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A Simulation Model for Vehicle Braking Systems Fitted with ABS

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ABSTRACT

Most vehicles built today are fitted with anti-lock braking systems (ABS). Accurate simulation modeling of these vehicles during braking as well as combined braking and steering maneuvers thus requires the effects of the ABS to be included. Simplified, lump parameter models are not adequate for detailed, 3-dimensional vehicle simulations that include wheel spin dynamics. This is especially true for simulating complex crash avoidance maneuvers. This paper describes a new ABS model included in the HVE simulation environment. It is a general purpose model and is available for use by any HVE-compatible vehicle simulation model. The basic operational and control characteristics for a typical ABS system are first reviewed. Then, the specific ABS model and its options as implemented in the HVE simulation environment and employed by the SIMON vehicle simulation model are described. To validate the model, pressure cycles produced by the model are compared with stated engineering requirements. In addition, pressure vs. time histories for two ABS simulations on surfaces with different frictional characteristics are compared with experimental data. Finally, the gross effects of ABS on two simulated maneuvers (straight-line braking and ISO 3888 lane-change maneuver) are presented.

IT IS AN OLD ADAGE: A locked tire can't steer. Few old adages are truer than this one, and the safety implications of a vehicle without steering are obvious.

Recognizing the importance of maintaining steering control, vehicle engineers have for many years designed methods to prevent tires from locking. Harned, et. al. [1] addressed the issue directly in 1969. In the mid-seventies, the US DOT enacted FMVSS 121 [2], essentially requiring some type of ABS control to achieve mandated stopping distances for heavy trucks. However, hardware technologies of that era were inadequate and unreliable. As a result, the essential elements of FMVSS 121 were revoked in the late seventies. The eighties saw substantial research into various ABS hardware technologies (e.g., [3, 4]). However, it was not until the common usage of on-board computer control systems, brought about in large part by major improvements in the speed and reliability of microprocessors and related electronic hardware, that ABS became a standard feature on most passenger cars and light trucks. The nineties saw a significant change in the focus of research from basic hardware issues to improvements and innovations in control algorithms (e.g., [5, 6]; there are countless others in the literature). By 1996, sixty-two percent of the US passenger car and light truck population incorporated ABS [7].

It is interesting to note that most researchers have concluded that the widespread usage of ABS-equipped vehicles has not brought about the expected reduction in crashes. Although there is some disagreement as to why this is the case, the most likely reason is that ABS-equipped vehicles still leave the road – albeit under the directional control of their drivers (suggesting that no technology can replace driver education and experience) [7].

Because vehicles are still crashing, safety researchers are still faced with the ongoing need to reconstruct those

[*]Numbers in brackets designate references found at the end of the paper.

crashes to determine their cause. However, their reconstruction has been further complicated by the introduction of ABS-equipped vehicles in two ways. First, ABS-equipped vehicles leave little or no skidmarks during straight-line braking, and second, the directional vehicle dynamics during a combined steering and braking maneuver (such as a loss of control preceding an off-road crash) may be significantly affected by the presence of ABS. For example, a non-ABS-equipped vehicle will typically skid straight during heavy braking - regardless of the amount of steering. An ABS-equipped vehicle, on the other hand, will typically respond to the driver's steering input.

Vehicle handling simulation has been an important tool in the study of loss of control crashes. To study the loss of control of ABS-equipped vehicles thus requires that the simulation be able to model the effects of the ABS system on the resulting vehicle trajectory.

This paper describes a new ABS model implemented in the HVE [8] simulation environment. It is a general purpose model available for use by any HVE-compatible vehicle simulation model. The model is applicable to the design of ABS systems as well as to the study of loss-of-control crashes of ABS-equipped vehicles. The basic operational and control characteristics of a typical ABS system are first reviewed. Then, the specific ABS model and its options as implemented in the HVE simulation environment and used by the SIMON [9] vehicle simulation model are described. To validate the model, pressure cycles produced by the model are compared with stated engineering requirements. In addition, pressure vs. time histories for two ABS simulations on surfaces with different frictional characteristics are compared with experimental data. Finally, the gross effects of ABS on two simulated maneuvers (straight-line braking and ISO 3888 lane-change maneuver) are presented.

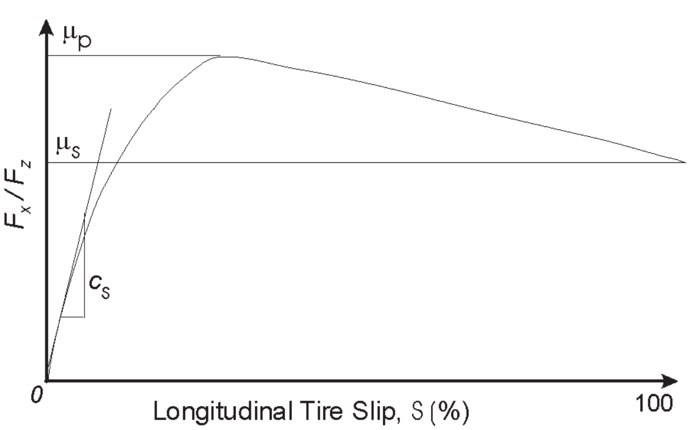

Figure 1 - Typical graph of normalized braking force vs. longitudinal tire slip (graph is also called a mu-slip curve).

OVERVIEW OF ABS

The basic concept behind ABS is quite simple and can be demonstrated by the graph of normalized braking force vs. longitudinal tire slip shown in Figure 1. This graph is traditionally called a *mu-slip curve*. It defines the relationship between longitudinal tire slip and the available longitudinal (braking) force. A key observation is that the maximum braking force occurs at μ_p (peak friction coefficient) in the vicinity of 10 to 15 percent longitudinal tire slip (this varies somewhat from tire to tire). Also, as the tire slip continues to increase to 100 percent, the available braking force falls off. The region of tire slip between μ_p and μ_s (slide friction coefficient, or 100 percent longitudinal slip, associated with locked-wheel braking) is a region of dynamic instability. As slip begins to increase beyond μ_p it quickly increases to 100 percent (i.e., the tire locks) with a commensurate reduction in available braking force.

The goal of an ABS system is simply to prevent the tire slip from increasing significantly beyond μ_p – regardless of how much brake pedal effort is applied by the driver. By limiting longitudinal slip, the tire continues to roll and, therefore, maintains directional control capability (i.e., the driver can steer the vehicle). In addition, as shown in Figure 1, the available braking force is larger than for a locked tire and, therefore, braking distance can be reduced.

ABS simulation takes advantage of the simulation's wheel spin degree of freedom, wherein the braking force is calculated from first principles, rather than simply specified as a force at the tire-road interface. To *truly simulate* ABS, the algorithm must modulate the simulated brake pressure, just as it does on an actual vehicle. The procedures for accomplishing this task are described below.

ABS Methodologies

All ABS methodologies work by controlling longitudinal tire slip. This is accomplished through the use of wheel sensors that compare the tire circumferential velocity to the current *reference velocity*, V_r, normally calculated using the current spin velocities of two or more wheels (see Reference 10 for a detailed discussion of the calculation of reference velocity). On the vehicle, longitudinal tire slip cannot be measured directly. Instead, slip is calculated:

$$Slip = \frac{V_r - \dot{\Omega}_w \times R_{tire}}{V_r} \qquad \text{(Eq. 1)}$$

where

V_r = Reference velocity

$\dot{\Omega}_w$ = Wheel spin velocity

R_{tire} = Tire rolling radius

State Variables

To accomplish the required control of longitudinal slip, the following state variables are monitored or calculated by the vehicle's ABS control module:

- Vehicle Velocity - Linear velocity of the vehicle sprung mass
- Wheel Spin Velocity – Angular velocity of each wheel (or axle on some systems)
- Tire Longitudinal Slip - Relative velocity between the tire and road, expressed as a fraction of vehicle velocity
- Wheel Spin Acceleration - Angular acceleration of each wheel
- Tire-Road Surface Friction – Ratio of the maximum braking force to the normal tire force
- Brake System Pressure – Pressure produced as a result of the driver's brake pedal application (input variable)
- Wheel Brake Pressure – Pressure supplied to the wheel brake assembly (output variable)

Typical Hardware

To monitor or calculate the above state variables, the typical vehicle ABS system includes the following hardware components:

- Electronic Control Unit (ECU) – This is one of the vehicle's microcomputers. It is programmed with the algorithm that reads the current state variables, determines the required pressure at each wheel and sends the appropriate signals to the brake pressure modulator (see below).
- Wheel Speed Sensors – These components directly measure the wheel spin velocity of each wheel using a wheel-mounted pulse rotor (a notched metal ring) and a fixed, magnetic sensor that measures the rotation of the pulse rotor.
- Brake Pressure Modulator – This component (or components, depending on the system) controls the wheel brake pressure according to the control conditions specified by the ECU.
- Brake Master Cylinder/Air Compressor – This component provides the fluid pressure source.
- Wheel Brake Caliper/Cylinder/Chambers – These components apply the braking force at each wheel according to the wheel brake pressure.

The basic hardware requirements are generally the same for all vehicle types, ranging from passenger cars to on-highway trucks. Reference 10 provides a detailed description of these required components.

Table 1. HVE ABS System Variables. These variables apply to the overall vehicle (compare with Wheel Variables in Table 2).

Variable	Description
Algorithm	ABS algorithm selected from a list of available algorithms
Control Method	ABS control method selected from a list of available control methods
Cycle Rate	Sets the time required for a complete ABS cycle
Threshold ABS Pressure	Minimum pressure for ABS activation
Threshold ABS Velocity	Minimum vehicle velocity for ABS activation
Friction Threshold	Tire-terrain surface friction threshold
Delay Method	Delay method selected from a list of available delay methods
Apply Delay	Time delay for controlled output pressure increase
Release Delay	Time delay for controlled output pressure release

ABS USER INTERFACE

The HVE ABS user interface allows the user to select an ABS algorithm and to enter and edit the independent parameters required by the selected ABS algorithm. The interface includes numerous options, thus, various algorithms may be supported. The interface is divided into two sections:

- System Variables – Variables that are applicable to the entire vehicle
- Wheel Variables – Variables that are applicable to (and may be specified independently for) each wheel

System Variables

The ABS system variables included in the HVE ABS model are shown in Table 1. A brief description of each variable follows:

- ABS Algorithm – This is the ABS algorithm, selected from a list of the various ABS algorithms available to the user. The algorithms currently available are *Tire Slip* and *HVE Bosch Version 1*. This list can be updated as new algorithms become available.
- Control Method – This option determines if all wheels are controlled by a single controller or if individual wheels or axles are controlled separately. Vehicle-based sampling

uses the same control cycle (see below) for all wheels; axle-based control allows different control cycles for the front and rear axles (typically only the rear axle is controlled); wheel-based control cycles allow different control cycles for each wheel.

