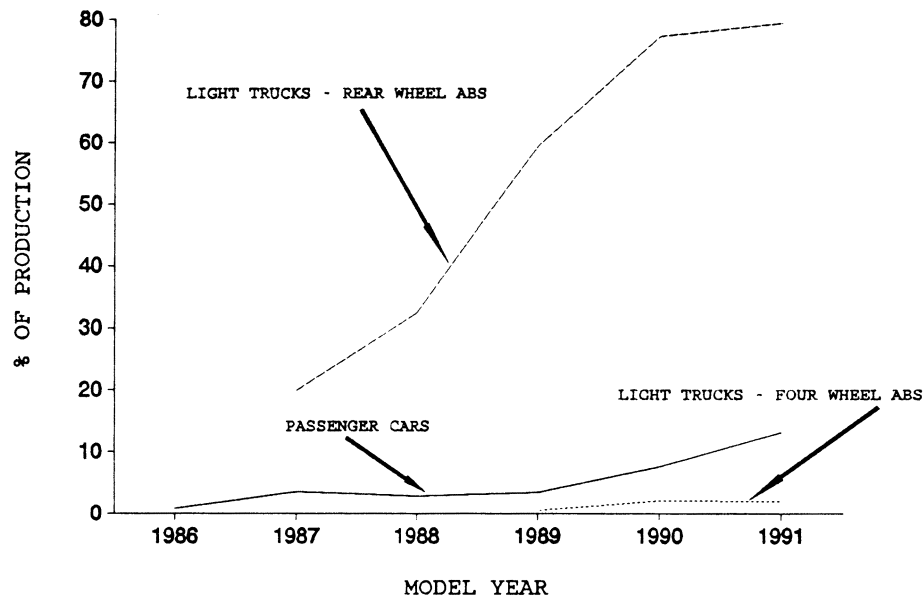


FIGURE 2—ANTILOCK BRAKE SYSTEM SIGNIFICANT EVENTS

6.2 ABS Installation Rates For Passenger Car And Light Trucks—Figure 3 illustrates ABS installations for passenger cars and light trucks as a percent of production. The information shown represents both rear wheel and four wheel ABS.



NOTE—ABS installation rates are based on passenger cars and light trucks assembled in the U.S., Canada, and Mexico, for the U.S. market. 1991 model year figures are estimates derived from production figures through March 31, 1991. Ward's Automotive Reports were used as a source for this data.

FIGURE 3—NORTH AMERICAN ABS INSTALLATIONS

7. Basic ABS Theory

7.1 Goals Of ABS Application—The application of ABS to a vehicle can provide improvements in the vehicle performance under braking compared to a conventional brake system. Improvement is typically sought in the areas of stability, steerability, and stopping distance. In the following sections, some basic approaches to achieving these goals are examined.

7.2 Inherent Limitations And Compromises—It must be remembered that the addition of ABS to a vehicle does not release it from compliance to the basic laws of physics. The interface between the road and tire still defines the maximum braking force that can be applied, the vehicle chassis will still determine steer responses and load transfer patterns, and the vehicle geometric and inertial properties will still be a major factor in these responses. In addition, the vehicle brake system still must provide for brake application up to the time that ABS begins to control the braking. Even then, the ABS must work through the foundation brakes.

7.3 Overview Of ABS—When a driver applies the brake pedal on a vehicle moving initially at a uniform rate of speed, the wheels tend to slow down relative to the ground, causing slip at the wheels. This slip between the tire and the road results in the generation of horizontal tire-road forces, which then govern the longitudinal, lateral, and yaw motion of the vehicle. As the brake apply is increased, the slip at each wheel increases, thus increasing the braking forces on the vehicle, in response to driver commands. This continues until the maximum braking capability of the particular tire and road surface is reached. Upon further application of the brake input, wheel slip increases uncontrollably, and the ability to follow driver commands is reduced considerably. In particular, the ability to steer the vehicle or counteract disturbing lateral forces is diminished.

ABS is a feedback control system that attempts to maintain controlled braking under all operating conditions. This is accomplished by controlling the slip at each wheel so as to obtain optimum forces within the limits of the tire-road combination.

In the following sections, the various aspects of braking dynamics are explained. The first part of the discussion, which centers on the control of the slip at a given wheel, is based on a single wheel model of a vehicle. Some of the important characteristics including capabilities and limitations are discussed. Subsequent discussion covers the coordination of slip at the four wheels in an automobile. A four wheel model is used for this purpose. The effect of ABS control on the stability, steerability, and stopping ability of the vehicle are outlined. The characteristics of some of the more common wheel lock control strategies are examined.

7.4 Braking Dynamics—Single Wheel Model—The various forces and torques acting on a single wheel vehicle are shown in Figure 4. The vehicle is modeled to have only longitudinal motion. In a hydraulic brake, torque is developed at the wheel brake by means of brake pressure. The brake torque per unit pressure is called the specific torque. The normal load, Z , corresponds to the weight of the vehicle. The longitudinal road force, X , is the product of the longitudinal force coefficient and the normal load. This force retards the motion of the vehicle. The rotational motion of the wheel is governed by the torques resulting from the brake pressure (brake torque) and the road force (road torque).

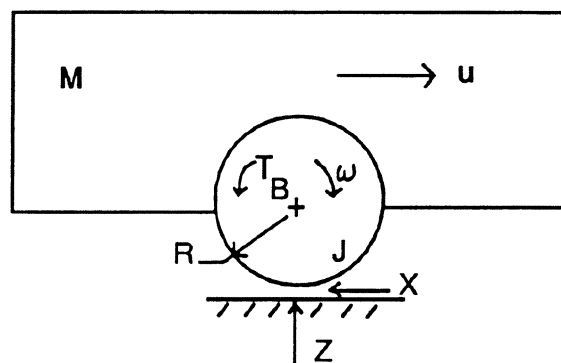


FIGURE 4—SINGLE WHEEL VEHICLE MODEL

The equations of motion can then be written as:

$$Z = M \cdot g \quad (\text{Eq. 2})$$

$$X = \mu \cdot Z \quad (\text{Eq. 3})$$

$$T_R = R \cdot X \quad (\text{Eq. 4})$$