

DEVELOPMENT AND EVALUATION OF ANTI-LOCK BRAKE SYSTEMS

Maurice H. Cardon, Bendix Research Laboratories
George B. Hickner, Bendix Automotive Control Systems Group
Ralph W. Rothfus, Bendix Heavy Vehicle Systems Group

Anti-lock systems which control wheel lock have been developed for passenger cars, trucks, articulated vehicles and buses. Six anti-lock system configurations involving individual wheel and axle control are discussed. Also discussed are techniques for evaluating the performance of anti-lock systems; included are straight line braking, the use of a split coefficient surface and braking in a turn. The results of computer simulation studies and vehicle tests conducted to evaluate performance of the various anti-lock system schemes are presented. It is concluded that the best anti-lock system configuration for a vehicle class requires a trade-off among vehicle design factors, desired level of braking, and vehicle handling performance and cost.

Anti-Lock Brake Systems have been developed for passenger cars, trucks, articulated vehicles, and buses to effectively prevent wheel lock in panic stop conditions. These systems assist the driver in vehicle control by allowing him to concentrate on vehicle handling and accident avoidance. They help the average driver maintain vehicle control under braking situations where maintaining the desired course would be nearly impossible with conventional braking systems.

Several studies of driver performance under controlled conditions have shown that most drivers are not able to effectively handle situations where heavy braking is required. Loss of control resulting from locked wheels is common. It is doubtful that the average driver can ever learn to handle the situation of braking where there is a transition from high coefficient to low coefficient surfaces unless his vehicle is equipped with an anti-lock system.

Vehicle stability and control as related to locked versus rolling wheels is common knowledge among engineers in the vehicle industry. In very general terms, a freely rolling wheel allows maximum directional control of a vehicle, while a locked wheel loses all ability to keep a vehicle on a controlled course. While the value of an anti-lock system in maintaining vehicle control is generally accepted, the configurations and designs

of various available systems have long been the subject of considerable discussion. Indeed, some questions relating to anti-lock system design have different answers depending on the constraints imposed by vehicle design and cost considerations.

Wheels to be equipped with an anti-lock system and control of each wheel independently or control of both wheels on an axle with a single modulator are issues which do not lend themselves to a single correct answer. Cost considerations, ratio of front to rear axle brake torque, load distribution and variation, and a host of other factors related to basic vehicle design influence the answer.

The primary purpose of this paper is to report on the evaluation of two-wheel, four-wheel and articulated vehicle anti-lock systems of various configurations. The paper discusses evaluation techniques used for both computer simulation and vehicle test as well as for evaluation results. Since the evaluation covers a span of many years and different vehicle types, direct comparisons for different systems are not always available. Therefore, the data will sometimes be presented in more-or-less qualitative terms. The conclusions represent the authors' judgment based on experience and the study of the available literature.

Conclusions

The basics of anti wheel-lock systems are now well understood and several conclusions relative to locked wheel braking can be offered.

A rear-axle system on a two-axle vehicle prevents "spin-out" under most normal braking conditions. In addition, it will generally provide a shorter stop than either a locked wheel or "driver-best-effort" stop. On an articulated vehicle, an anti-lock system on the rear axle of the towing vehicle has some value in preventing "jackknife" conditions.

A four-wheel system generally provides even shorter stops than a rear-axle system while at the same time allowing the driver to steer the vehicle around hazards during panic stops. Individual wheel control offers shorter stops with some sacrifice in vehicle stability.

The best anti-lock system configuration for a particular vehicle requires a tradeoff among

vehicle design characteristics, desired level of braking, and vehicle handling performance and cost. The "best" configuration is likely to be different for different vehicle types and market segments.

Anti-lock systems allow more flexibility in brake system design and ensure better braking over a wide range of load and road conditions. The systems also provide considerable compensation for brake parameter variation due to production tolerances and changes due to brake system component aging or severe braking inputs.

Anti-Lock System Configurations

Conceivable configurations of an anti-lock system range from fully independent single-wheel control to a common control for all wheels on the vehicle. However, practical considerations generally limit the selection to either individual wheel control or common control of the wheels on a single axle. Six systems involving individual wheel and axle control are depicted in Figure 1. Each is described in some detail below.

Four Wheel: Individual Wheel Control (Type A)

In a fully individual four-wheel anti-lock system (Type A, Figure 1) each of the four wheels of the vehicle has a wheel speed sensor, a control logic device, and a brake pressure modulator. The brake pressure modulator isolates its brake from the remainder of the brake system and modulates the brake pressure when the driver-generated brake pressure is enough to cause a wheel to lock. With a properly designed anti-lock system acting to prevent wheel lock, the brake force being developed at a particular wheel is mainly dependent on the tire-road surface coefficient at the wheel. This system configuration may be considered as ideal (with respect to braking force) as it has the potential of developing the maximum braking effort regardless of how the tire-road surface coefficient of each wheel differs. However, with this system configuration yaw moments can be generated if the road surface coefficients are different. Also depending on steering/suspension design, differing coefficients at the front wheels can generate an input to the steering system tending to make steering difficult or even impossible.

Four-wheel anti-lock systems with individual wheel control have not been marketed by U. S. automotive manufacturers. Such a system was experimentally evaluated and compared to other four- and two wheel systems by Teldix. (1)* The results of this experimental evaluation will be discussed later.

Four Wheel: Front, Individual Wheel Control; Rear, Axle Control (Type B)

The Type B system configuration of Figure 1 is similar to the four-wheel individual wheel control system except that a single modulator controls the rear-axle brakes of the vehicle. Two rear-wheel speed sensors are used, and the control logic is generally designed to select either the high-speed wheel (select-high) or the low-speed wheel (select-low) for controlling the brake pressure on the rear axle. This system is less costly than the Type A system as one less modulator and control logic device is used. The philosophy behind this system is that individual wheel control on the front axle provides steering control along with maximum braking effort. The select-low logic is usually used on

the rear axle of passenger car systems since this approach generally keeps both rear wheels rolling and reduces the tendency for spin-out. On a passenger car, the select-low rear axle control does not greatly compromise the total braking force because rear axle load is considerably less than the front axle load during braking.

This system was available on a U.S. passenger car in the 1971 through 1973 model years.

Both simulation and vehicle tests of this system were conducted and will be discussed later.

Four Wheel: Axle Control, Front and Rear (Type C)

In the Type C system of Figure 1, a single modulator is used to control brake pressure on each axle. Each wheel on the axle has a speed sensor and the control logic can be either select-high or select-low. Select-low (or a modified select-high) is the most common choice. This configuration offers low cost and maximum vehicle stability. The braking performance on split coefficient surfaces and while braking in a turn is less than ideal; however, the system provides good vehicle control and stability as no yaw moments are generated as a result of unequal side-to-side brake forces. Most air-brake anti-lock systems are of this type.

Since each axle is controlled independently, this configuration can also apply to multi-axle articulated vehicles. We will use a Type C-1 designation for multi-axle vehicles with axle control anti-lock systems.

Both simulation and vehicle tests of this system have been conducted and will be discussed later.

Two Wheel: Rear-Axle Control (Type D)

The two-wheel, rear-axle-control system configuration (Figure 1, Type D) has been used on passenger car anti-lock brake systems in the United States. In this system, only the rear axle has the anti-lock feature. Each wheel has a speed sensor, a single brake pressure modulator is used, and the control logic is generally of the select-low type.

This system provides vehicle stability but does not provide steering control. Since only one axle has anti-lock equipment, this configuration is about one-half the cost of a Type C four-wheel system. Both simulation and vehicle test data are available describing the performance of this system configuration.