- Cycle Rate – If the *Control Method* is vehicle-based, this parameter provides the maximum time required to perform a complete ABS cycle. It is the same for all wheels.
- Threshold ABS Pressure – This parameter provides a minimum system pressure threshold for ABS actuation. ABS is bypassed when the system pressure is below this value.
- Threshold Vehicle Velocity – This parameter provides a minimum vehicle velocity threshold for ABS actuation. ABS is bypassed when the vehicle velocity is below this value.
- Low Surface Friction Threshold – This parameter sets a threshold defining low friction surfaces. Algorithms can use this parameter to invoke friction-dependent modulation behaviors. For example, the *Delay Interval* (see below) may be reduced for low friction surfaces.
- Delay Method – This parameter determines if control pressure delays are vehicle-based, axle-based or wheel-based. Vehicle-based delay uses the same delay period for each wheel; axle-based delay allows different delay periods for each axle; wheel-based delay allows different delay periods for each wheel.
- Apply Delay – If the *Delay Method* is vehicle-based, this parameter determines the delay period for all wheels before output pressure is increased. (See below for axle-based and wheel-based delay.)
- Release Delay – If the *Delay Method* is vehicle-based, this parameter determines the delay period for all wheels before output pressure is reduced. (See below for axle-based and wheel-based delay.)

Wheel Variables

Wheel variables are those ABS parameters that are assigned independently for each wheel. The ABS wheel variables included in the HVE ABS model are shown in Table 2. A brief description of each variable follows:

- Cycle Rate – If the ABS System *Control Method* is *At Axle* or *At Wheel,* this parameter determines the maximum time required to perform a complete ABS cycle for the selected wheel.
- Threshold Wheel Velocity – This parameter specifies a minimum wheel velocity threshold for ABS actuation. ABS is bypassed for this wheel when the wheel forward velocity is below this value.
- Minimum Tire Slip – This parameter may be used in an algorithm to establish a lower threshold for tire longitudinal slip.
- Maximum Tire Slip – This parameter may be used in an algorithm to establish an upper threshold for tire longitudinal slip.

Table 2. HVE ABS Wheel Variables. These variables apply to individual wheels (compare with System Variables in Table 1).

Variable	Description
Cycle Rate	Sets the time required for a complete ABS cycle
Threshold Wheel Vel	Minimum wheel forward velocity for ABS control
Tire Min Slip	Minimum tire longitudinal slip for ABS control
Tire Max Slip	Maximum tire longitudinal slip
Wheel Min Spin Accel	Minimum wheel angular acceleration
Wheel Max Spin Accel	Maximum wheel angular acceleration
Apply Delay	Time delay for controlled output pressure increase
Primary Application Rate	Initial rate of controlled output pressure increase
Secondary Application Rate	Secondary rate of controlled output pressure increase
Release Delay	Time delay for controlled output pressure decrease
Release Rate	Rate of controlled output pressure decrease

- Minimum Wheel Spin Acceleration – This parameter may be used in an algorithm to establish a lower threshold for wheel spin acceleration.
- Maximum Wheel Spin Acceleration – This parameter may be used in an algorithm to establish an upper threshold for wheel spin acceleration.
- Apply Delay – If the *Delay Method* is *At Axle* or *At Wheel*, this parameter determines the control pressure delay period before output pressure is increased at the selected wheel.
- Primary Application Rate – This parameter determines the initial rate of output pressure increase.
- Secondary Application Rate – This parameter provides an alternative rate of output pressure increase, usually substantially lower than the *Primary Application Rate*.
- Release Delay – If the *Delay Method* is *At Axle* or *At Wheel*, this parameter determines the control pressure delay period before output pressure is reduced at the selected wheel.
- Release Rate – This parameter determines the rate of output pressure decrease.

The ABS System and Wheel Variables are provided as a palette of parameters available to the designer of an ABS system. The selection of individual parameters and their effect on the simulated characteristics of any specific ABS system are algorithm-dependent.

DESCRIPTION OF CURRENT MODELS

Two ABS algorithms are currently implemented. These are the *Tire Slip* algorithm and the *HVE Bosch Version 1* algorithm. These algorithms are described below.

Tire Slip Algorithm

This is a simple and straight-forward ABS algorithm. Its design is based on the fundamental goal of an ABS system, that is, to maintain tire slip in the vicinity of peak friction coefficient, μ_p (refer to Figure 1). It is generally applicable to any type of vehicle (passenger car, truck, etc). Tire *Minimum Slip* and *Maximum Slip* parameters are selected to be about 5 percent below and above, respectively, the tire peak friction coefficient.

Upon brake pressure application, once ABS is invoked (that is, the minimum vehicle velocity and brake pressure thresholds are exceeded), the algorithm incorporates two switches, depending on the current tire slip:

- Tire Slip ≤ Minimum Slip – Under this condition, the status of the ABS during the previous sample determines how pressure is modulated for the current sample. If the ABS modulation status was off, the output pressure is set equal to the input pressure and the ABS system parameters (delays, etc.) are reset. Otherwise, brake pressure will be controlled. One of two possibilities exists: a) Input pressure is decreasing. In this case, output pressure is set equal to input pressure and the ABS status is turned off, or b) Input pressure is constant or increasing. In this case, the output pressure is maintained at a constant for the specified *Apply Delay,* after which output pressure is increased according to the *Primary Apply Rate*.
- Minimum Slip < Tire Slip < Maximum Slip – Under this condition, pressure control will occur according to the specified *Cycle Interval*. One of two possibilities exists: a) Input pressure is decreasing. In this case, output pressure is set equal to input pressure and the ABS status is turned off, or b) Input pressure is constant or increasing. In this case, the pressure is maintained at a constant for the specified *Apply Delay,* after which output pressure is increased according to the *Secondary Apply Rate*.
- Tire Slip ≥ Maximum Slip – Under this condition, sampling will occur according to the specified *Cycle Interval*. The output pressure is maintained at a constant for the specified *Release Delay*, after which the output pressure is reduced according to the *Release Rate*.

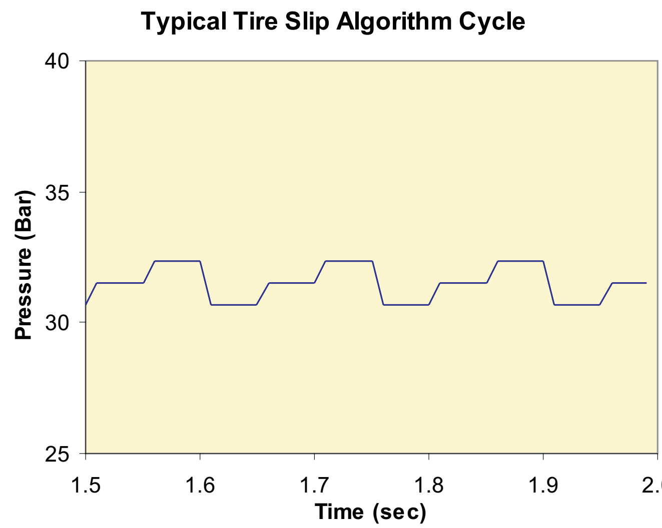

Figure 2 - Typical control cycles for Tire Slip ABS algorithm.

Figure 2 shows a typical pressure vs. time history for a few cycles of a hard brake pedal application (i.e., enough system pressure to lock the wheel). The flow chart for the *Tire Slip* algorithm is shown in Appendix II.

HVE Bosch Version 1 Algorithm

The HVE Bosch Version 1 ABS algorithm* is based on the information provided in reference 10. The Bosch ABS system is used on many passenger cars. The algorithm is based on wheel spin acceleration and a critical tire slip threshold.

Upon brake pressure application, once ABS is invoked (i.e., the thresholds are exceeded), the current brake pressure application is divided into eight phases (see Figure 3).

Phase 1 – Initial application. Output pressure is set equal to input pressure. This phase continues until the wheel angular acceleration (negative) drops below the *Wheel Minimum Spin Acceleration*, -α.

Phase 2 – Maintain pressure. Output pressure is set equal to previous pressure. This phase continues until the tire longitudinal slip exceeds the slip associated with the *Slip Threshold*. At this time, the current tire slip is stored and used as the slip threshold criterion in later phases. This slip corresponds to the maximum slip; the tire is beginning to lock.

*This implementation was developed by EDC based on the information provided in reference 10. Version 1 is the HVE version number, not the Bosch version number.

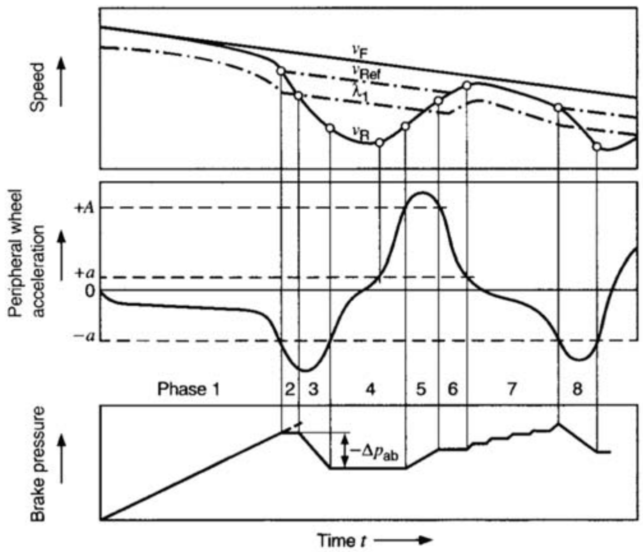

Figure 3 - Idealized control sequence for the Bosch algorithm (reprinted from reference 10). Compare the lower portion with the pressure cycles displayed in Figure 4.

