A Review of Antilock Braking and Traction Control Systems

4.1 BRAKING SYSTEM FUNDAMENTALS, FOUNDATION BRAKES

THERE ARE TWO USUAL FORCE INPUTS to a motor vehicle: engine torque to provide acceleration (+X acceleration) and brake friction to provide deceleration (–X acceleration).

When an operator actuates the brake pedal, he or she is actually pushing on a lever that pushes a piston in a master cylinder to generate hydraulic pressure that is transmitted through the brake lines to the wheel actuators (either wheel cylinders or caliper pistons). The wheel actuators force a friction material (brake shoes or disk pads) against a rotating surface (brake drums or disk rotors) to generate a force that stops the vehicle. The energy to stop the vehicle is normally dissipated as heat in the drums or rotors. Thus, applying the brakes is really the act of dissipating the rolling energy of the vehicle as heat, hence slowing the vehicle down. A simplified schematic of a foundation brake system is shown in Fig. 4.1.

The operation of the braking system depends on the integrity of the hydraulic system. Modern boosted master cylinders can generate 2000 psi or more, and the hydraulic system must distribute that pressure without leaking. Almost all modern braking systems use a booster (or operator force amplifier) that uses engine vacuum to increase the force the brake lever applies to the master cylinder. Generally, disk brakes require higher application pressure than do drums because they are not self-actuating. When drum brakes are combined with disk brakes in a vehicle (usually with drums in the rear), there is always "a proportioning valve" to proportionally reduce the effective hydraulic pressure at the drum brake wheel cylinders and to always keep the rear wheels turning to preserve directional stability.

4.2 ANTILOCK BRAKING SYSTEMS

A vehicle braking system, including the tires, is most effective, i.e., produces the optimum retarding force, when the wheel speeds are approximately 85 to 90% of the vehicle speed. The difference (100% − 85% = 15%) is called the percent slip of a particular wheel. The 10 to 15% slip retarding force is greater than the locked wheel retarding force, so optimum braking is achieved when the slip is 10 to 15% and no more. Over-applying foundation brakes can cause wheels to lock (100% slip), so a system that prevents this can improve braking effectiveness. Antilock braking systems (ABS) have been developed to do this.

However, prevention of lock to improve braking effectiveness is not the most important reason for ABS. Once a wheel is locked, it does not provide any lateral control of the vehicle (+/−Y axis), and, if multiple wheels lock, the vehicle will start to yaw. This means that if the rear wheels lock, the vehicle will tend to spin out (rear end moving forward), and if the front wheels lock, the vehicle cannot be steered. Control of vehicle track is the most important reason for the use of ABS.

It has been shown that for poor road conditions (sand, ice, snow, water, etc.), a system that prevented wheel lockup and gave significantly increased directional control, in exchange for a small loss of absolute stopping distance, provided a major benefit to overall vehicle performance. This is accomplished by using an ECU to sense individual wheel speeds, and then isolate and reduce brake fluid pressure to the wheel or wheels that are locking up. A schematic of such a feedback system is shown in Fig. 4.2, where the controller is an ECU, the controlled parameter is wheel cylinder pressure (via electrical solenoid valves), and the feedback elements are individual electronic wheel speed sensors (WSS). The WSS signals are typically generated via a pickup coil mounted adjacent to a toothed ring at each controlled wheel, where the pickup coil generates a varying voltage output proportional to the amplitude and frequency of the magnetic flux change as the ring teeth pass by it.

By monitoring the frequency output of each WSS, the ECU can decide if an individual wheel slip exceeds a desired threshold.[1] When such a threshold is exceeded at a particular wheel, the ECU directs the hydraulic control unit to isolate that wheel and reduce hydraulic pressure at that wheel, so that the wheel can resume rotation. Once the wheel is again rotating at about optimum slip (assuming the brakes are still applied) pressure is reapplied to that particular wheel. Typically, each wheel control circuit is called a channel and the hydraulic control unit is typically called a hydraulic modulator. Hydraulic modulators typically include three functions for each controlled wheel circuit: isolation, pressure-dump, and pressure-reapply. This control sequence causes a pulsed apply/release/apply[2] as ABS is controlling a wheel in an emergency stop, often up to ten times per second.[3]

Because of practical slip-threshold tradeoffs, ABS equipped vehicles may show a slightly increased stopping distance, but a marked increase in track control over the

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[1]Usually a rate of wheel speed deceleration exceeding 1 *G*, or −21.95 mph/s (−35.33 kph/s).

[2]Often called *pumping* the brakes. However, drivers can only pump all circuits equally, whereas ABS systems can modulate individual wheel channel pressures many times a second when activated.

