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Forensic Engineering Tools and Analysis of Heavy Vehicle Event Data Recorders (HVEDRs)

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Abstract

Since the 1990s, domestic passenger vehicles have been equipped with increasingly more sophisticated supplemental restraint system event data recorders (EDRs) that have become more commonplace in collision analysis. Many collision analysts are aware that most heavy commercial vehicles are likewise equipped with heavy vehicle event data recorders (HVEDRs) that may trigger during a hard braking or sudden deceleration event — or when the driver activates a signal to trigger an event to the system. Some heavy commercial vehicle engine manufacturers even provide an additional record of the last stop of the vehicle. Unfortunately, there are no uniform standards as to the information recorded or even the triggering criteria for an event regarding heavy commercial vehicles. HVEDR records oftentimes provide valuable information that assists the forensic engineer in analyzing collision or failure events. This paper provides the forensic engineer with HVEDR engine manufacturer download coverage and tools needed (as of the presentation of this paper), and explores anomalies in event recording that the forensic engineer should be aware may exist. A case study pertaining to an HVEDR record of a commercial vehicle having a peculiar recording anomaly is presented. This paper outlines the process of how the anomaly was resolved and the process of plotting the sequence of events for courtroom presentation.

Keywords

Forensic engineering, HVEDR, ECM, Caterpillar Electronic Technician, DDDL, DDEC Reports, Cummins PowerSpec, Cummins Insite, International ServiceMaxx, Paccar DAVIE, Volvo PTT/VCADS, Mack/Volvo V-MACK IV, commercial vehicle reconstruction

Background

As vehicles equipped with event data recorders (EDRs) become more ubiquitous, the forensic engineer must stay abreast of current developments within the applicable technology. Heavy vehicles (Class 3-8), as defined within this paper, contain a special subset of heavy vehicle event data recorders (HVEDRs), which lack the standardization prevalent within passenger vehicle EDRs. In general, the EDR function in passenger vehicles is contained within the electronic modules of the supplemental restraint system (airbags, seatbelt pre-tensioners, etc.), excluding certain Ford vehicles. In heavy vehicles, the HVEDR function is contained within one or more modules designed for operating the vehicle's drivetrain and emissions system, which are not specifically designed for collision sensing.

Heavy vehicles are equipped with standardized communication networks; the SAE J1708/J1587 is a serial network (low speed), or the SAE J1939 is a controller area network (CAN) (high speed and data). These communication networks connect to the diagnostic port (in-cab Deutsch connector) where a forensic engineer can access the vehicle's communication network and thereby image any event-related data stored on the vehicle. The in-cab Deutsch connector on most heavy trucks is usually located under the dashboard. However, there are exceptions, such as in certain Kenworth tractors, which have the in-cab Deutsch connector located near the driver's side door jamb behind the driver's seat.

Electronic control units (ECUs) for operating a heavy vehicle's drivetrain first became prevalent in the 1990s. Mainly spurred by emissions regulations, ECU technology has grown rapidly from its initial primitive form into the advanced computer controls equipped on newer vehicles. The manufacturers quickly determined that ECU modules could do more than just store the operating parameters of an engine and the vehicle. ECU units could record event data related to vehicle

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diagnostic faults, hard or quick stops, and the last or most recent stop of the vehicle — all useful data for analyzing mechanical operations and issues. In this paper, the term "ECU" will refer to systems with multiple electronic control units storing event-related data, and engine control module or "ECM" will refer to systems where only one module need be accessed for a complete download of event-related data.

Methods for Imaging HVEDR Data

Imaging HVEDR stored data is facilitated through one of four methods:

- On-vehicle, in-cab Deutsch connector with adapter.
- Surrogate vehicle connection.
- Benchtop download using a simulator harness.
- Benchtop download without simulator harness.