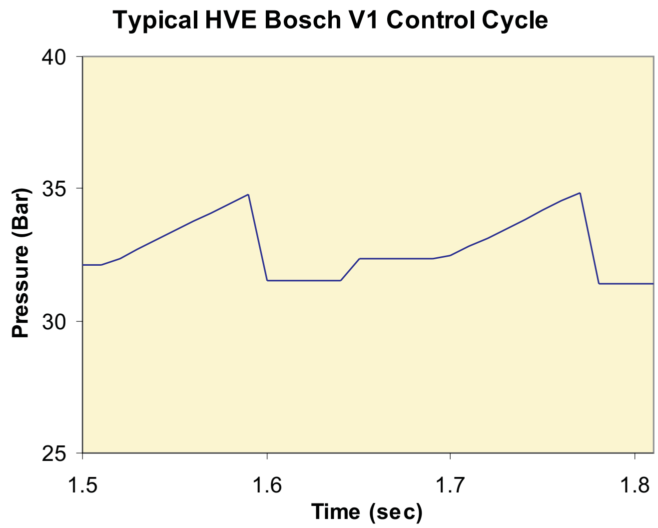

Figure 4 - A single control cycle produced by the HVE Bosch Version 1 ABS algorithm. Comparison of this cycle with the idealized brake pressure control cycle shown in Figure 3 reveals the basic characteristic of the Bosch algorithm has been achieved.

Phase 3 – Reduce pressure. Output pressure is decreased according to the *Release Rate* until the wheel spin acceleration becomes positive (this is a slight modification to the sequence shown in Figure 3, in which the pressure is decreased until the spin acceleration exceeds -a).

Phase 4 – Maintain pressure. Output pressure is set equal to the previous pressure for the specified *Apply Delay*, or until the wheel spin acceleration (positive) exceeds +*A*, a multiple (normally 10x) of the *Wheel Maximum Spin Acceleration,* +a, (signifying the wheel spin velocity is increasing at an excessive rate).

Phase 5 – Increase pressure. Output pressure increases according to the *Primary Apply Rate.* This phase continues until the wheel spin acceleration drops and again becomes negative (this is a slight modification to the sequence shown in Figure 3, in which the pressure is increased until the spin acceleration drops below +*A*).

Phase 6 – Maintain pressure. Output pressure is set equal to previous pressure for the specified *Apply Delay*, or until wheel angular acceleration again exceeds the *Wheel Minimum Wheel Spin Acceleration* (negative).

Phase 7 – Increase pressure. Output pressure increases according to the *Secondary Apply Rate*, normally a fraction (1/10) of the *Primary Apply Rate*. This achieves greater braking performance while minimizing the potential for wheel lock-up at tire longitudinal slip in the vicinity of peak friction. This phase continues until wheel angular acceleration drops below the *Wheel Minimum Angular Acceleration* (negative), indicating wheel lock-up is eminent.

Phase 8 – Reduce pressure. At this point an individual cycle is complete, the process returns to Phase 3 and a new control cycle begins.

As stated, some minor differences exist between the HVE implementation and the Bosch description provided in Reference 10. These differences reflect some inconsistencies between the acceleration and pressure profiles shown in Figure 3. For example, unless the throttle is applied, it is physically inconsistent that the wheel acceleration would be positive, let alone increase (as shown in Phase 5), in the presence of increased brake pressure (and, therefore, brake torque).

Each of the above phases begins with a comparison between the current tire longitudinal slip and the value stored during Phase 2. If the current slip exceeds this value, the normal logic is bypassed and resumed at Phase 3. This effectively allows the algorithm to “learn” the wheel slip associated with wheel lock-up on the current surface. This is referred to as “adaptive learning”, and is a key to the success of this ABS algorithm. As the tire travels onto surfaces with differing friction characteristics, the ABS model is able to maximize its performance accordingly.

Default parameters used by the HVE Bosch Version 1 algorithm were developed through the evaluation of numerous simulation runs. See Appendix I for typical parameters applicable to a P195/75R14 passenger car tire.

Figure 4 shows a typical pressure vs. time history for a few cycles of a hard brake pedal application (i.e., enough system pressure to lock the wheel). The flow chart for the HVE Bosch Version 1 algorithm is shown in Appendix III.

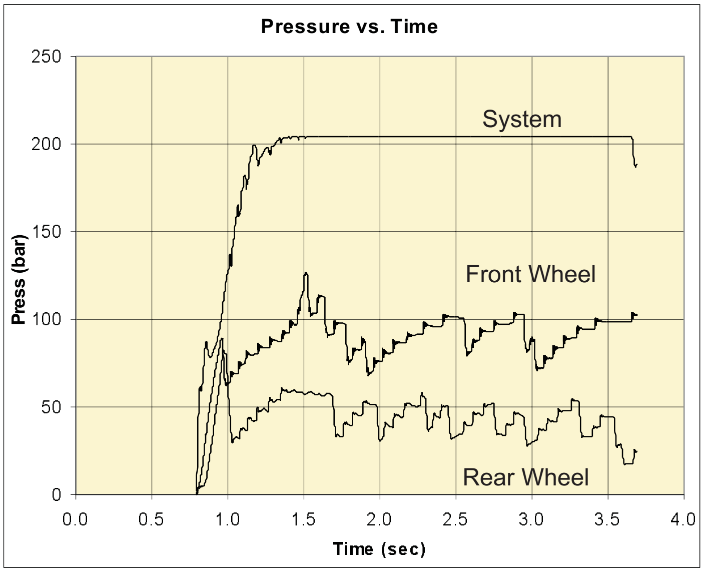

Figure 5 - Experimental braking test results for an ABS-equipped vehicle on a high-friction (asphalt) surface.

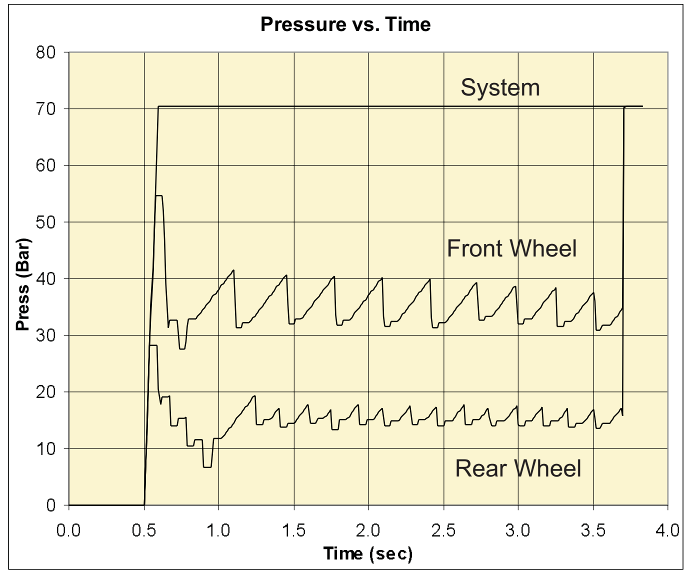

Figure 6 - Simulated braking test results for an ABS-equipped vehicle on a high-friction (asphalt) surface.

Other Algorithms

The ABS model implemented in HVE is not restrictive in terms of the algorithms it can support, other than its need to provide the parameters required by the algorithm. Endless tweaking of an algorithm is possible, resulting in different ABS system characteristics, each with its advantages and disadvantages. Thus, it is certain that new ABS algorithms will be developed and implemented in HVE over time, both to develop and to model new ABS systems.

COMPARISON WITH EXPERIMENT

Results from simulations using the HVE ABS model were compared against experimental data provided by Robert Bosch USA GmbH. These straight-line braking tests were performed on various surfaces at various speeds. The vehicle type and Bosch ABS version were not identified, although the vehicle probably used Bosch ABS 5.2. Because specific and detailed data for the vehicle, ABS system and tire-road frictional characteristics were lacking, no attempt was made to duplicate the experimental runs. Rather, the purpose of these comparisons was to isolate the general characteristic trends found in the experimental pressure vs. time histories and compare them against time histories simulated using the HVE ABS model with default parameters. The specific parameters are provided in Appendix I.

High Friction Surface

Figure 5 shows experimental test results on a high friction surface (asphalt) at an initial speed of 100 Km/h (62 mph). Master cylinder and front and rear wheel pressure histories are presented. Figure 6 shows SIMON simulation results for a Generic Class 2 Passenger Car [12] with the HVE ABS model enabled. The simulation uses the HVE Bosch Version 1 algorithm.

Comparison of Figures 5 and 6 reveals the basic characteristics are quite similar. Both show approximately 2 to 4 cycles per second for the front wheels and 4 to 6 cycles per second for the rear wheels. A similarity in the detailed pressure characteristics within each control cycle is also seen.

Comparison between experiment and simulation also shows a similar proportion of front and rear brake pressures, as well as system pressure (the actual pressures are different because the vehicle weights and brake torque ratios are different; insufficient test data were available to attempt to duplicate the Bosch tests).

Control pressure at the end of the simulation increases quickly back to system pressure as the vehicle velocity drops below the velocity threshold and comes to rest (the test vehicle's brakes are released and it does not come to rest within the time presented in Figure 5).

Low Friction Surface

Figure 7 shows experimental test results on a low friction surface (ice) at an initial speed of 50 Km/h (31 mph). Master cylinder (i.e., system) and front and rear wheel pressure histories are presented. Figure 8 shows SIMON simulation results for a Generic Class 2 Passenger Car [12] with the HVE ABS model enabled. The simulation uses the HVE Bosch Version 1 algorithm with the same default parameters as those used in the test on the high friction surface (see Appendix I).