[3]Since this is faster and more precise than almost any driver can modulate brake channel pressures, and modulation can be selectively applied to individual wheel channels, drivers of ABS-equipped vehicles are instructed to never pump antilock brakes. Instead, drivers are instructed to apply firm and continuous pressure to the brake pedal to activate braking action and achieve optimum braking efficiency.
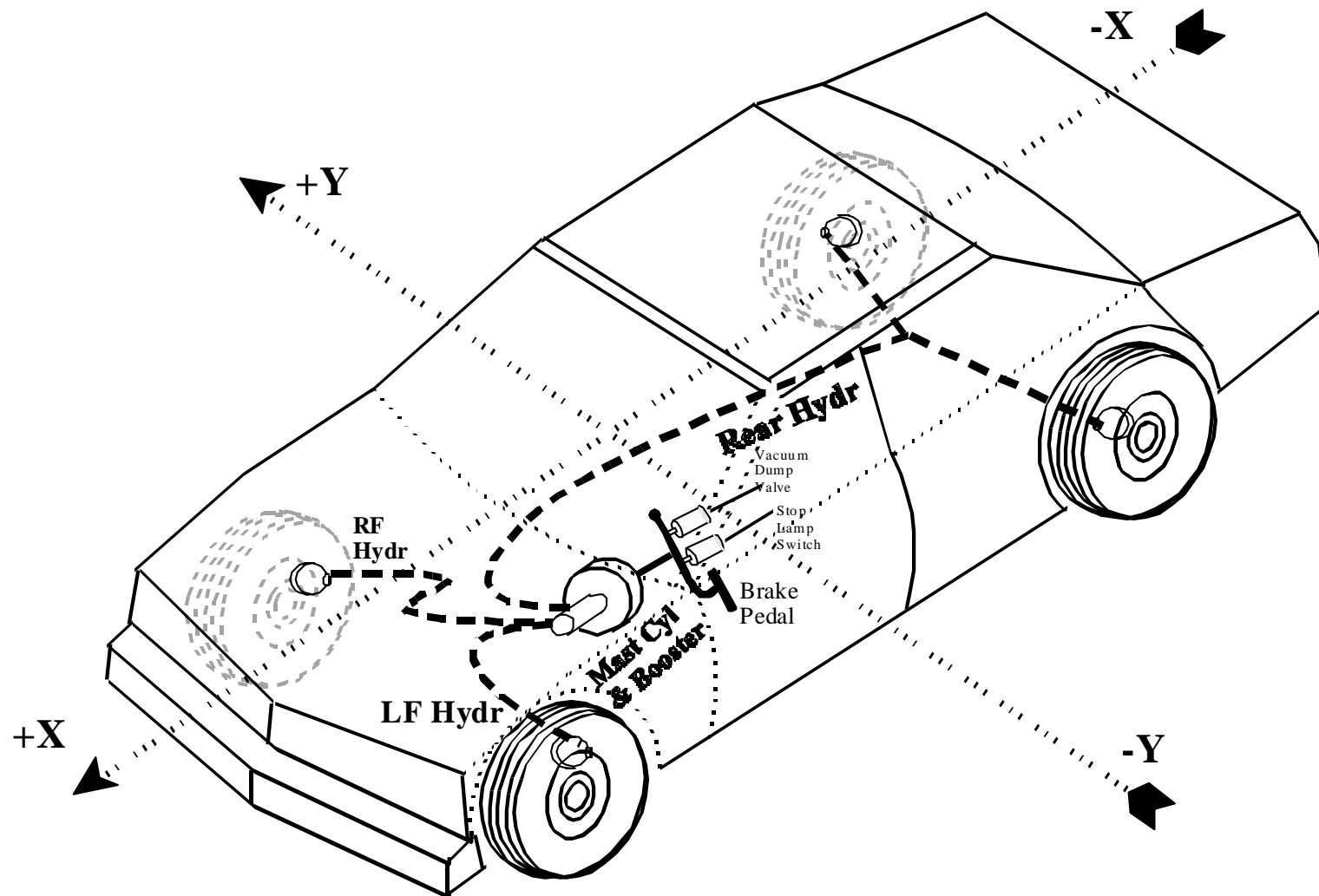
FIG. 4.1—Foundation brake system with planar SAE J211/J670e axes superimposed.
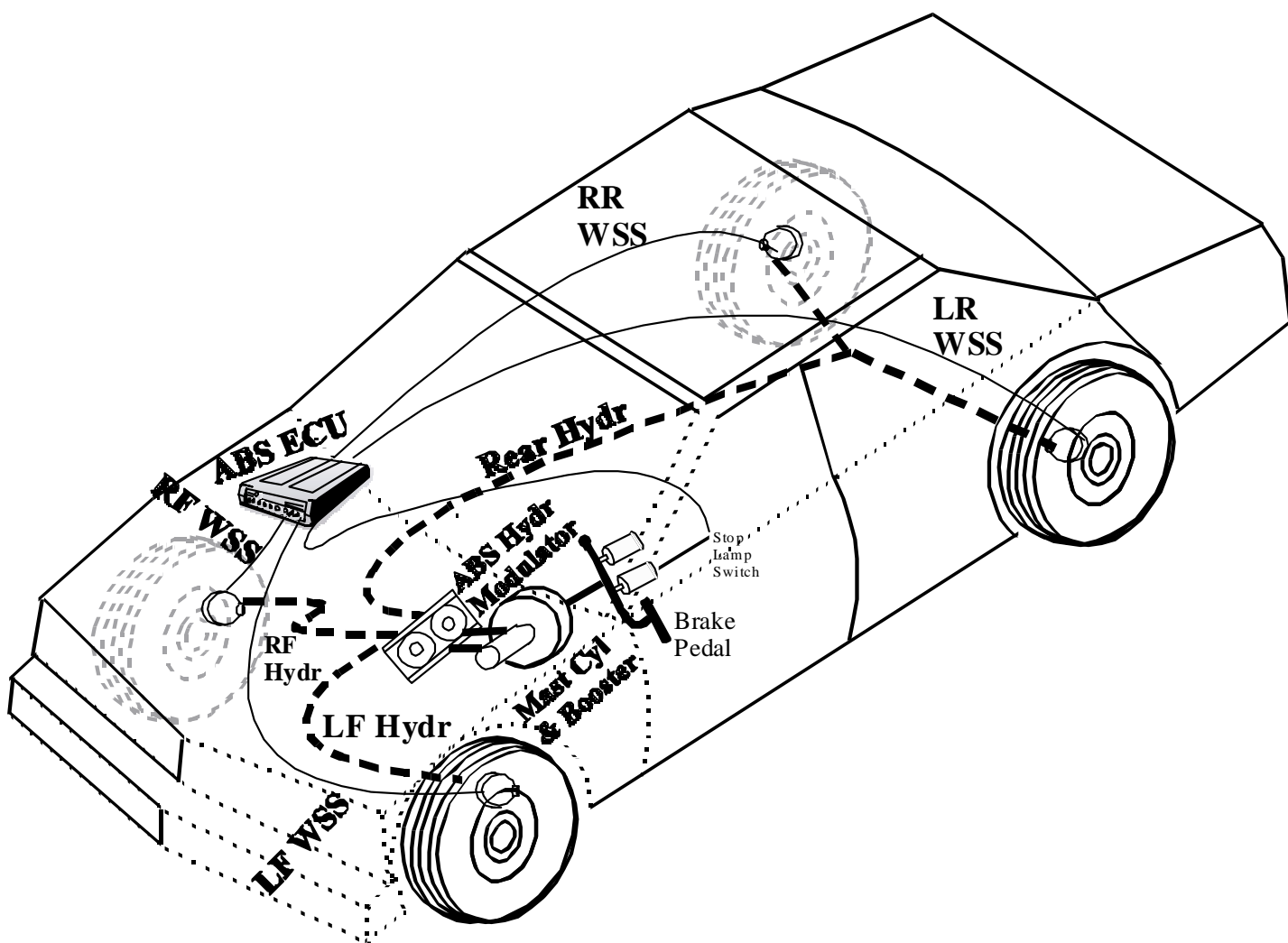
FIG. 4.2—Basic ABS schematic showing ECU, individual wheel speed sensors, and hydraulic modulator.