The first and preferred method using the in-cab Deutsch connector and adapter facilitates imaging the data while all ECUs and sensors are still attached to the vehicle and accessed through the vehicle's communication network. On-vehicle imaging entails attaching an RP-2010A-compliant communications adapter to the vehicle's diagnostic data port (Deutsch connector). There are multiple RP 2010A adapters available — some are manufacturer-specific and may not work well for connecting to all manufacturers' ECUs, whereas some aftermarket systems are universal. The recommended communication adapters by vehicle manufacturer are as follows:

- Detroit Diesel, Mercedes, and Paccar; RP-2010A Nexiq USB-Link adapter.
- Caterpillar; the CAT communication Adapter 3.
- Cummins; the INLINE 7.
- Volvo; either the Movimento or the Volvo Link.

Although imaging the ECU on-vehicle is the preferred method, in certain situations it may not be feasible or desirable. Imaging ECUs on the vehicle requires that the ignition be turned to the "ON" position, either by using the vehicle's key, if available, or by bypassing the ignition lock cylinder.

The second method of imaging a heavy vehicle ECU(s) is by using a surrogate vehicle, which must have an identical configuration to eliminate the potential for generating new faults that were not present or recorded by the damaged vehicle's ECU(s). Prior to swapping the ECU(s), the surrogate vehicle should be checked for active faults. If no fault codes are present, the ECU(s) from the damaged vehicle are swapped out and connected through the communication cables of the surrogate vehicle so that the ECU(s) can be interrogated by communication through the surrogate vehicle's in-cab Deutsch connector when imaging the damaged vehicle's ECU(s).

The third preferable download methodology consists of a benchtop download of the ECU(s) using either a simulator harness or a programming harness. A simulator harness has sensors or resistors that "trick" the ECU(s) into sensing a connection with a vehicle communication system during interrogation, and therefore prevents setting new fault code and possibly fault snapshots. The simulator harness must also be configured to match the vehicle the subject ECU(s) was removed from to avoid generating new fault codes during the imaging process of the interrogated ECU(s). Simulator harnesses can be costly and are time consuming to construct.

The final and least-preferred option is completing a bench download of the ECU(s) using a programming harness. A programming harness allows the user to connect to the ECU(s), but does not simulate any of the engine or vehicle sensors. Using a programming harness to interrogate the ECU(s) will generate new fault codes. To minimize setting new fault codes while imaging an ECU with a programming harness, the programming harness can be plugged into the "chassis" connector on an ECU while leaving the "motor" connector attached to all of the wiring for the motor (**Figure 1**), thus eliminating most, but not all, faults. However, circumstances may dictate that a benchtop download without a simulator harness may be the only method available for imaging HVEDR data.

Caterpillar

Since 1994, Caterpillar has equipped heavy- and medium-duty engines with an ECM accessible while using Caterpillar Electronic Technician (CAT ET). Starting in 1995, most Caterpillar ECMs recorded vehicle snapshots. Caterpillar stopped manufacturing over-the-road engines in 2009. Engines offered in new Caterpillar vocational trucks are manufactured

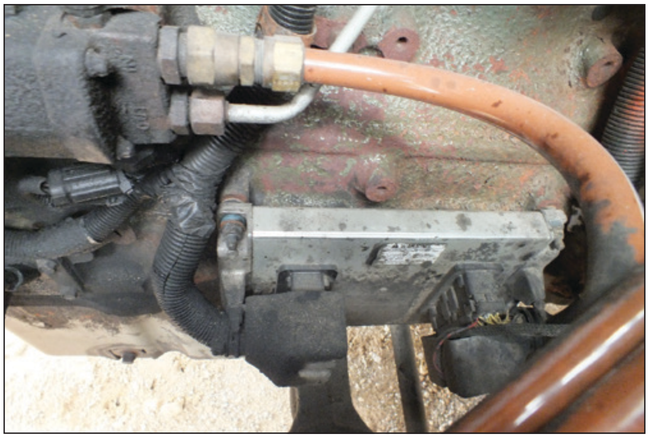

Figure 1
ECM chassis and motor connectors DDEC V.

by Navistar, which are accessible using Navistar ServiceMAXX software. A single ECM generally located on the left side of the engine block manages most downloadable Caterpillar engines (**Figure 2**). Caterpillar engines have three generations of ECMs with accessible HVEDR data; ADEM II, ADEM 2000/III, and ADEM IV.

Figure 2
Typical Caterpillar ECM location.