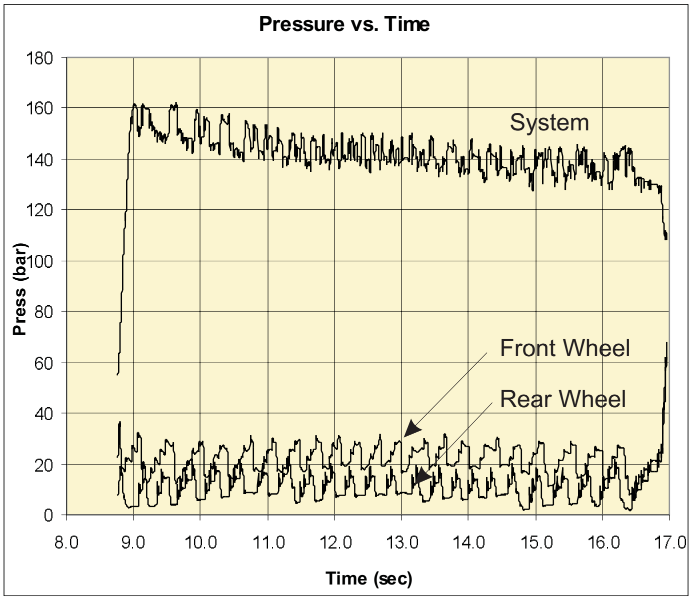

Figure 7 - Experimental braking test results for an ABS-equipped vehicle on a low-friction (ice) surface.

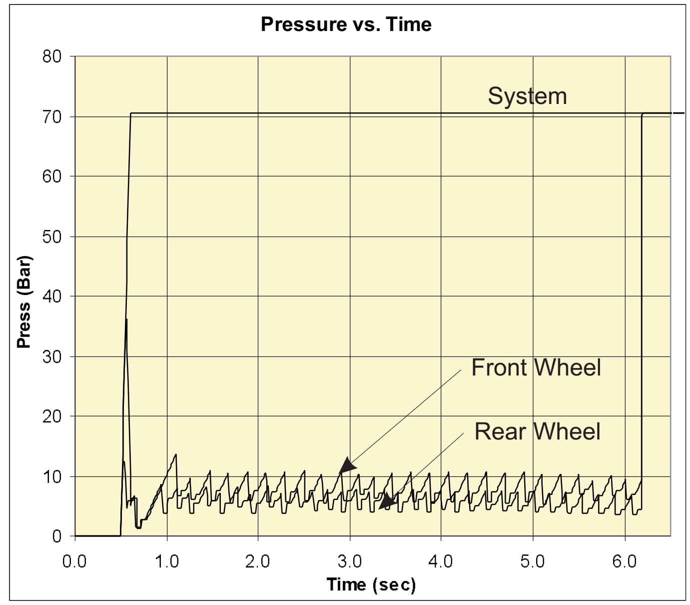

Figure 8 - Simulated braking test results for an ABS-equipped vehicle on a low-friction (ice) surface.

The source of the noise in the master cylinder pressure trace is unknown (because the master cylinder pressure is significantly greater than the controlled wheel pressures, this factor is not considered important in the test results). Again, the basic characteristics of the controlled wheel pressures are quite similar. Both show approximately 4 to 6 cycles per second for the front wheels and slightly higher cycle rates for the rear wheels. The cycle frequency is a natural consequence of the wheel spin dynamics (spin accelerations are higher on a low-friction surface; see earlier discussion of the eight phases in a Bosch cycle). Comparison between experiment and simulation again shows a similar proportion of front and rear brake pressure.

Control pressures for both the test and the simulation increase quickly to master cylinder pressure as the vehicle velocity drops below the velocity threshold comes to rest.

EXAMPLES

The effects of an ABS braking system on vehicle handling are illustrated through the use of two simulation examples. The first is a straight-line braking test with and without ABS model invoked. The second is an ISO 3888 lane-change maneuver during hard braking with and without the ABS model invoked. Both examples use default ABS parameters. The purpose of these simulations is to confirm the expected behavior of the ABS model, that is, to reduce braking distance and provide steering control during a hard braking and steering maneuver.

Straight-line Braking

A reduction in stopping distance is expected to be provided by ABS during straight-line braking. This example illustrates the reduction in stopping distance on a typical asphalt surface. The vehicle is a Generic Class 2 Passenger Car [12] fitted with Generic P195/75R14 tires. The initial velocity is 100 km/h (62 mph). A 300 N force is applied to the brake pedal. No steering is applied. The HVE Bosch Version 1 algorithm is used in this example.

Figures 9 and 10 show distance, velocity and acceleration vs. time with and without the ABS system activated. Braking begins at t = 0.5 seconds. Stopping distance is reduced from 48.7 m (160 ft.) to 47.2 m (155 ft), a 3.2 percent reduction. Braking time is reduced from 3.44 seconds to 3.33 seconds. The calculated average deceleration rate increased from 0.80 g to 0.83 g. Close inspection of the acceleration vs. time history in Figure 9 shows the modulation due to the ABS (compare with Figure 10, which is smooth due to the locked wheels).

ISO 3888 Lane-change Maneuver

The chief benefit of ABS is that the driver's ability to maintain vehicular control during a heavy braking and steering maneuver is significantly improved. To illustrate this point, a simulation of an ISO lane change maneuver is executed during a panic brake application. The vehicle is a Generic Class 2 Passenger Car. The initial velocity is 80 km/h (50 mph). The HVE Driver Model (path follower) [8] was used, and a 300 N sudden brake pedal force was applied at t= 0.5 seconds. The HVE Bosch Version 1 algorithm is used in this example.

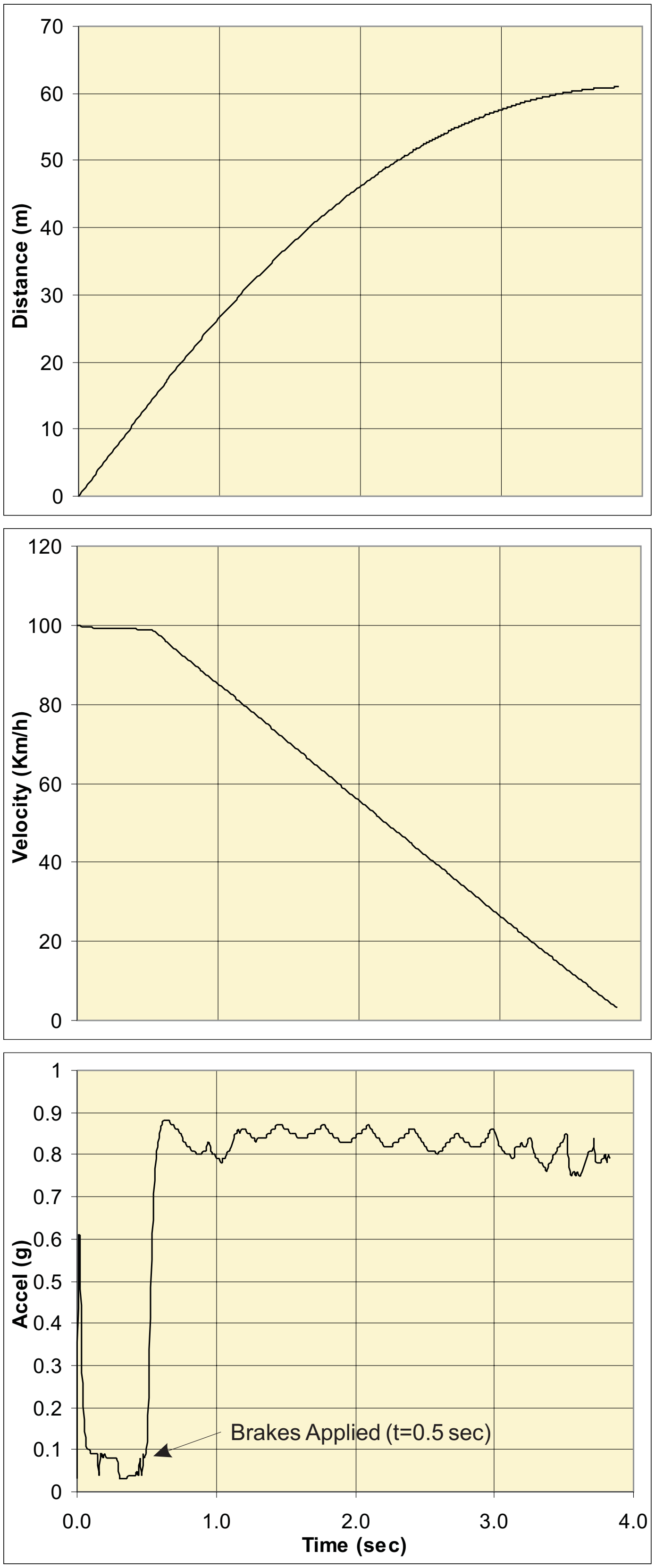

Figure 9 - Simulation results on a high-friction surface for an ABS-equipped vehicle during straight-line braking from 100 km/h.