ensemble of many emergency braking situations. That trade-off is deemed to be beneficial for the average driver on modern vehicles. Thus, the primary purpose of ABS is to preserve directional stability and allow the driver to continue steering during emergency braking, with an acceptable tradeoff of slightly longer stopping distance. Also, because wheel slip is limited with ABS vehicles, hard braking stops will not produce typical tire scrub artifacts on road surfaces, thus, complicating traditional accident reconstruction methods. When ABS is not activated, the foundation brakes operate normally; thus, normal stops are unaffected by ABS.

4.3   TRACTION CONTROL SYSTEMS

In the past few years, selected manufacturers have introduced systems that add traction and tracking control functions during acceleration as well as braking. ABS releases the brakes momentarily whenever wheel speed sensors indicate a locked wheel during braking, whereas traction control applies the brakes momentarily to one of the drive wheels whenever the wheel speed sensors indicates a wheel is going faster than the others during acceleration. Figure 4.3 shows a schematic of a basic TCS (traction control system) architecture. Note that the TCS is designed to operate only in the engine-acceleration mode, and its function is suspended if the operator applies the brake.

Some TCS systems also have the capability to also reduce engine power via electronic control of fuel injectors and/or spark timing. This is accomplished via bidirectional communications between the TCS ECU and the PCM.