Two Wheel: Rear-Axle Control With Prop Shaft Sensor (Type E)

The major difference between this configuration (Figure 1, Type E) and the Type D configuration just discussed is that a single prop shaft sensor is used in place of two wheel-speed sensors. The configuration is particularly attractive from a cost viewpoint in that a single sensor, control logic device and modulator can be used. Some compromises are made in performance however, as the information derived from the prop shaft sensor, which represents the average of the rear axle wheel speeds, results in poorer anti-lock system control. The system generally cannot handle a wide range of surface coefficients and is not as effective as other systems on split coefficients or maneuvers involving braking.

Two Wheel: Individual Wheel Control, Rear Axle Only (Type F)

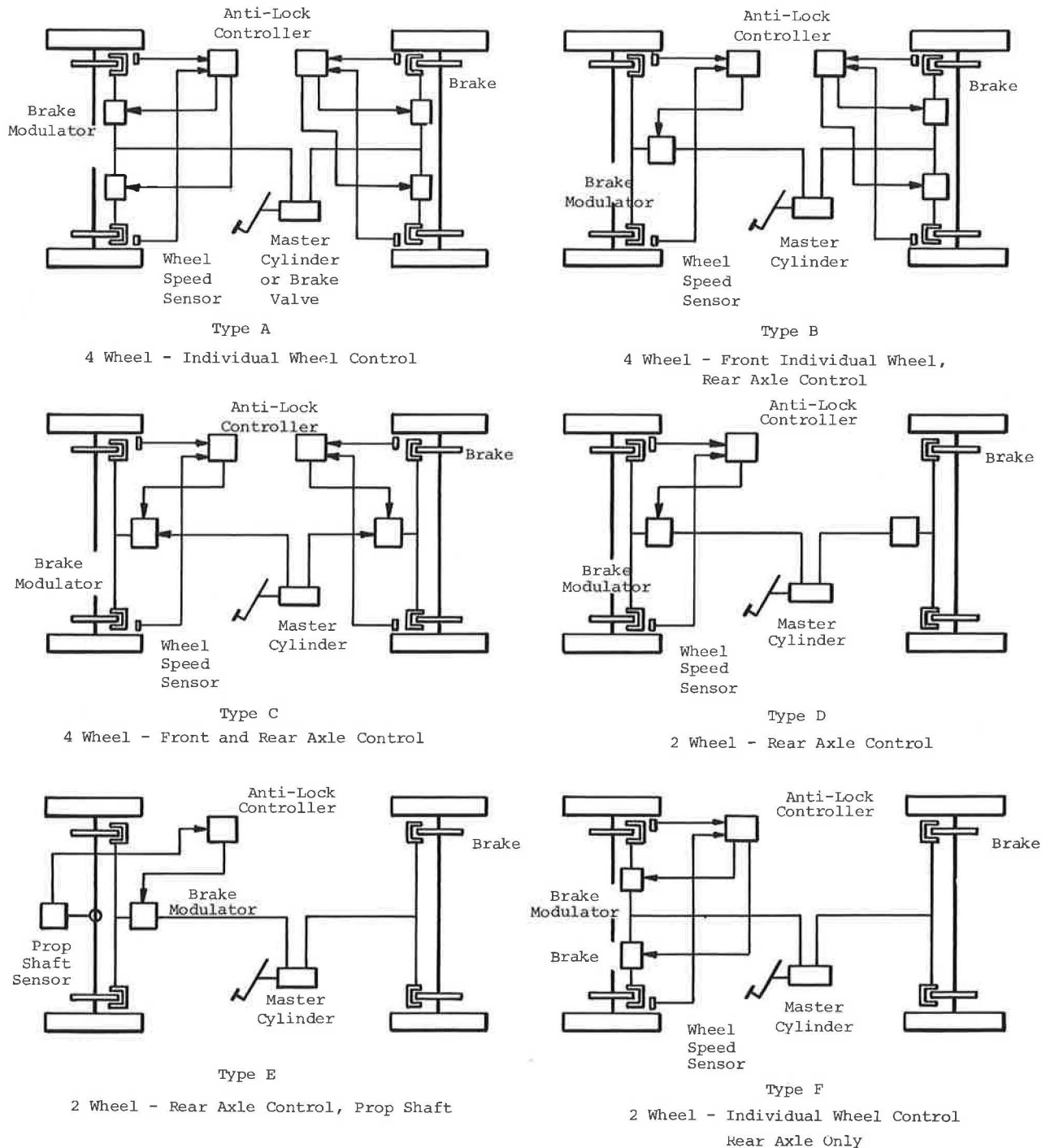
This configuration (Type F of Figure 1) was evaluated in the tests reported by Czinzal (1). Generally, this system does not fare well in a cost-benefit analysis and is not used commercially, to our knowledge. Its advantage is that it provides stability without sacrificing rear axle braking capability as the Type D & E configurations do. However, the cost is almost as high as the cost of a four-wheel Type C system, yet it does not provide the steerability of a Type C system because the front wheels can lock.

Summary

The choice of an anti-lock system configuration for a given vehicle depends upon many factors. Two vehicle types that exemplify the range of designs that must be accommodated by the anti-lock system designer are the standard passenger car and the short wheelbase highway tractor.

In the passenger car, cost is a prime consideration. Since the vehicle is generally quite stable even without anti-lock and the load variation on any wheel is relatively small, the performance demands placed on an anti-lock system are less severe than in most other applications. Consequently, most

Figure 1. Anti-Lock System Configuration



anti-lock systems that have been put in production for passenger cars have been rear-axle Type D or E systems which can be implemented at minimum cost.

The highway tractor imposes a different set of constraints on the anti-lock system designer. Stability and stopping performance are established by government regulation. There is greater concern about inputs to the steering system caused by unbalanced brake forces across the front axle. Rear axle loads can vary by a factor of ten. Cost, while not as critical as for the passenger car, is still a very important consideration. Thus, most anti-lock systems which meet the requirements of FMVSS 121 are of the Type C, axle-control configuration, which represents a compromise on the cost-benefit scale that is biased toward greater benefit at higher cost.

Other applications would impose yet a different set of constraints. Indeed, there will probably be applications for most of the system configurations described above as anti-lock systems are designed to fit a wide range of vehicle types. A study by J. M. Ehlbeck and R. W. Murphy of Freightliner Corporation (2) demonstrates rather conclusively that the designer has a choice in optimization considerations, and that the final performance of any system or class of systems is going to reflect his emphasis during the design trade off studies. The study, which covered six anti-lock systems tested on different surfaces and with different vehicle configurations, showed that a given anti-lock system could be "best" in one case and "worst" in another case. Since the actual anti-lock configurations were not disclosed, no specific judgment relative to configuration effect can be made.

Evaluation Techniques

The performance of anti-lock systems is established by conducting tests involving straight line braking and braking/turning maneuvers. Test procedures for straight line braking and braking during a lane change maneuver have been formalized by the SAE in the Recommended Practice, "Wheel Slip Brake Control System Road Test Code-SAE J-46". The lane change maneuver is applicable only to vehicles with four-wheel anti-lock control where steering capability can be maintained. Braking in a turn or on a surface with large side-to-side coefficient differences has been generally conceded to be a true test of anti-lock system performance. Abrupt high level braking causing locked wheels under such conditions on the highway is sure to result in running off the road or spinning out of control.

Straight Line Braking

Straight line braking tests are usually driver controlled. That is, the driver both steers and applies brakes, while trying to achieve the minimum stopping distance without going out of a lane of some fixed width. Tests are conducted on surfaces representing dry, wet, and icy pavements. Results are indicative of stopping performance of various systems, and, on the lower coefficient surfaces, results are also indicative of stability and steering control. Even on straight line stops a vehicle may tend to spin out due to wheel lockup, or require a steering input to stay within the specified lane; however, this problem is more pronounced on low- or split-coefficient surfaces.