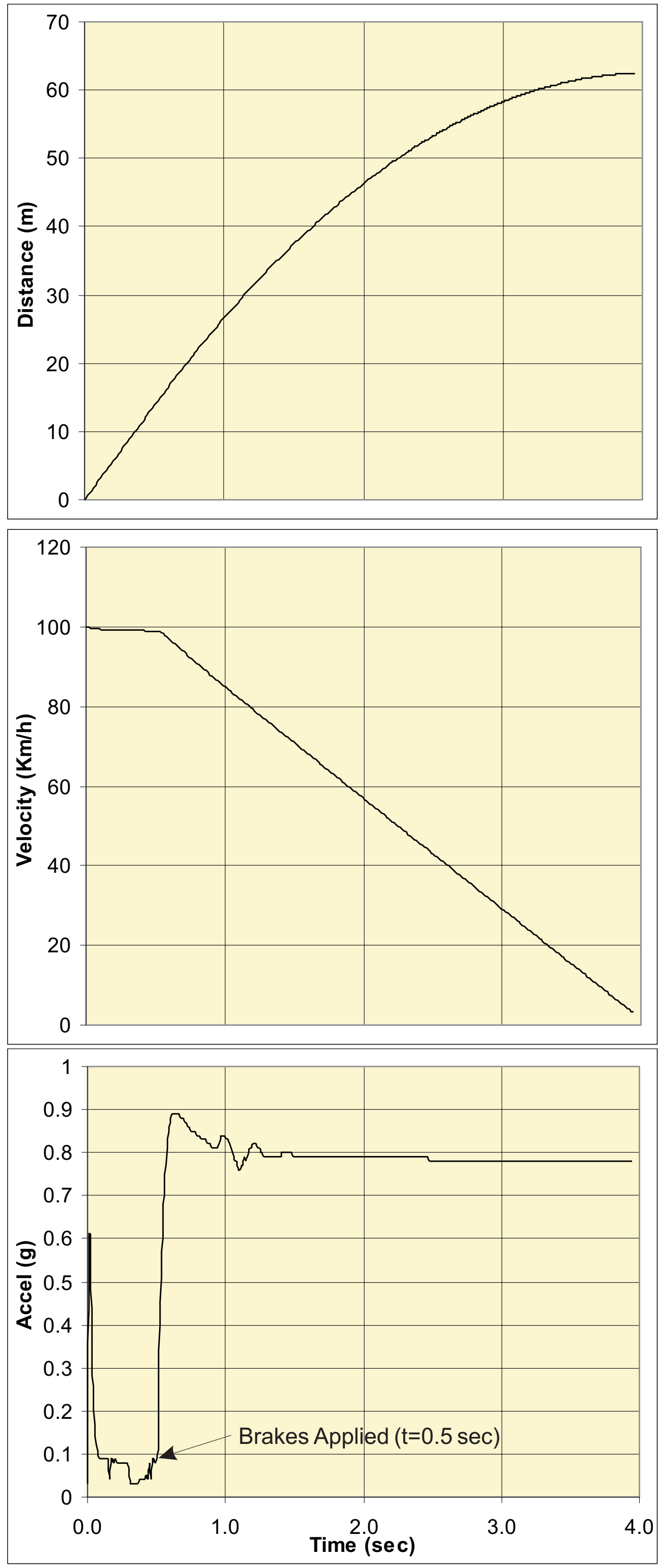

Figure 10 - Simulation results on a high-friction surface for a non-ABS-equipped vehicle during straight-line braking from 100 km/h.

Figures 11 and 12 provide a visualization of the trajectory of each vehicle. Note that the vehicle with ABS successfully stays within the cones, while the vehicle without ABS fails to perform the lane-change, skidding almost straight ahead (because steering preceded braking in this example, there is a change in direction prior to skidding). This result is typical for non-ABS-equipped vehicles.

DATA REQUIREMENTS

From a vehicle design engineer's standpoint, the HVE ABS model provides a palette of parameters used by ABS systems. New ABS algorithms may be written and then tested directly against experiment. Parameter optimization may likewise be performed via simulation prior to reprogramming the vehicle's ABS controller (ECU) firmware.

From a crash reconstruction engineer's standpoint, the most important task of the HVE ABS model is to allow the simulation analysis of vehicular loss of control of ABS-equipped vehicles. This requires the use of parameters that maintain high levels of braking force while also preventing wheel lock-up.

For the Tire Slip algorithm, minimum and maximum tire slip values are required by the model. These values are tire-specific and can be determined by inspection of the tire's mu vs. slip curve. The default values used by the HVE ABS model are 0.05 and 0.15 for minimum and maximum slip.

For the HVE Bosch Version 1 algorithm, minimum and maximum wheel spin accelerations are required by the model. These values vary according to tires size (specifically, tire spin inertia). Default values used by the HVE ABS model were assigned according to vehicle class category [12] and were determined via simulation experiments. Default values for apply and release rates were also determined via simulation experiments.

The values chosen for the HVE Bosch comparisons presented in this paper are shown in Appendix I.

TRUCK (AIR BRAKE) SYSTEMS

Preliminary results show the HVE ABS model is applicable to air brake systems such as those used by on-highway trucks. The Tire Slip algorithm works well. However, the Bosch algorithm requires additional study to determine the minimum and maximum wheel spin accelerations required by that algorithm. The difference in required wheel spin acceleration values is attributed to the significantly larger spin inertia of a truck tire compared with a passenger car tire. It is expected that time delays will also require adjustment. Research on the parameters required for truck air brake ABS simulation is underway.

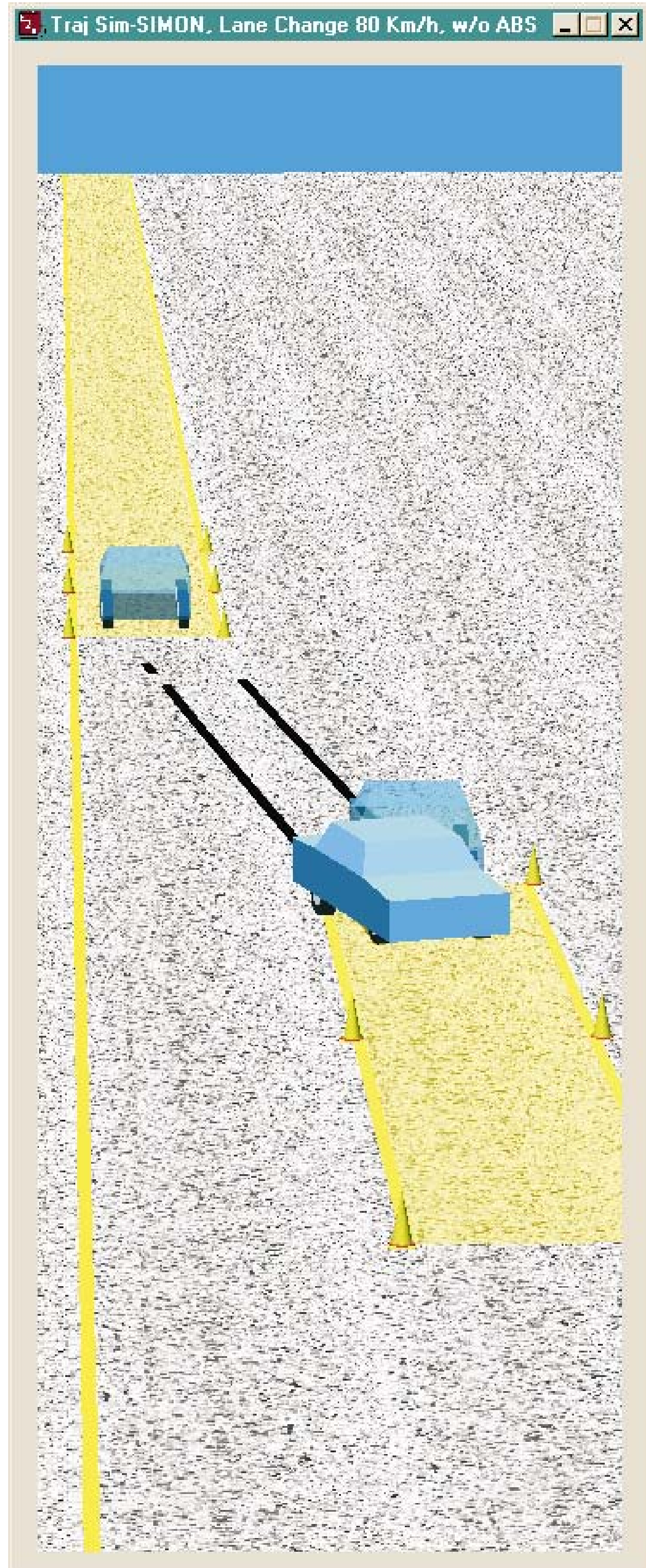

Figure 11 - Visualization of a lane-change maneuver with hard braking, non-ABS-equipped vehicle. The solid vehicle is the simulated position; the translucent vehicles are path "target" positions.

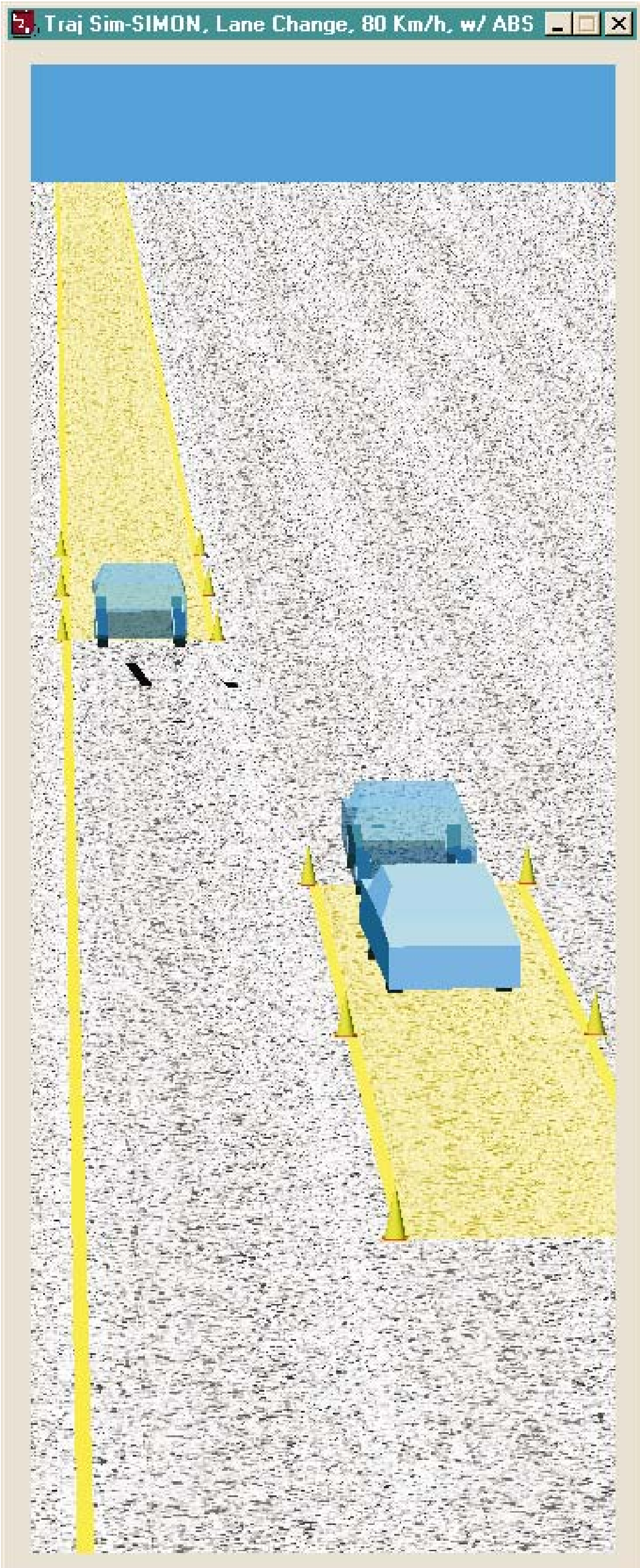

Figure 12 - Visualization of a lane-change maneuver with hard braking, ABS-equipped vehicle. The solid vehicle is the simulated position, the translucent vehicles are path "target" positions.