4.4   COMBINED ABS AND TCS

Since the primary function of both TCS and ABS is control of a wheel whose speed significantly varies from the averaged speed of the other wheels (+ for TCS, – for ABS), where both features are incorporated in a vehicle, these functions are usually combined into one hydraulic control unit, sharing a common ECU. Figure 4.4 shows such a combined system architecture, with its combined ABS/TCS ECU. The ob-
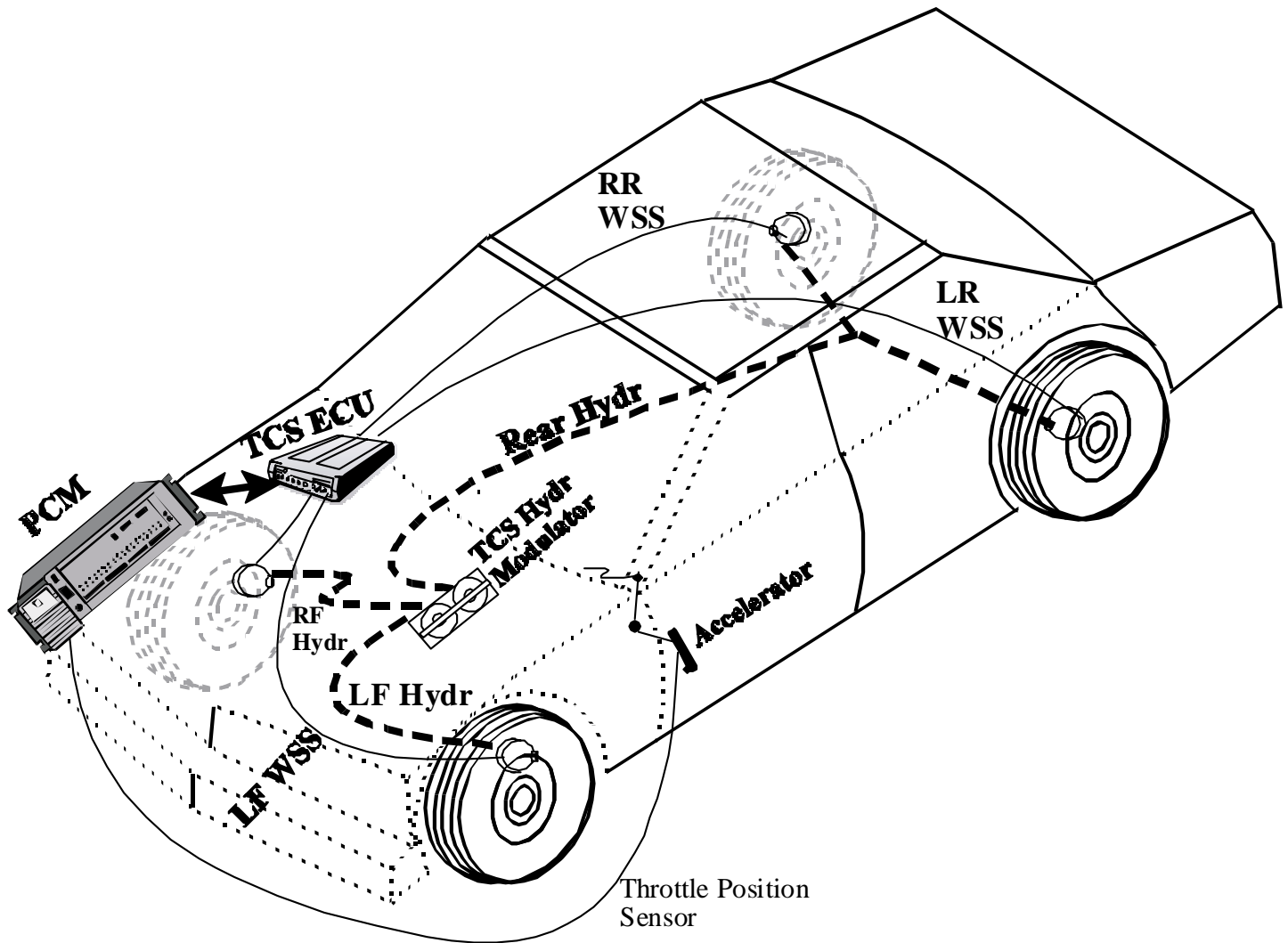
FIG. 4.3—Basic TCS schematic showing ECU, individual wheel speed sensors, hydraulic control and inter-PCM-TCS communications.

jective of both ABS and TCS is for them to operate transparently to the consumer operator so as to provide enhanced vehicle tracking stability under both braking and acceleration under adverse road surface conditions. This feature provides the ordinary driver with advanced tracking stability that was previously accomplished only by skilled racing and police drivers.

Thus, for combined ABS/TCS ECUs with the brake applied in ABS modes, if the speed of one wheel drops significantly compared with the other wheels, the brake pressure on that wheel is momentarily reduced (using isolation and dump valves) to stop the wheel from locking, and it is reapplied (using a motor/pump) when the wheel speed is near the average of the other wheel speeds. With no brake applied and under acceleration in TCS modes, if the speed of one wheel increases significantly compared to the other wheels, that wheel brake is momentarily applied to reduce that wheel speed (and with differential systems to redistribute traction power to the opposite wheel). Braking is removed when that wheel speed returns to near the average of the other wheel speeds.