Straight line braking tests are also conducted on surfaces with a split coefficient. That is,

the road surface under the wheels on one side of the vehicle has a lower coefficient than that of the wheels on the other side. This test is indicative of stability and control imparted by the anti-lock system. When a vehicle is braked on a split coefficient surface, a yaw moment is induced in the vehicle that must be counteracted by lateral forces developed at the tire-road interface. This type of test does not require a large skid pad when compared to braking/turning maneuvers; therefore it is rather an inexpensive way of evaluating stability and steering control characteristics of various anti-lock systems. The stopping characteristics of the various configurations can also be ascertained.

A third type of straight line braking test specified by J-46 is a transition from low to high coefficient (or vice versa). This test evaluates the capability of an anti-lock system to adjust quickly to new road conditions. Results of this type of test will not be discussed in this paper.

Braking/Turning Maneuvers

The criterion of performance in the braking-in-a turn maneuver is the maximum deceleration that can be achieved while the vehicle is in a turn of some fixed initial lateral acceleration without losing stability or control of the vehicle. These maneuvers result in uneven side-to-side wheel-load distribution which results in a lateral force on the vehicle that must be overcome by lateral forces at the tire-road interface. This uneven load distribution allows evaluation of the relative lateral stability of different anti-lock system configurations. There are two types of braking-in-a-turn maneuvers; one is termed a fixed-radius input turn and the other is termed a fixed-steering input turn.

In the fixed-radius turn, a driver is required to keep a vehicle in a fixed-radius path of a given width. The radius and initial velocity of the vehicle define the initial lateral acceleration. From the initial velocity, the driver applies the brakes while trying to achieve a minimum stopping distance without going out of the fixed path. This maneuver requires considerable driver skill and is sometimes conducted with a brake machine that automatically applies the brakes and maintains a given brake force. When using such a machine, the brake force is incrementally increased in successive stops until the vehicle can no longer stay within the prescribed path.

In the fixed-steering input maneuvers, the step steering input is introduced to the vehicle. The amplitude of the input is such that, for a given initial vehicle velocity, the desired lateral acceleration is achieved. As with the previous tests, the braking force is incrementally increased in successive stops until vehicle control or stability is lost. The loss of vehicle control or stability is most easily detected when either front or rear wheels of the vehicle lock. The measure of performance is the maximum deceleration that can be achieved before loss of control.

Neither of the above maneuvers has been extensively used to evaluate anti-lock systems experimentally. The need for a large skid pad, brake machine and some inertial instrumentation makes conducting such tests expensive. It also is difficult to uniformly wet and/or ice a large pavement area. The procedure has been used effectively in simulation studies; the results of these will be reported.

Another common maneuver for evaluating anti-lock systems involves a lane change while braking. The lane change induces both lateral forces and uneven

load distribution on the wheels on the vehicle. The measure of performance is the initial velocity at which the vehicle can enter the lane change without leaving the prescribed path. Achievable stopping distance is or can also be a criterion. The maneuver requires considerable driving skill, but is relatively easy to set up and conduct. It requires less skid pad area, and the surface is more easily wet and iced than the braking-in-a-turn evaluation. This test maneuver is defined in SAE J-46.

Simulation Studies

Four-wheel vehicle computer simulations useful for studying maneuvers discussed above have been available for a number of years. Performance studies on three of the system configurations (Type B, C & D) have been completed. The studies included straight line braking on uniform surfaces with various friction coefficients as well as split coefficient surfaces. Braking-in-a-turn maneuvers on uniform coefficient surfaces with both fixed radius and fixed steering wheel procedures have also been studied.

The four-wheel vehicle model used is a direct adaptation of the McHenry-Deleys model which was developed at Calspan (formerly the Cornell Aeronautical Laboratories). (3) It is implemented on an AD-4/SEL-86 hybrid computer.

The model has seventeen degrees of freedom: (See Figure 2.)

- The sprung mass is free to move in the x, y and z directions and to rotate through the Euler angles roll, pitch and yaw, accounting for six degrees of freedom.
- The front wheels are free to move in a vertical direction, accounting for two more degrees of freedom.

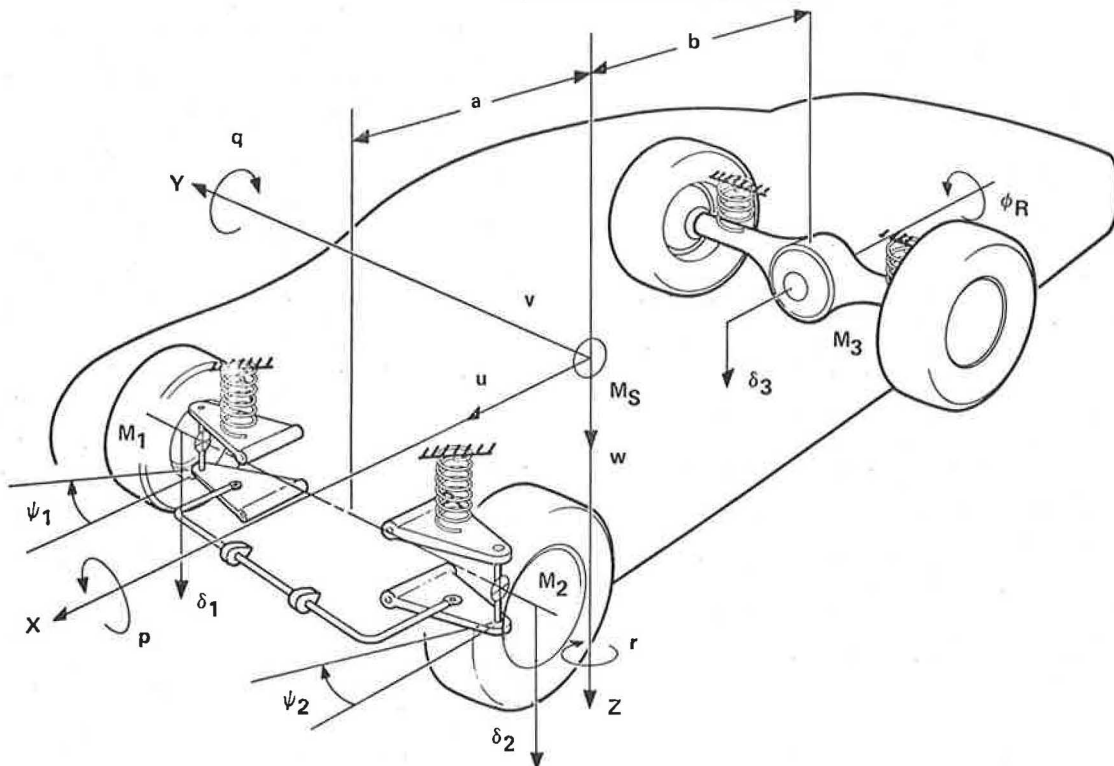
- A solid axle rear suspension is free to move in a vertical direction, and the axle is free to rotate relative to the sprung mass about a longitudinal axis, accounting for two more degrees of freedom.
- Independent rear suspension vehicles also have been modeled, in which case the rear wheels move independently in a vertical direction, accounting for two degrees of freedom.
- The steering system accounts for three degrees of freedom. Each front wheel is free to move in steering angle, indicated by ψ_1 and ψ_2 in the figure, and in addition the steering wheel angles are subject to the steering system constraints, of course.
- The last four degrees of freedom are accounted for by four independent wheel rotational equations of motion which allow us to simulate the wheel rotational behavior which occurs in braking-in-a-turn situations and on "split coefficient" roads.