DISCUSSION

Validation of the HVE Bosch Version 1 algorithm is provided in the comparison between Figures 3 and 4, wherein it is shown that the Bosch control cycle has been nearly duplicated by the HVE Bosch Version 1 algorithm.

Additional comparisons between experimental maneuvers and simulations should be performed. It is important to recognize, however, that such comparisons would not serve to validate the HVE ABS model, per se, because of the difficulty in separating any differences attributable to the HVE ABS model from differences attributable to other parts of the vehicle simulation model (especially the tire model). Note, for example, that the same HVE ABS model implemented in two different vehicle simulators would undoubtedly yield slight differences in vehicle kinematics during the simulation used in the ISO 3888 lane-change example provided earlier in this paper. In addition, the vehicle and tire data requirements for such a study would be immense. It is unrealistic to believe that such data would be available to most researchers. The primary benefit from comparisons between experimental maneuvers and simulations would be an increased level of confidence in the trends predicted by simulation of ABS-equipped vehicles.

The simulations presented in this paper used a Generic Class 2 Passenger Car having a weight of 1119 kg (2469 lb), a wheelbase of 254 cm (99.9 in) and Generic P195/75R14 tires with μ_p in the range of 0.767 - 0.903 (load-dependent) and μ_s in the range of 0.684 - 0.804 (again, load-dependent) [12].

The HVE Bosch algorithm is more sophisticated than the Tire Slip algorithm, and while it has additional capabilities, such as adaptive learning, its input data requirements are also more demanding. The Tire Slip algorithm simply requires estimates for minimum and maximum slip; these values are available by inspection of the tire's mu vs. slip curve. Although the Tire Slip algorithm was not used for the examples cited in this paper, its effect on vehicle gross handling behavior is remarkably similar to the HVE Bosch Version 1 algorithm. When simulating an ABS-equipped vehicle with an unknown ABS type, the Tire Slip algorithm is recommended.

The primary purpose of ABS is to prevent the wheels from locking so directional control can be maintained. The secondary purpose of ABS is to maintain (higher) braking force associated with peak friction, rather than slide friction, in order to reduce braking time and distance.

The requirements for the vehicle simulation model include a brake system model, a robust tire model that includes μ_p and μ_s, and a spin degree of freedom for each wheel to calculate current wheel velocities and accelerations.

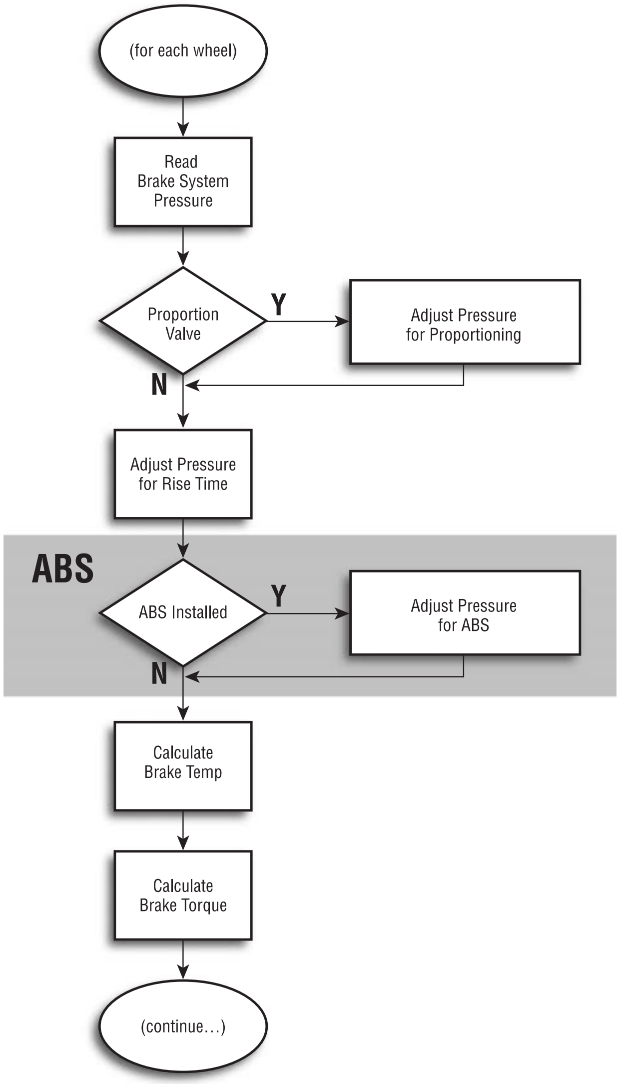

Figure 13 - Flow chart showing integration of the HVE ABS model into the simulation.

Incorporating the ABS model into an HVE-compatible simulation model is a relatively straight-forward task. The ABS model is incorporated as a C-style function call in the vehicle simulation model. The ABS function call typically is placed directly before the wheel brake temperature or brake torque function call (see Figure 13).

Implementing ABS in a simulation model is significantly easier than designing, manufacturing and installing ABS on a vehicle. There are several practical reasons for this. First, the computer simulation has no vehicle hardware issues, either mechanical or electrical. Manufacturers of brake system components will readily appreciate the difficulty in developing adequate solenoid-actuated valves, wheel speed sensors, computer controllers and electrical connectors. None of these is required for simulation of ABS on a computer.

Vehicle reference velocities are required by ABS algorithms for the computation of tire slip (a key component in all algorithms). In the vehicle, the reference velocity cannot be generated from the speedometer, since wheel lock-up at certain wheels would yield misleading information. Therefore, reference velocity is derived via comparison of multiple individual wheel velocities, typically using proprietary algorithms. In simulation, the required velocity is directly accessible since it is a dependent variable in the equations of motion.

The ABS model described in this paper is extendable to traction control systems (TCS) and yaw moment stability (YMS) as well. However, additional control algorithms are required for implementation of these models.

This paper describes two possible systems (Tire Slip and HVE Bosch Version 1). However, experience has shown that the development of ABS algorithms is a highly creative process. One could envision the possibility of endless modifications or extensions to these and other algorithms. The ABS model implemented in HVE is extendable in this regard.

SUMMARY

1. A basic overview of ABS has been provided, both in terms of the operational characteristics and the required parameters.

2. The required parameters have been defined in terms of overall vehicle system parameters and individual wheel parameters.

3. The HVE ABS user interface has also been described, and is likewise defined in terms of overall vehicle system parameters and individual wheel parameters.

4. Requirements for implementing an ABS module into a simulation were provided. These include a brake system model and spin degrees of freedom for each wheel.

5. Two ABS models have been implemented in HVE to date. These two models, the Tire Slip algorithm and the HVE Bosch Version 1 algorithm, were described and an example of a typical ABS cycle for each algorithm was presented.

6. Comparison between the Bosch control cycle and the cycle simulated using the HVE Bosch Version 1 algorithm reveals they are substantially similar.

7. Experimental results for two tests were compared with simulation results using the HVE Bosch Version 1 algorithm. The results compared favorably.

8. Two simulations illustrating the effect of ABS on vehicle handling were presented. These simulations showed that the ABS system reduced straight-line braking distance by approximately 3 percent and allowed the driver to maintain directional control during a lane-change maneuver with panic braking. Simulation of the latter maneuver without ABS resulted in a loss of control (failure to successfully execute an ISO 3888 lane-change maneuver).

9. It follows from the latter maneuver (see Summary 8, above), that successful simulation of such maneuvers requires a simulation model that has the capability to simulate ABS.

10. The HVE ABS model is a general purpose model, applicable to all vehicle types. Development of default data sets and validation for for heavy trucks is under way.

11. Since the vast majority of the US vehicle population now includes ABS, the ability to model ABS is an important advancement in vehicle simulation modeling.

ACKNOWLEDGMENT

The authors wish to extend their appreciation to Robert Bosch USA for providing the test data used in this paper.

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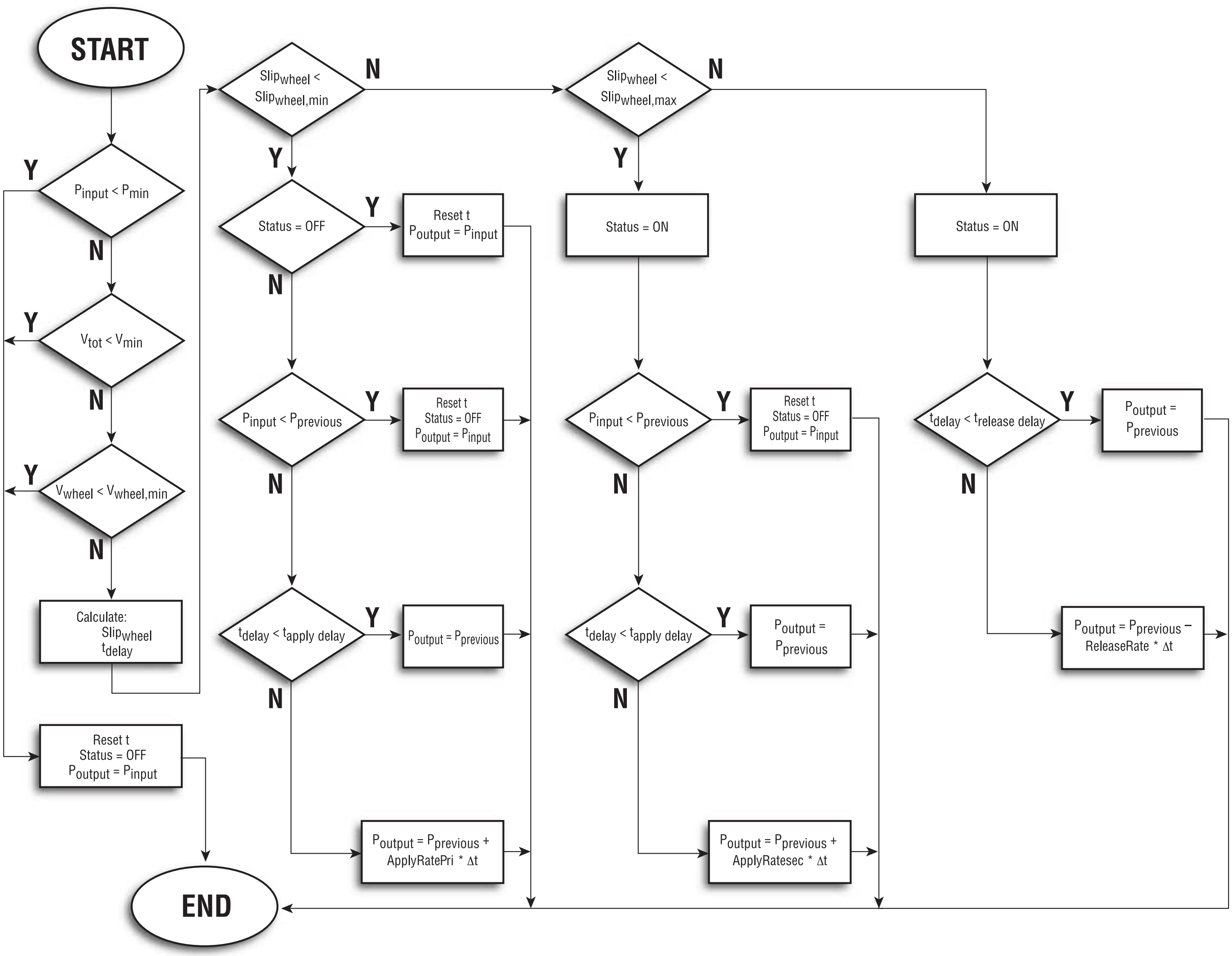
APPENDIX I