Given that ABS, TCS, and ABS/TCS systems variously monitor parameters such as wheel speeds, brake application, accelerator application, etc. for normal operation, there is an obvious capability to save them in event triggered snapshot/freeze frames. These parameters can indicate critical aspects of operator-vehicle interaction and, thus, become an important element of the analysis of post-crash vehicle data.

4.4 COMPONENTS OF ABS/TCS UNITS

4.4.1 Common Components

All ABS-equipped vehicles have certain common components. These consist of an electronic control unit (ECU), one or more hydraulic modulator assemblies, one or more wheel speed sensors, and a wiring harness. The ABS system is transparent to the operator in normal operation, except for the (ABS) malfunction indicator lamp (MIL) in the instrument cluster. The ABS MIL is normally activated during key-
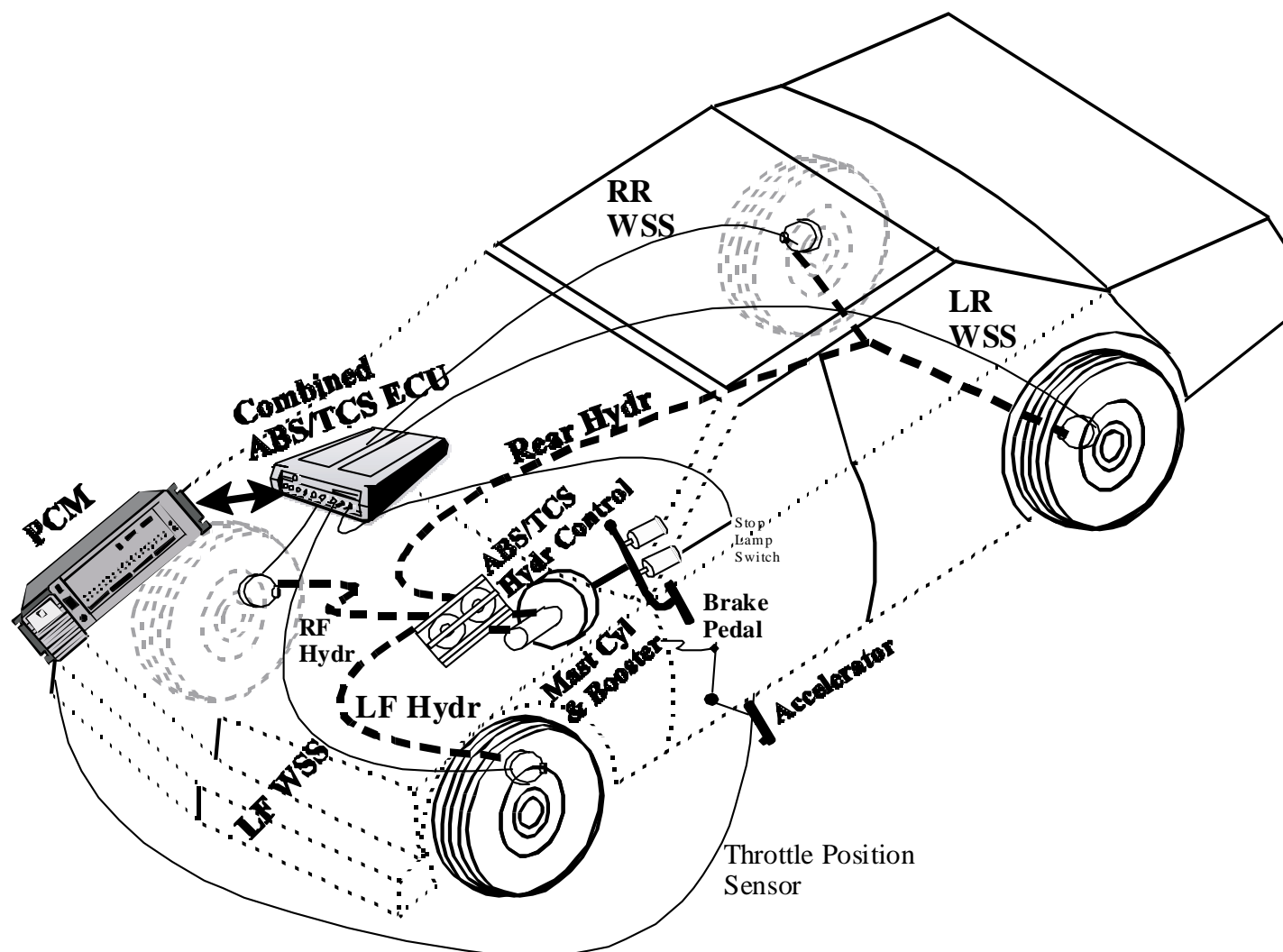
FIG. 4.4—Basic combined ABS/TCS schematic showing ABS/TCS ECU, individual wheel speed sensors, hydraulic control, and inter-PCM-ABS/TCS communications.

on diagnostic checks and remains off unless a system problem is detected.[4] In general, each channel operates with a dedicated wheel sensor circuit, hydraulic modulator subassembly, and sense/control portion of the ECU.