The major sub-models of this system are the suspension system, the brake system, and the tire/road interface sub-model. The latter is an empirical model in which actual tire test data is stored in the computer and used to determine the tire side forces and longitudinal forces during simulated maneuvers.

The results of two studies will be discussed. The first study evaluated the performance of three anti-lock system configurations on a large, luxury-type U.S. passenger car. Braking performance with locked wheels was compared to that achievable using anti-lock systems. For the braking in the turn portion of this study the vehicle was directed to follow a fixed-radius path.

The second study evaluated different brake system configurations for the AMF Advanced Systems

Figure 2. Analytical representation of the four-wheeled vehicle



Laboratory Experimental Safety Vehicle (ESV) projects sponsored by the National Highway Traffic Safety Administration. (4) The braking performance at impending slide was studied and the braking in a turn maneuver involved a fixed steering wheel input.

Large Passenger Car Anti-Lock Systems

The three system configurations studies were as follows:

- o Four-wheel: - Front, individual wheel control; Rear, Axle control (Type B)
- o Four-wheel: - Axle control, front and rear (Type C)
- o Two-wheel: - rear axle control (Type D)

Straight Line Braking. In the straight line braking performance studies, surfaces representing icy, wet, and dry pavements were investigated along with pavement having split coefficients. The straight line braking performance of these systems was compared to the locked wheel stops.

The summary of the results is shown in Figure 3. In straight line braking on the uniform coefficient surface there was little difference in performance between the four-wheel systems; however, the four-wheel systems outperformed the two-wheel systems.

A comparison of actual vehicle test data with the simulating results partially validated the simulation results. The computer results for the wet jennite surface compare favorably with actual test data. On icy pavements, the simulation predicted slightly greater improvement over locked-wheel stops with the anti-lock brake system than demonstrated by vehicle test. Vehicle test data for dry jennite was not available for comparison to simulation results.

A major difference in straight line stopping performance between the two four-wheel control systems showed up on split coefficient surfaces. Typical results are shown in Figure 4. The figure shows the extended stopping distances that occur with the axle control system when stopping with two wheels on one side of the car on a slippery pavement (SN 30) and the other two on a high coefficient surface (SN 70).

Braking In A Turn

For the braking-in-a-turn study, the vehicle was programmed to steer the vehicle along a constant-radius path throughout the stop. Of course, if the required tire force could not be generated, the vehicle would not follow the prescribed path. The intent of the study was to determine maximum braking levels allowable while still maintaining some vehicle control. The vehicle was started along a prescribed path at the desired initial velocity and the brakes were then applied. On successive runs, the brake force was increased in fixed increments to determine minimum stopping distance achievable without deviating from the prescribed path by more than two feet. A summary of the results for an initial velocity of 45 miles per hour is shown in Figure 5.

The Type B system with individual front wheel control has best overall performance because all of the available front axle brake force is used to retard the vehicle.

ESV Anti-Lock Systems. This study evaluated

the performance of a 5000-lb. Experimental Safety Vehicle with six different brake systems. We will discuss only the standard brake system and two anti-lock systems.

The systems studies were:

- o Standard brake system without anti-lock with fixed ratio of front/rear brake torque.
- o Four wheel front, individual wheel control; rear, axle control (Type B)
- o Two Wheel, rear axle control (Type D)

Simulation runs were made for all combinations of two vehicle maneuvers, two vehicle loading conditions, and two different skid numbers. The vehicle maneuvers that were simulated were (1) braking to a stop from 60 miles per hour in a straight line and (2) braking with a constant steering wheel angle from 40 miles per hour. Two road/tire friction characteristics were chosen from data on hand for SN 20 and 80 surfaces. Computer runs were made for the straight line stop to determine the pedal force which yields minimum stopping distance with no wheels locked. For the turn maneuver, brake pedal force was increased until at least one axle set of wheels locked.

In the braking performance study, simulation runs were made to determine the minimum stopping distance without wheel lock. A brake pedal force rate of 500 lb/sec, simulating a driver in a panic situation, was used in all cases. On successive runs, the maximum pedal force level was increased in increments of 1 pound. The runs were repeated until the minimum stopping distance was achieved or a wheel locked, for those cases where an axle did not have an anti-lock system.

For the braking-in-a-turn simulation, the steering wheel was linearly ramped to 37.0 deg. to the right and maintained at this angle, resulting in an initial lateral acceleration of about 0.3g at 40 miles per hour. Application of the brakes was made 2.0 seconds after the start of the steering input.

The straight line stopping distances obtained with no wheel lock on wheels controlled by the anti-lock system are shown in Table 1. The original runs were made with the anti-lock parameters set for a standard production vehicle of similar weight. The two wheel system was then re-run with control logic parameters modified to be consistent with the ESV vehicle configuration.

Comparison of results shows that the anti-lock systems have comparable performance on dry pavement while the four wheel system provides shorter stops on wet pavement. This is to be expected since the four wheel system controls all wheels more near the peak road coefficient and the peak to locked wheel coefficient ratio is higher on the low coefficient.

Selecting more optimum control logic allowed the anti-lock performance to approach the stopping distances obtained when brake pressures are set at a level which barely prevents wheel lock.

The simulation for the two-wheel system with more optimum control logic parameters is also depicted in the table. The results show marked improvement for operation on dry pavement, with a slight improvement on wet pavement. A corresponding improvement on the four-wheel anti-lock system with more optimal control logic parameters would be expected. Actual test experience has confirmed this effect.

Considering only the data in Table 1, one would be led to conclude that the anti-lock systems offer no advantage over standard braking systems. However, one should be reminded that the figures in Table 1 were generated by carefully increasing pedal force on successive runs until the wheels lock. Thus, the data shown for the standard brake system

Figure 3. Straight line braking, wet and dry jennite and ice

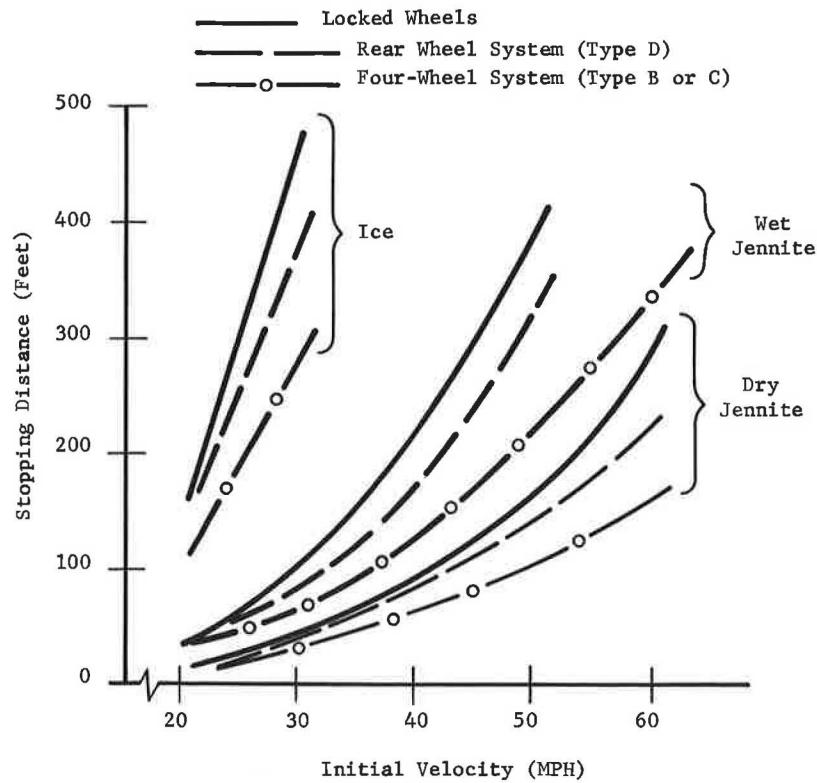


Figure 4. Four-wheel anti-lock system performance on split coefficient surfaces, skid numbers 30 and 70