ABS variables and values for simulation examples using the HVE Bosch Version 1 Algorithm.

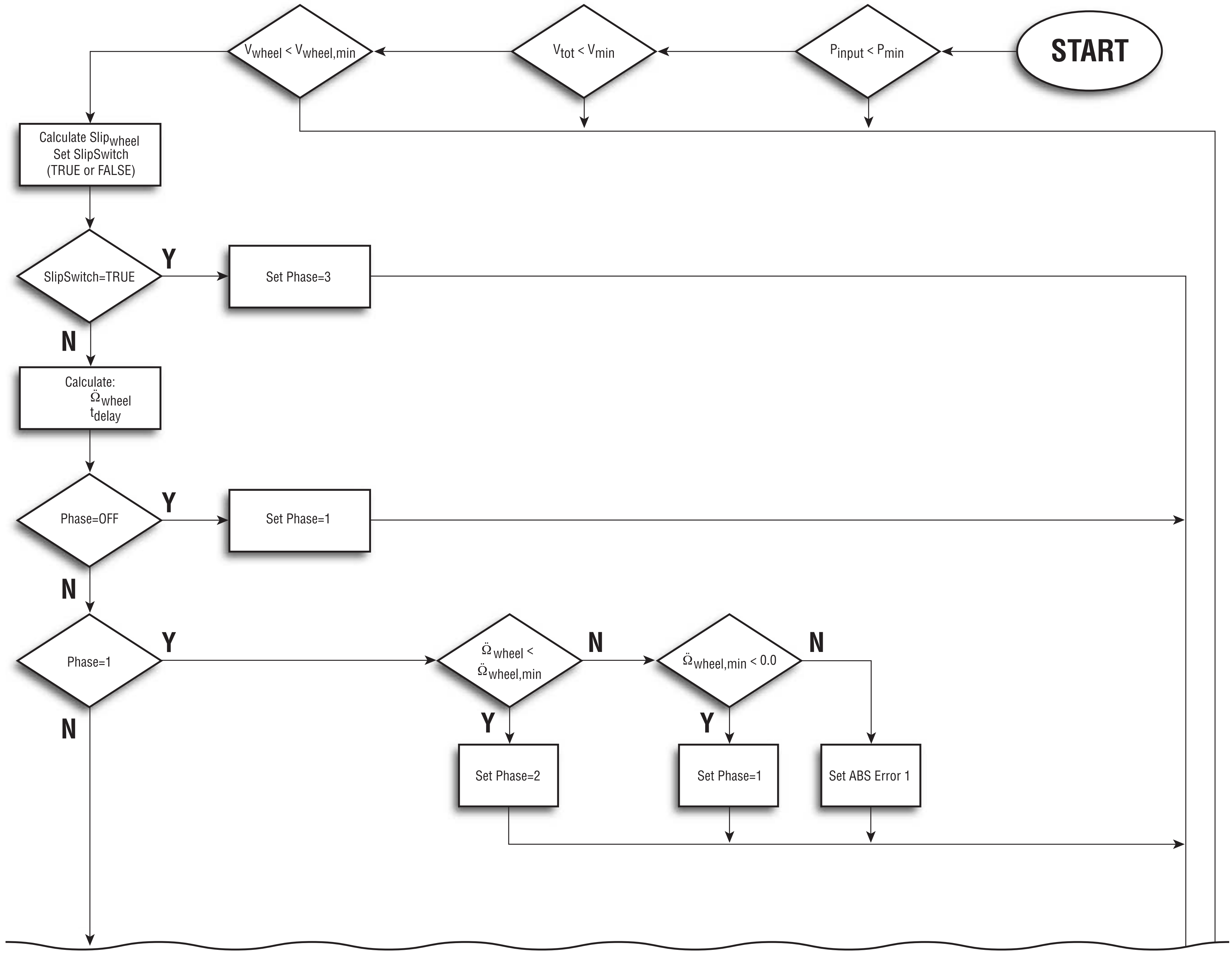
Variable	Value
Algorithm	HVE Bosch Version 1
Control Method	At Wheel
Threshold Wheel Velocity	70.4 rad/sec
Threshold ABS Pressure	70 kPa (10 psi)
Low Friction Threshold	0.35
Delay Method	At Wheel
Apply Delay	0.05 sec
Primary Application Rate	35000 kPa (5000 psi/sec)
Secondary Application Rate	3500 kPa (500 psi/sec)
Release Rate	7000 kPa/sec (10000 psi/sec)
Wheel Minimum Spin Accel	-175 rad/sec^2
Wheel Maximum Spin Accel	50 rad/sec^2
Wheel Maximum Slip	0.15