4.4.2   Wheel Sensors

Wheel sensors are the key components of both ABS and TCS systems. In order to determine vehicle wheel speeds, a wheel speed sensor (WSS) is placed on each wheel. Figure 4.5 shows a wheel speed sensor using an electrical coil to detect a change in the magnetic field of its magnetic core as a toothed wheel attached to the brake disk/drum rotates past it. As the teeth pass by the pickup core, a sinusoidal pulse train is generated with a frequency proportional to the speed of the wheel. This generated frequency is directly proportional to wheel revolutions/time and is said to be an analog of the wheel ground speed (at the circumference of the tire). Scaling arithmetic in the ECU microprocessor software is used to convert the input frequency analog to commonly understood units of ground speed (mph or kph). That wheel pulse train is monitored by the ABS/TCS ECU, which compares it to the speeds (frequencies) of the other wheels in order to determine individual wheel slip.

4.4.3   Pumps, Valves, Accumulators, and Motors

ABS and TCS hydraulic control units (HCUs) contain pumps, valves, accumulators, and motors that perform the ECU commanded functions for system operation. Most HCUs are relatively insulated from crash damage, but a few are located in the frontal crush zone, like the front wheel speed sensors. Since our purpose here is to focus on the sources of crash related data we will skip a discussion of HCU internal hydraulic function and close by observing that when an electro-hydraulic DTC is detected and saves a freeze

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[4]The ABS MIL is usually colored amber, indicating a problem with an auxiliary safety system in the vehicle. The foundation brake MIL is colored red, indicating a problem with the primary foundation brake system (red being considered a more severe alert to the operator).
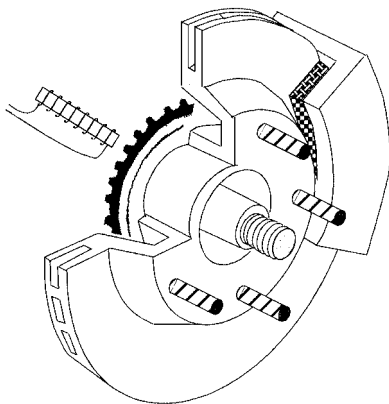

FIG. 4.5—Wheel speed sensor on a disk brake that uses variable reluctance magnetic pickup.

frame for any reason, it can add intelligence to the crash investigation.

4.4.4   ABS and TCS ECUs

Similarly, most ABS and TCS ECUs are relatively insulated from crash damage. Thus, it is often the case that crash damage to a wheel sensor, causing a DTC and a snapshot/freeze frame, is available after a crash.

In order to interrogate an ABS or TCS ECU and prevent alteration of any data in the subject units when a vehicle is repowered, subject units are usually interrogated out of the subject vehicle. This prevents adding DTCs for conditions that may have been introduced in the towing after a crash and while battery power was lost. In certain ECUs, freeze frame data from an existing DTC can be overwritten by the detection and saving of a new DTC. Thus, a crash-event DTC (and its snapshot/freeze frame) could be "pushed down" and the snapshot/freeze frame overwritten to reflect the conditions at the last DTC (i.e., a DTC generated after the crash, and possibly reflecting post-crash damage). When such a unit is interrogated, the test bed (either another vehicle or a laboratory fixture) is always first exercised with an exemplary unit to prove that the test bed will not add to, or alter, the subject unit data contents.

4.5   ABS/TCS DIAGNOSTICS AND DATA EXAMPLE

4.5.1   Format and Scaling of the Freeze Frame Data

For various versions of ABS/TCS systems as applied to different model vehicles, there are various versions of the content, format, and scaling of its crash-event snapshot/freeze frame data. Since each version of such data has a specific format and mathematical interpretation scheme, a hexadecimal list with no translation of its contents is not very useful.

The content and interpretation format(s) of various data fields of EEPROM data are often summarized in a worksheet similar in purpose to the SRS EEPROM worksheet. Such worksheets are derived from multiple engineering specifications, software listings, and electrical schematics. These documents actually define how the ECU operates and the content, format, and scale factors with which the ECU records data in EEPROM or flash memory.[5]

To illustrate such a data scheme and its interpretation process, a fragment of hypothetical example crash event data is shown below, with its worksheet interpretation. Such data would have been obtained by a vehicle download as shown in Fig. 4.6. In Fig. 4.6, the data inset shows the hexadecimal data used in the example worksheet below.