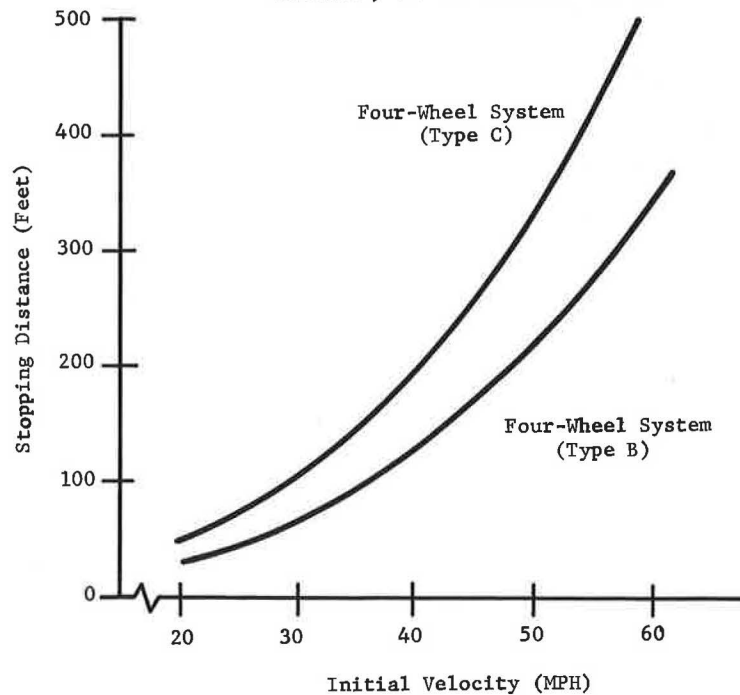
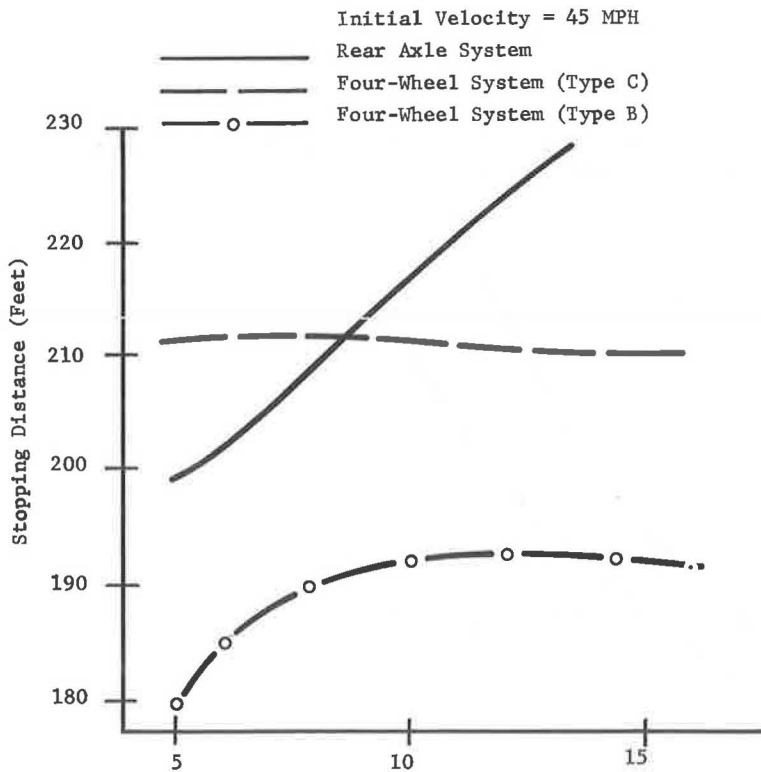


Table 1. Straight Line Stopping Distance for the Anti-Lock Systems and Standard Brake System Configuration

System	Dry $\mu_{PK} = 1.0$		Wet $\mu_{PK} = 0.45$	
	40% Load	100% Load	40% Load	100% Load
Four-Wheel Anti-Lock (Type B)				
● Stopping Distance	172 ft	172 ft	315 ft	292 ft
● Sustained Deceleration	0.08g	0.82g	0.41g	0.43g
Two-Wheel Rear Anti-Lock (Type D)				
● Stopping Distance	172 ft	172 ft	328 ft	305 ft
● Sustained Deceleration	0.77g	0.76g	0.37g	0.42g
Results with Improved Logic Values ^a				
● Stopping Distance	150 ft	155 ft	315 ft	300 ft
● Sustained Deceleration	0.90g	0.85g	0.39g	0.43g
Standard Brake System Configuration				
● Stopping Distance	150 ft	160 ft	315 ft	300 ft
● Sustained Deceleration	0.85g	0.79g	0.39g	0.42g

^aSee text on ESU

Figure 5. Braking in a turn



in Table 1 is close to the optimum that can be achieved with a "perfect" brake system. In the vehicle, it is unlikely that a driver could control brake pressure accurately enough to achieve the Table 1 stopping distances.

This point is further illustrated in Figure 6. This figure compares the stopping distance for the three systems over a limited range of brake pedal force. The importance of the comparison is seen in the large increase in stopping distance for all but the four-wheel anti-lock system as the pedal force is increased to the point where wheel lock occurs. In addition to the increase in stopping distance under the locked-wheel condition, vehicle stability and steerability are lost. (The Figure 6 data was also taken from the simulation where control logic parameters were not optimized.)

Another important consideration for the standard brake system with the fixed ratio of front-rear brake torque is the effect of variation in brake gain on braking performance. Even if the proportioning valve tolerances are ignored and one assumes the valve acts the same every time, performance can be significantly affected. If a proportioning valve is fitted to the nominal tolerance curve, as was done for this program, the performance of the vehicle would be nearly optimal. However, if the brake gains were at either extremes of tolerance, the performance resulting from the proportioning characteristic shown would result in longer stopping distances.

The effect of tolerances due to expected variations in front and rear brake gains was examined in the study. The tolerances assumed for the brake gains resulted in a change of front-to-rear torque ratio of +15% and -30% from the nominal values. The nominal stopping distances and the stopping

distances at the brake gain limits are shown in Table 2. It is seen that little improvement in stopping distance can be made in most cases while far worse performance could result. These values have all been calculated assuming that there is a perfect driver able to ramp and hold pedal force exactly as prescribed. If normal driver variations are accounted for, a wider tolerance range on stopping distance will result.

Braking in a 0.3g turn from 40 miles per hour, with a constant steering wheel angle, was used as a second maneuver to determine the brake system performance of the ESV. Table 3 shows the deceleration which could be achieved while braking in a turn with the two anti-lock systems and a standard brake system. Once again, the four wheel anti-lock system showed improved performance.