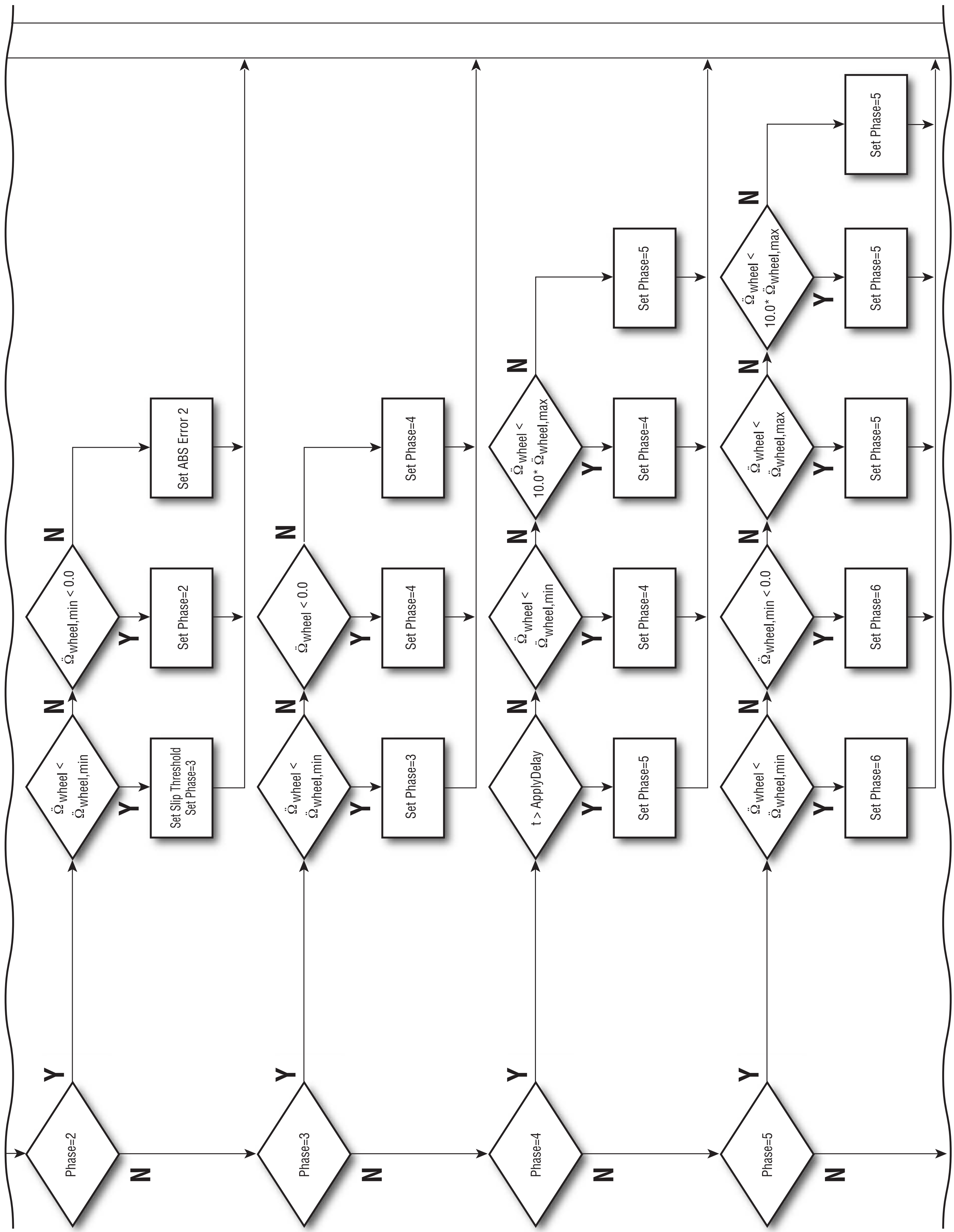
APPENDIX II

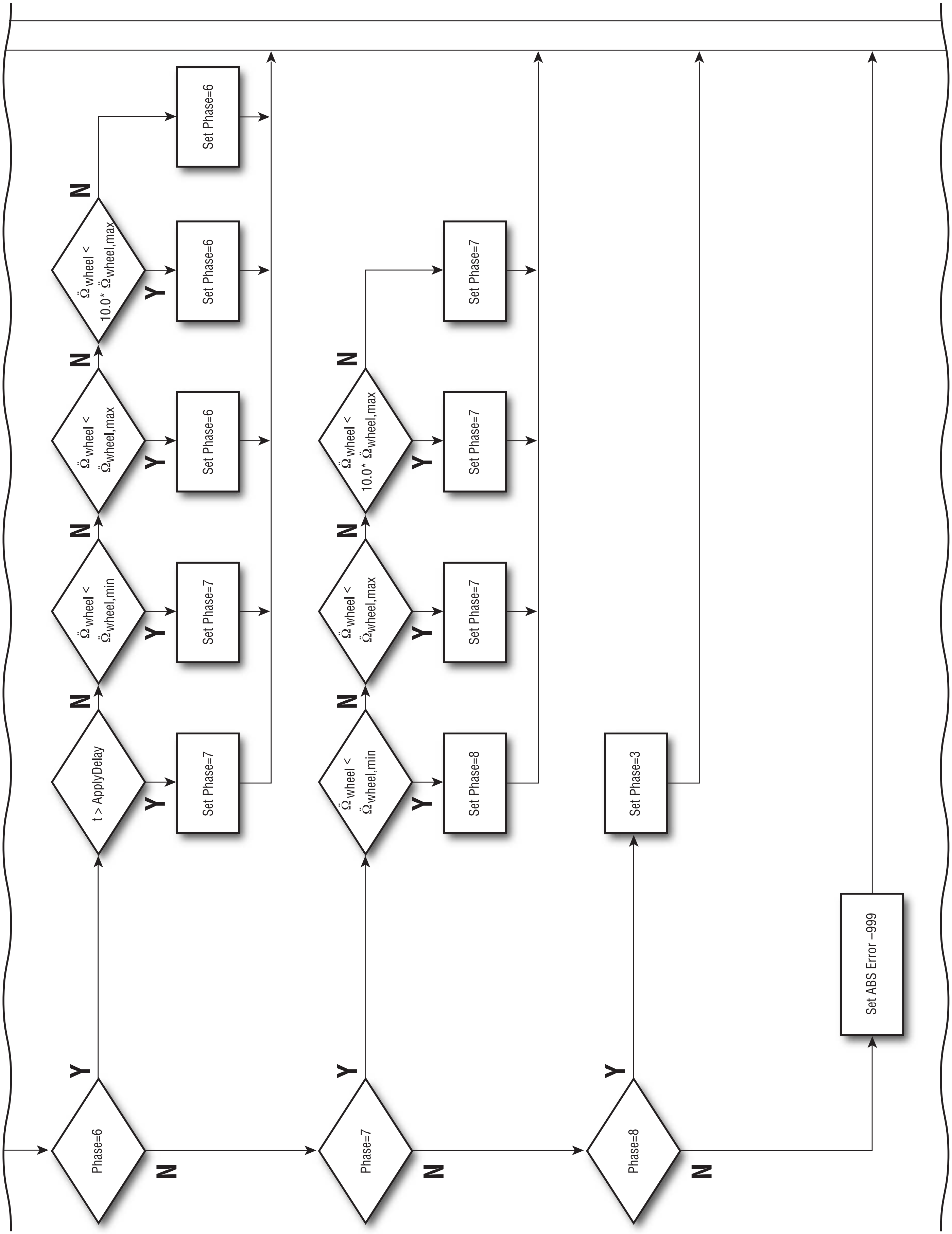
Flow chart for the HVE ABS Tire Slip Algorithm



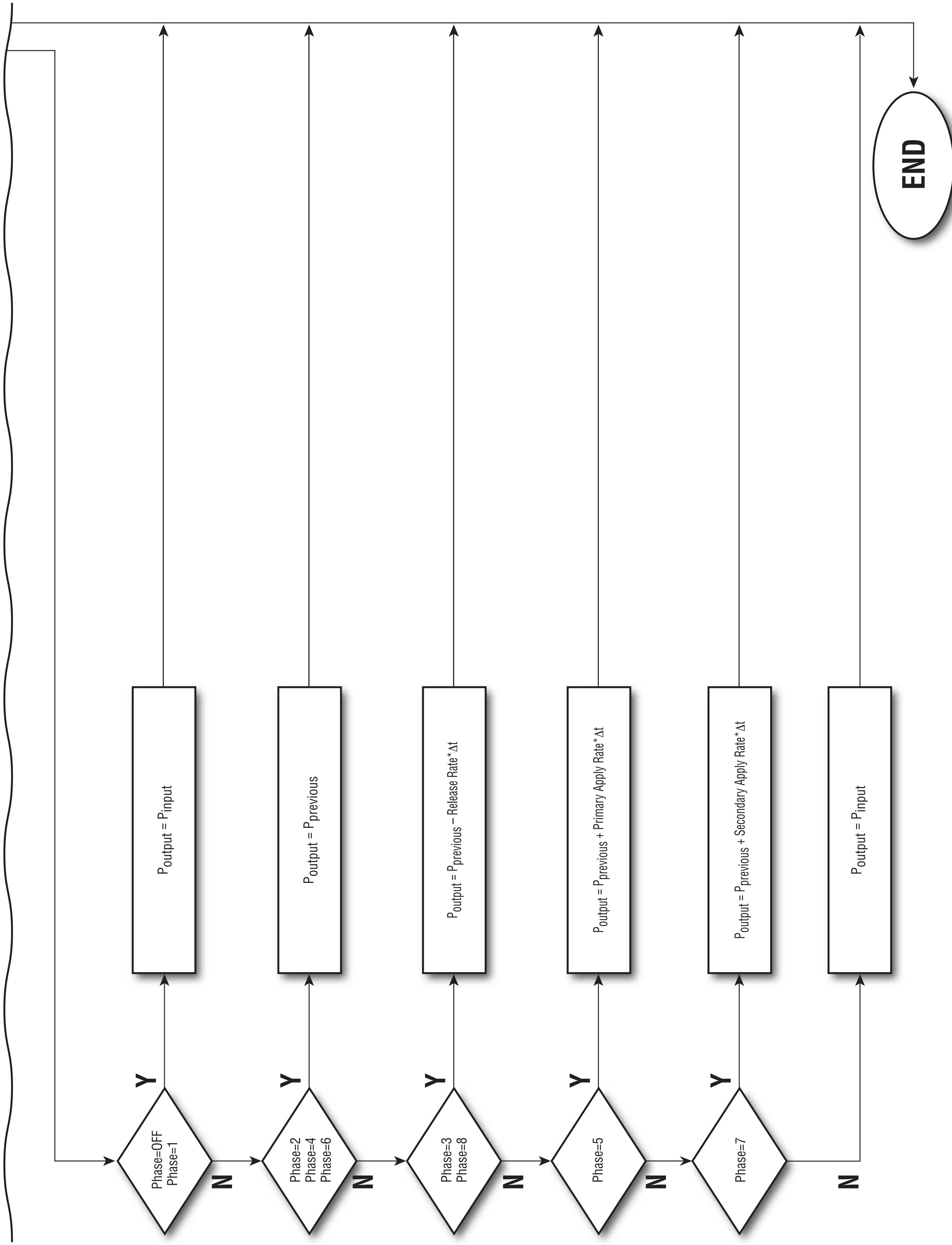
APPENDIX III - *Flow chart for the HVE Bosch Version 1 Algorithm*




Phase=2
Y
N
$\ddot{\Omega}_{wheel} < \ddot{\Omega}_{wheel,min}$
Set Slip Threshold
Set Phase=3
$\ddot{\Omega}_{wheel,min} < 0.0$
Set Phase=2
Set ABS Error 2
Phase=3
$\ddot{\Omega}_{wheel} < \ddot{\Omega}_{wheel,min}$
Set Phase=3
$\ddot{\Omega}_{wheel} < 0.0$
Set Phase=4
Set Phase=4
Phase=4
t > ApplyDelay
Set Phase=5
$\ddot{\Omega}_{wheel} < \ddot{\Omega}_{wheel,min}$
Set Phase=4
$\ddot{\Omega}_{wheel} < 10.0 * \ddot{\Omega}_{wheel,max}$
Set Phase=4
Set Phase=5
Phase=5
$\ddot{\Omega}_{wheel} < \ddot{\Omega}_{wheel,min}$
Set Phase=6
$\ddot{\Omega}_{wheel,min} < 0.0$
Set Phase=6
$\ddot{\Omega}_{wheel} < \ddot{\Omega}_{wheel,max}$
Set Phase=5
$\ddot{\Omega}_{wheel} < 10.0 * \ddot{\Omega}_{wheel,max}$
Set Phase=5
Set Phase=5



Phase=6
Y
N
t > ApplyDelay
Set Phase=7
$\ddot{\Omega}_{wheel}$ < $\ddot{\Omega}_{wheel,min}$
Set Phase=7
$\ddot{\Omega}_{wheel}$ < $\ddot{\Omega}_{wheel,max}$
Set Phase=6
$\ddot{\Omega}_{wheel}$ < 10.0* $\ddot{\Omega}_{wheel,max}$
Set Phase=6
Set Phase=6
Phase=7
$\ddot{\Omega}_{wheel}$ < $\ddot{\Omega}_{wheel,min}$
Set Phase=8
$\ddot{\Omega}_{wheel}$ < $\ddot{\Omega}_{wheel,max}$
Set Phase=7
$\ddot{\Omega}_{wheel}$ < 10.0* $\ddot{\Omega}_{wheel,max}$
Set Phase=7
Set Phase=7
Phase=8
Set Phase=3
Set ABS Error −999



Phase=OFF
Phase=1
Y
N
$P_{output} = P_{input}$
Phase=2
Phase=4
Phase=6
Y
N
$P_{output} = P_{previous}$
Phase=3
Phase=8
Y
N
$P_{output} = P_{previous}$ – Release Rate * Δt
Phase=5
Y
N
$P_{output} = P_{previous}$ + Primary Apply Rate * Δt
Phase=7
Y
N
$P_{output} = P_{previous}$ + Secondary Apply Rate * Δt
$P_{output} = P_{input}$
END