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[5]These engineering specifications, software listings, and electrical schematics are universally considered to be manufacturer-proprietary and are usually available only under confidential non-disclosure orders.

Excerpt of Hypothetical ABS EEPROM Data (Hex Data Paragraph and Interpretation)

<u>**Original Data Format**</u>

```
0000    5D 84    11 01    84 0C    87 20
0008    0C C2    2D 01    A7 0A    BA 13
0010    25 01    01 A6    FF FF    FF FF
0018    FF FF    FF 35    4A 21    0B 0A
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HEX DATA BYTE ADDR	DATA - BYTE VALUE - HEX	DEC	BINARY	INTERPRETED MEANING & ENCODING EVALUATION, HYP EXAMPLE
0000:	5D	93	0101 1101	SOFTW IDENT version,level, Version 5, Level D
0001:	84	132	1000 0100	SOFTW DATE HI yr, month, {199}8, April
0002:	11	17	0001 0001	SOFTW DATE LO day, 17th day
0003:	01	01	0000 0001	# ABS Stops, Counter, HiByte}
0004:	84	132	1000 0100	# ABS Stops, Counter, LoByte} 0184 hex ==> 388 dec
0005:	0C	12	0000 1100	# Global Ign Cycles, Ctr, HiByte}
0006:	87	167	1000 0111	# Global Ign Cycles, Ctr, LoByte} 0C87 hex ==> 3207 dec
0007:	20	32	0010 0000	Global History DTCs mask: 0, 1, 2, 3, 4, 5, 6, 7
0008:	0C	12	0000 1100	Global History DTCs mask: 8, 9, A, B, C, D, E, F
0009:	C2	194	1100 0010	First DTC = C, 2nd DTC = 2
000A:	2D	45	0010 1101	Last-1 DTC = 2, Last DTC = D
000B:	01	01	0000 0001	# Ign cycles @ first DTC, HiByte }
000C:	A7	167	1010 0111	# Ign cycles @ first DTC, LoByte } 01A7 hex ==> 423 dec
000D:	0A	10	0000 1010	# Ign cycles @ last DTC, HiByte}
000E:	BA	186	1011 1010	# Ign cycles @ last DTC, LoByte} 0ABA hex ==> 2746 dec
000F:	13	19	0001 0011	Averaged WSS @ first failure ==> 19 MPH (30.6 KPH)
0010:	25	37	0010 0101	Averaged WSS @ last failure ==> 37 MPH (59.6 KPH)
0011:	01	01	0000 0001	# Resets since factory [does not reset any Ign Counter]
0012:	01	01	0000 0001	# Ign cycles @ last Reset, HiByte}
0013:	A6	166	1010 0110	# Ign cycles @ last Reset, LoByte} 01A6 hex ==> 422 dec
0014:	FF	255	1111 1111	Factory Data
0015:	FF	255	1111 1111	Factory Data
0016:	FF	255	1111 1111	Factory Data
0017:	FF	255	1111 1111	Factory Data
0018:	FF	255	1111 1111	Factory Data
0019:	FF	255	1111 1111	Factory Data
001A:	FF	255	1111 1111	Factory Data
001B:	35	53	0011 0101	Engine Option 5.3 Liter
001C:	4A	74	0100 1010	Transmission option, 4 speed Automatic
001D:	21	33	0010 0001	Axle ratio, 3.3:1
001E:	0B	11	0000 1011	Front tire size code
001F:	0A	10	0000 1010	Rear tire size code

From the above example, we can see that:

1. The unit under examination incorporates software Version 5, Level D, which was released on the 17th day of April 1998.
2. There are 15 possible DTCs, identified by their hex symbols, 1 to 9 and A to F, with 0 not used.
3. The ignition cycle counter and averaged wheel sensor speeds (WSS) are saved as freeze frame data for the first and last DTC recorded (in the current record after the last system reset).
4. There was one reset at ignition cycle 422.
5. A new DTC was saved on the very first cycle after reset (423), DTC "C," and there was an average wheel speed of 19 mph.
6. The last DTC, "D," was saved at ignition cycle 2746, and the average WSS was 37 mph at that time. Since the total ignition cycle count is now 3207, we know that there is no relationship between the last saved WSS and any event in the current (or current –1) ignition cycles. However, if the Last −1 cycle was also the crash cycle,[6] then we may have a good indication of a minimum speed of impact.[7] This can be compared with the cumulative Delta V saved in the SRS ECU to determine if the SRS recorded deceleration was final, or if the vehicle proceeded on after air bag deployment.
7. One can check the tire sizes to see if they match the EEPROM data. Incorrect tire sizes can contribute to control problems.
8. In this history cycle (after the reset), we know that there were only three DTCs saved. Note how the second DTC, "2" (address $0009) is also the Last −1 DTC (address $000A).

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[6]Sometimes saved in the SRS ECU and/or EDR.

[7]Since the ABS ECU may not recognize the DTC until some time into the impact, and then record speed, the vehicle may have slowed from its pre-impact speed.

FORMATTED HEX DATA LISTING