Summary of Simulation Results

In the simulation studies discussed, the performance of anti-lock system configurations and a standard brake system in straight line braking and braking in a turn was evaluated. A distinct difference in the two simulation studies conducted was that in one, performance was established at a locked wheel condition and in the other, performance was established at incipient lock-up or just prior to wheel lock-up. The performance in the locked wheel condition presents minimum braking performance that can be derived from braking system and is also probably representative of the performance that can be expected by a large segment of the driver population. Performance at incipient lock-up is representative of the maximum braking performance that can be derived from a vehicle and performance

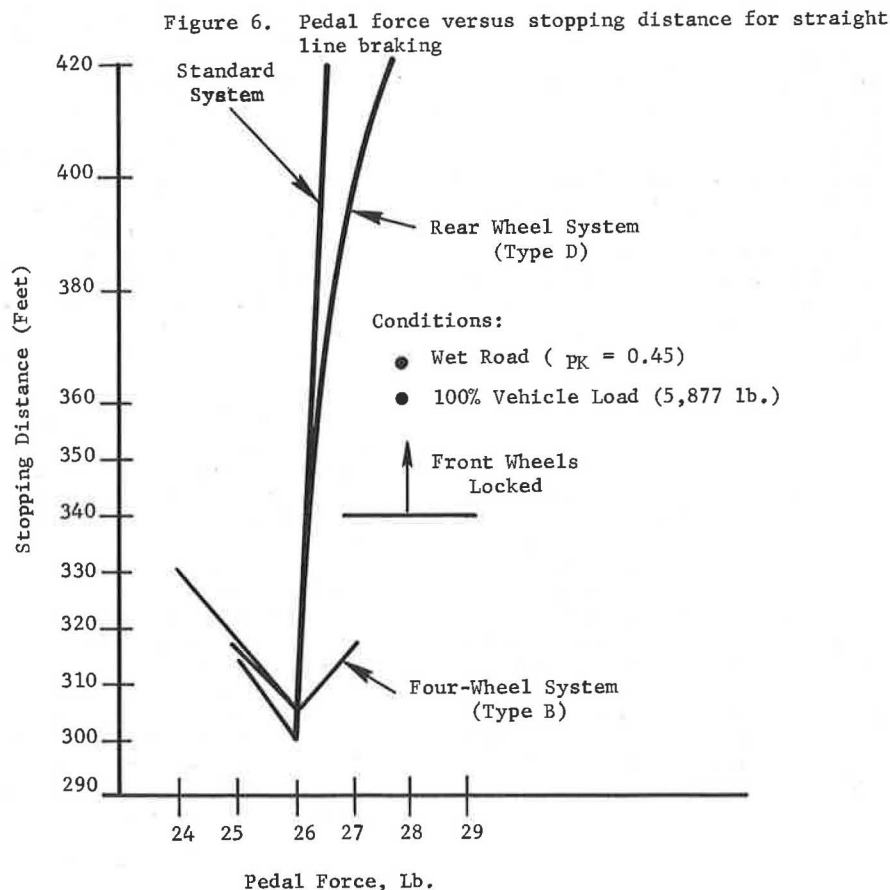


Table 2. Effects of Tolerances on Straight-Line Stopping Distances

System	Dry ($\mu_K = 1.0$)		Wet ($\mu_K = 0.45$)	
	40% Load	100% Load	40% Load	100% Load
Standard Brake System				
• Nominal Stopping Distance	150 ft	160 ft	315 ft	300 ft
• Stopping Distance Range with Limited Values of Brake Gain	138-171 ft	155-180 ft	277-365 ft	290-344 ft

Table 3. Maximum Achieved Deceleration Prior to Wheel Lock for Anti-Lock Systems and Standard Brake System Braking in a Turn

System	Dry Pavement		Wet Pavement	
	40% Load	100% Load	40% Load	100% Load
Standard Brake System Configuration	0.72g	0.72g	0.35g	0.34g
Four-Wheel Anti-Lock	0.75g	0.73g	0.39g	0.38g
Rear Wheel Anti-Skid	0.65g	0.70g	0.35g	0.37g

that cannot be extracted from a vehicle even with a very experienced test driver. With respect to this difference, results of these two studies indicate the following:

With respect to stopping distance:

1. An anti-lock system, particularly a four-wheel system, prevents any significant degradation in braking performance at pedal efforts beyond that of incipient lock-up.

2. Anti-lock will give an improvement over locked-wheel performance, particularly on wet surfaces; this can be beneficial to less experienced drivers.

With respect to vehicle control and stability:

1. A four-wheel anti-lock system provides stability and steering control in both straight line braking and in situations in which lateral force is induced and steering is required.

2. A rear-wheel system provides stability only.

As mentioned previously actual test programs have verified that most drivers have difficulty handling braking in extreme road conditions and the improved stability and handling characteristics provided by the anti-lock systems extend to transition surfaces. No definitive computer studies have been run for this condition but a brief study did support this conclusion.

Vehicle Tests

Over the past several years there has been much development and performance evaluation testing of a wide range of vehicles equipped with anti-lock systems. Some of the results have been published but much more is unpublished. The data covers passenger cars, mostly in the large vehicle category, some non-commercial articulated vehicles, and commercial vehicles in both single and articulated vehicle configurations.

This section covers results of some of that testing for straight line braking on both uniform and split coefficient surfaces as well as for braking/turning maneuvers.

Straight Line Uniform Coefficient Stops

Examination of a considerable amount of passenger car tire test data shows the peak-to-locked wheel friction coefficient varies with road surface and with tire construction. For all tires and for all surfaces except gravel and loose snow covered roads, the peak coefficient is always higher than the locked wheel coefficient and ranges from 5 to 20% above locked wheel. Therefore, theoretically, stopping distances can be reduced significantly with an anti-lock system. Practically, the full improvement cannot be realized because no operational system has been developed which will seek and maintain optimum traction throughout a complete stop on all surfaces. Fortunately, the most improvement occurs in situations where it is most needed -- namely, on wet surfaces and for other conditions when the driver is most likely to lock wheels or need help in stopping quickly.

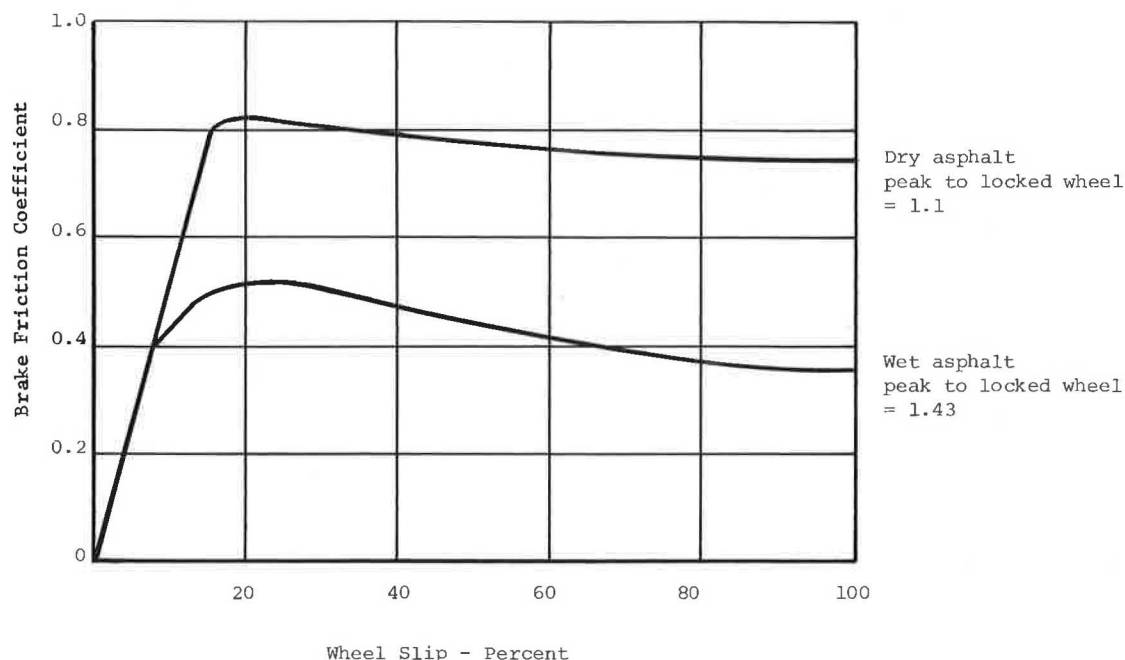
Figure 7 shows representative curves for dry and wet asphalt longitudinal friction versus per cent wheel slip. Vehicle velocity has an effect on the curves and low speed data tends to have higher values than high speed data. Also the speed effect tends to be greater for wet surfaces than for dry surfaces.

Available data on truck tires shows that the peak-to-locked-wheel friction coefficient ratio is higher than for passenger cars. It also shows that variation with speed and with load is also greater than for passenger car tires. Therefore, a judgment of performance improvement capability is more difficult.

Data is available (6) to support the accepted conclusion that anti-lock systems give only minor stopping distance improvement on high coefficient surfaces when compared with locked wheel. However, the data also shows that the anti-lock system gives significant stopping distance improvement even on high coefficient surfaces over stopping distances attainable by even skilled drivers stopping with no wheel allowed to lock.

Test data in the Douglas and Schafer paper was generated quite early in the history of commercially available anti-lock systems. Since that time considerable unpublished data has become available to verify those results. Also data for

Figure 7. Tire Brake Force Characteristics



heavier hydraulically braked vehicles and air braked vehicles show the same trends.

A significant amount of data on the effect of anti-lock systems on braking performance for commercial air braked vehicles is presented by C. W. Booth of PACCAR, Inc.(7). His study supports the thesis that anti-lock systems have a more difficult time improving on locked wheel stopping distances on high coefficient surfaces than they do on low coefficient surfaces.

Four Wheel Systems. First, a Type B and Type C anti-lock system configuration will be compared. Both systems use select-low logic for the rear axle. For the Type C system, the front axle was tested with both select-high and select-low logic. All four-wheel systems showed a considerable decreased stopping distance over locked wheel stops on all but the very high coefficient surfaces. The Douglas and Schafer paper (6) presents similar data for the Type B system. The Type C system operated very effectively but, in general, showed about five to ten percent less performance improvement over locked wheel than the Type B system. The select-high system gave shorter stopping distances on the high coefficient surfaces, and the select-low system had shorter stopping distances on the low coefficient surface. The results are consistent with the fact that the select-low system keeps the wheels out of lock longer and better on the low coefficient surfaces.

Another set of test data comparing a Type B system against a Type C system with the front axle using select-high logic showed similar results. The vehicle was run in both configurations on surfaces with skid numbers ranging from low (as represented by wet jennite) to high (as represented by dry asphalt). The stopping distance performance in these tests was marginally better with the individual front wheel control. For surfaces with a uniform friction coefficient, these results will hold.

Two-Wheel Control Versus Four-Wheel Control.

Tests with a passenger car system were run to compare a Type D rear axle control system with select-low logic against a Type C control system using both select-low and select-high logic on the front axle. Test surfaces included ice at about 20°F ambient temperature, wet and dry jennite, and wet painted asphalt. On all of the wet surfaces and on the ice, all systems had improved stopping distances over locked wheel stops. As has been mentioned previously, high coefficient surfaces generally have shorter locked-wheel stops than anti-lock controlled stops due to the relatively small friction peak for rolling tires on high coefficient surfaces.

On the very slippery surfaces, the Type C system showed a significant improvement in stopping distance over the Type D system. This is because the high peaks in the μ -slip curve on low coefficient surfaces result in the anti-lock systems having better performance than locked wheel. The select-low system also out performed the select-high system because all wheels were prevented from locking until the vehicle was almost stopped.

On the high coefficient surfaces the select-high system provided shorter stopping distances than the select-low system. The Type D system out-performed the Type C system and generally had only marginally longer stopping distances than locked wheel.

Tests were also run to compare braking performance with a rear axle anti-lock system using two wheel speed sensors and select low logic (Type D) with the same anti-lock system using a prop shaft speed sensor (Type E). The tests were run with the same vehicle to eliminate extraneous variables from the data. This particular vehicle also had a front axle anti-lock system using a single pressure modulator and two wheel speed sensors with select high logic. Test surfaces included wet painted asphalt, wet and dry asphalt, wet and dry jennite and gravel. The system using two speed sensors for the rear axle had marginally better performance on all coefficients. The improvement was in the 1% to 5% range and did not seem to be dependent on the test surface.

A recent test with an air-braked truck showed the same trends as passenger car tests. Table 4 compares stopping distances for a Type C four-wheel anti-lock system, a two-wheel Type D system, and locked wheel conditions. The stopping distances with anti-lock were shorter than locked wheel stops for both low coefficient surfaces. In addition, the vehicle was brought to a straight stop with either type of anti-lock system while the locked wheel stops generated vehicle yaw angles of up to 45°. On the high coefficient surface (SN 75), the Type C anti-lock system produced a stop 8% longer than with locked wheels while the Type D anti-lock system showed a slight improvement.

Articulated Vehicles. Tests with passenger car and station wagon type vehicles were run on low coefficient surfaces to demonstrate the advantages of an anti-lock system on the tow vehicle. Stops made with the tow vehicle rear wheels locked but

the tow vehicle front wheels and the trailer wheels unlocked resulted in very violent jackknives. With the anti-lock system on, well controlled, straight ahead stops were made.

Results of tests with an articulated heavy duty air-braked vehicle are shown in Table 5. Again, the advantage of anti-lock on the SN 10 surface is apparent in that the locked wheel stops produced enough yaw to have the combination vehicle straddle two-lanes. In this test, the improvement in stopping distance with anti-lock compared to a locked wheel stop on the SN 10 surface was not apparent. However, the trend for the SN 30 and 75 surfaces was consistent with other test results.

Split Coefficient Stops

The split coefficient test is ideal to determine the ability of a wheel lock control system to maintain directional stability. A locked wheel stop on

Table 4. Braking Performance, 4 X 2 Tractor, Unladen, Air Brakes

Surface Skid No.	Initial Vehicle Speed MPH	Stopping Distance		Locked Wheel	Comments
		Anti-Lock 4-Wheel Type C	Anti-Lock 2-Wheel Type D		
10	20	104 (8) ^a		113	
	20		90 (6)	96	10-15° Yaw on Locked Wheel Stops
	30	326 (2)		334	Up to 45° Yaw on Locked Wheel Stops
30	20	65 (3)		67	10-20° Yaw on Locked Wheel Stops
	40	308 (20)		381	20-30° Yaw on Locked Wheel Stops
75	20	31	28		No Locked Wheel Stops
	30	70 (-8)	61 (6)	65	

^aNumber in () indicates % improvement over locked wheel stop.

Table 5. Braking Performance, Combination Vehicle 4 X 2 Tractor, 40' Tandem Trailer, Unladen, Air Brakes

Nominal Surface Skid No.	Initial Vehicle Speed (MPH)	Stopping Distance		Comments
		Anti-Lock Type C	Locked Wheel	
10	20	65 (-3) ^a	63	30-45° Yaw on Locked Wheel Stops
	30	161 (-2)	158	30-50° Yaw on Locked Wheel Stops
30	20	38 (3)	39	
	40	174 (8)	188	
75	20	30 (-11)	27	

^aNumber in () indicates % improvement over locked wheel stop.

such a road will result in very large yaw angles at low speeds and vehicle "spin-out" at even moderate speeds. A rear axle anti-lock system will halt the vehicle fairly straight but will allow sideways drift and small yaw angles. Both effects are aggravated as vehicle speed increases. A four-wheel system allows the driver to offset the yaw torques with steering maneuvers and hold the vehicle in a straight course throughout the stop.