```
Address  00 01    02 03    04 05    06 07
Ident   (08 09    0A 0B    0C 0D    0E 0F)

0000     5D 84    11 01    84 0C    87 20
0008     0C C2    2D 01    A7 0A    BA 13
0010     25 01    01 A6    FF FF    FF FF
0018     FF FF    FF 35    4A 21    0B 0A
0020     FF FF    FF FF    FF FF    FF FF
0028     FF FF    FF FF    FF FF    FF FF
0030     FF FF    FF FF
                           ERROR CODES &
                           EEPROM DATA
```
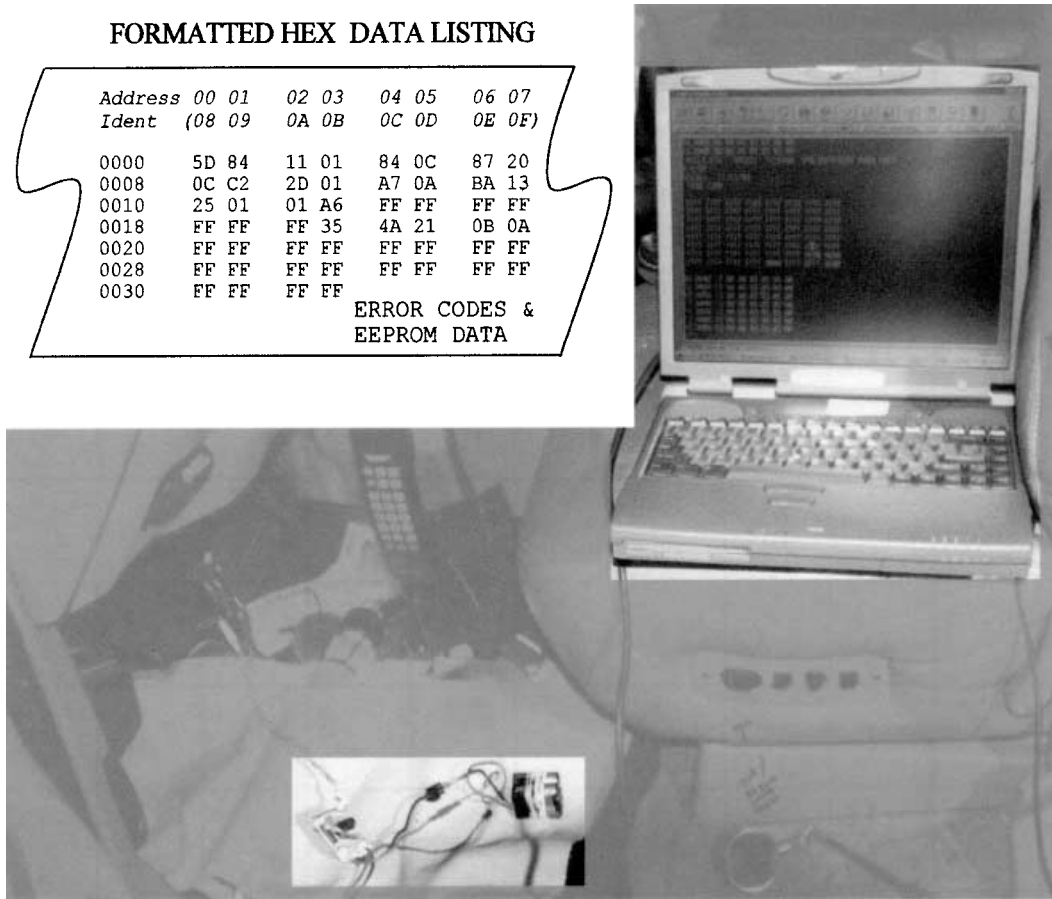
FIG. 4.6—Laptop computer and data interface operating as a scanner to download and record ABS EEPROM data from a 1995 domestic pickup truck. Data shown in the inset is from the example of Section 4.5.1.

4.5.2 Freeze Frame Parameters That Can Be Associated with Crash Events

Below is a representative list of parameters that can be saved in a freeze frame associated with a crash-related ABS/ETR event. Some parameters will obviously be saved in the ABS ECU, and others may be saved elsewhere, depending on design complexity and the level of systems integration.

- Wheel Speed
- Active Faults
- History Faults
- Brake Switch Status
- Number of ABS Occurrences
- Number of Ignition Cycles Before First Fault
- Number of Ignition Cycles After First Fault
- Warning Lamp Status
- Vehicle Speed
- Pump Motor
- Valve Relay
- Engine Torque
- Solenoids
- ABS State
- Engine Speed
- Tire Size

Examples of ABS/TCS freeze frame parameters useful in crash investigations are shown in Chapters 1, 6, and 7.