One of the most complete experimental evaluations of anti-lock system configurations in passenger cars on a split coefficient surface was conducted by Teldix and reported by Armin Czinczel in a paper entitled, "Problems of Brakes with Different Brake Control Types on Split Coefficients".

(1) Czinczel presents the results of an evaluation of differences in vehicle performance for three types of steering configuration and several anti-lock configurations. Included were vehicles with positive, neutral and negative steering roll radius (scrub radius). Anti-lock configurations evaluated included four wheel individual control (Type A), front individual and rear axle control (Type B), rear axle only (Type D) and individual rear wheel control (Type F). Tests were run with a free turning steering wheel and a locked steering wheel, and with driver control.

The results generally demonstrated the superior stability of the negative scrub radius under very heavy braking and especially when brake pressure was high enough to lock the wheels. This steering configuration had a very noticeable effect on performance of the vehicles with anti-lock control.

The study demonstrated a significant feature of four-wheel anti-lock system performance. A four-wheel system prevents lockup of all four wheels and allows steering control. However, on a split coefficient surface or under other conditions where unbalanced side to side forces can be induced, the Type A anti-lock system is not as inherently stable as the Type B or Type D systems. If the driver freezes the steering wheel rather than steering to correct for these disturbances, the vehicle yaw with a Type A system will be greater than the yaw with a Type B or Type D system under the same conditions. In fact, the Type A system had very large yaw angles when the vehicle with the positive steering roll radius was stopped with the steering wheel locked. The Type B system in general operated with lower lateral movement and with lower yaw angles. Also, less steering wheel input was required to hold the vehicle straight. The only exception was that the Type B system with the negative steering roll radius vehicle caused a significantly larger lateral displacement when the steering wheel was loose.

The tests demonstrated the superiority of individual wheel control in terms of stopping distance on split coefficient surfaces. The Type A system resulted in approximately 10% shorter stopping distances than the Type B system. The rear axle Type F system had significantly longer stopping distance than the Type B system but slightly shorter than the rear-axle select-low system, Type D. The select-low rear axle was more stable. However, in a panic situation, non-professional drivers were unable to hold a course with either of the rear axle systems.

The Teldix study did not include an evaluation of vehicles without an anti-lock system. In tests of European vehicles of a similar size conducted by Bendix, it was found that, without an anti-lock system, vehicle yaw angle increased very rapidly from about 10-15° for a 10 miles per hour stop to over 100° at 30 miles per hour. A few stops at up to 50 miles per hour produced spins of 1-1/2 to 2

revolutions on a combination of normal wet asphalt on one side and a special wet painted surface on the other. Another point of interest regarding safety is the lateral movement that occurs in addition to the spin. At low speeds, the movement tends to be pure rotation, but at higher speeds the vehicle center of gravity moves 3 to 4 feet away from the original path.

Several luxury type passenger cars were run through similar tests to determine the yaw with and without the anti-lock systems. Speeds were limited to 30 miles per hour and vehicles with rear-wheel-only systems and with four-wheel systems were tested. Yaw angles in excess of 200° were encountered with all vehicles without the anti-lock systems. With rear wheel only, some systems held the yaw angle to 5 to 10° and some allowed as much as 30° yaw angle. The four-wheel system which allowed the driver directional control had minimal yaw angles of less than 5°. Similar tests run on glare ice show the same general results in terms of yaw angle control and differences between the two wheel and the four wheel systems.

Braking In A Curve Or Lane Change

Testing on a passenger car has demonstrated the advantages of anti-lock systems for stopping in curves and during lane changes. Unpublished data shows that with anti-lock a driver can safely come to a stop while negotiating a lane change at high speed. In most cases he was able to approach the lane change course without braking at all. The testing showed the advantage of a four-wheel system with individual front wheel control (Type B). A system with axle control both front and rear (Type C) worked well but was less effective (with respect to stopping distance) than the individual front wheel control.

Another test of braking during a vehicle maneuver was conducted on a short wheelbase air-braked truck. The object of the test was to measure the reduction in maximum safe speed with the truck braked with a full brake (panic) application during a maneuver, as compared to driving through the maneuver without any braking. The maximum safe speed was the speed at which the driver could negotiate the maneuver without hitting any of the pylons marking the maneuver courses. The two maneuvers were the lane change (specified in SAE J-46) and a 356-foot radius curve.

The test vehicle was a 4x2 truck with a wheelbase of 134 inches and equipped with a Type C anti-lock brake system. Empty vehicle weight was 14,000 pounds, laden weight was 31,000 pounds. The test surface was wet jennite with a skid number of 27. The test results are shown in Table 6.

The maximum safe speed for the above maneuvers in a panic stop without four-wheel anti-lock braking, where the wheels lock, is 25 miles per hour and 22 miles per hour for the lane change and curve, respectively.

Table 6. Maximum Safe Speed for Braking Maneuvers

Maneuver	Vehicle Load	Drive Thru	Braking with
			Anti-Lock Brake System
Lane Change	Laden	32	30
	Unladen	40	38
Curve	Laden	40	40
	Unladen	40	40

A more recent test with an articulated vehicle further illustrates the advantage of an air-braked anti-lock system on each axle. The vehicle used in this test was a short wheel-base air-braked 4x2 tractor coupled to a 40 foot tandem axle trailer. The maneuver was a 356 foot radius curve on wet jennite as above. The anti-lock system was select-low, axle-by-axle (Type C-1). With the anti-lock system on, the vehicle could easily negotiate the curve during a panic stop at 40 miles per hour and stop in about 175 feet. Without anti-lock the driver could not make the curve in a panic stop at 40 miles per hour, if he allowed the wheels to lock. With a careful brake application to 30 psi he was able to stop safely in the curve in 200 feet from 40 miles per hour. A second attempt at 30 miles per hour resulted in a 145 foot stop (equivalent to 225 feet at 40 miles per hour).

Thus, the data shows that with anti-lock on all wheels, a driver can safely brake in maneuvers found in the real world at almost the same speed he can safely drive through them. On the other hand, the maximum safe speed for a maneuver is substantially reduced if the vehicle wheels are allowed to lock. If the driver elects to brake lightly to avoid wheel lock, his stopping distance will be considerably longer than that achievable with an anti-lock system on each braked wheel. In the light of studies showing the difficulty the average driver has in controlling the vehicle in heavy braking situations, especially on low coefficient surfaces, the advantages of anti-lock equipment becomes more apparent.

Recent Developments

A recent development in the commercial vehicle anti-lock industry has been a trend toward a cost-effective system which modulates both axles of a tandem axle from a single logic command. The configuration which appears to be most cost-effective uses a single sensor on each axle along with a single modulator on one axle for controlling both axles from one command. The signal processing used to derive this single command has been under considerable study. System differences in terms of total number of sensors and the effect of suspension types also have entered into the studies. This whole question will be discussed in a paper to be presented by The Bendix Corporation at the August, 1977, meeting sponsored by the Society of Automotive Engineers on the West Coast.

Acknowledgments

Much of the content of this paper was presented at the Society of Automotive Engineers February, 1976, meeting.

The authors would like to acknowledge the work of their colleagues within the Bendix Corporation from which the data for this paper was collected. Their names are too numerous to mention, but in the aggregate, they have contributed many man-years to anti-lock system development within Bendix.

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