All three CAT ADEM generations have *Quick Stop* recording capabilities, but, by default, all CAT engines manufactured prior to January 2007 had the *Quick Stop* function turned off at the factory[1]. However, a technician could activate the *Quick Stop* function using CAT ET software, and some fleets running Caterpillar engines enabled the *Quick Stop* function on pre-2007 CAT engine-equipped vehicles. After January 2007, the *Quick Stop* function was defaulted as "ON" from the factory. Caterpillar *Quick Stop Records* record 44 seconds of data prior to the trigger point and 15 seconds after the trigger point at a 1 Hz frequency (one data point per second). The factory-default *Quick Stop* trigger on post 2007 is unknown, as Caterpillar's literature cites a rate of 0 miles-per-hour-per-second (mphps), which has been found to be incorrect[2]. The *Quick Stop* trigger on all Caterpillar ECMs can be user defined. Caterpillar *Quick Stop* data records consist of the vehicle's speed, accelerator pedal position, clutch pedal position, service brake pedal position, engine speed (RPM), cruise control status, and more.

Aside from recording *Quick Stops,* Caterpillar ECMs record diagnostic snapshots, triggered snapshots, and engine parameters. Both the diagnostic snapshots and the triggered snapshots record 9.12 seconds prior to the fault/trigger and 3.36 seconds after at 2.083 Hz (one data point per 0.48 seconds). The vehicle operator can trigger a snapshot record by toggling the cruise control set/resume switch on and off on a Caterpillar-equipped heavy road vehicle with ECM software post-dating November 2005.

In order for a Caterpillar ECM to write a complete *Quick Stop* record, the vehicle must maintain adequate battery voltage for 15 seconds after trigger activation. This indicates that if a power interruption occurs during a collision event, a *Quick Stop* record cannot be extracted using CAT ET. Synercom Technologies' TruckCRPT software has had some success in obtaining and decoding partially written *Quick Stop* records due to a power loss during the event[3].

Several known data irregularities exist within data extracted from Caterpillar ECMs, most of which are related to the date stamping of reports and snapshots. Several Society of Automotive Engineers (SAE) papers outline the specifics of Caterpillar ECM recording irregularities[2,4,5]. Another significant irregularity the forensic engineer must be aware of when examining data from a Caterpillar ECM is that all ADEM 2000, ADEM III, and ADEM IV EPA07 modules reported a 1 Hz recording rate on both *Quick Stops* and *Diagnostic Snapshots,* which, in reality, were gathered for the record at 2 Hz and 2.08 Hz, respectively. A software update for the ADEM IV EPA07 corrected this issue. To date, the recording rate anomaly remains a concern for engines equipped with the ADEM 2000, ADEM II "Bridge" module and the ADEM IV MXS/NXS ECMs[2]. Forensic engineers should be aware that the data obtained from an affected module will require adjustment to the proper time intervals between data points when using the information for a time and distance analysis of a particular recorded event.

Cummins

Cummins produces one of the most widely used engines in heavy over-the-road vehicles. In 2002, Cummins first equipped its engines with an ECM having the necessary hardware to record event-related data, but not the necessary firmware to access the data from the module. The early 2002 through 2005 Cummins ECMs recorded event-related data only after the ECM software was updated with firmware released in 2005. ECMs produced by Cummins in late 2004 or early 2005 shipped with the updated firmware, allowing for the recording of event-related data without software updates[1]. The specific ECMs requiring a re-flash in order to record EDR data and the production dates where the updated firmware was implemented in specific ECMs are beyond the scope of this paper. However, the information is covered during most in-depth training classes on HVEDRs.

Vehicles equipped with Cummins engines store event-related data on a single ECM, which is generally located on the left side of the engine (**Figure 3**). To access the complete event-related data, the forensics engineer uses two software applications: Cummins Insite and Cummins PowerSpec. Cummins Insite is a technician-level program that allows for the access of engine and vehicle parameters, in-depth fault information, audit trails, and other information. Cummins PowerSpec allows the forensic engineer to access most of the "event-related" data recorded by the ECM, including *Sudden Deceleration Reports*, vehicle trip information, fault codes, feature settings, data plate, and maintenance monitor data. Cummins PowerSpec is generally not utilized by technicians, and most dealerships and/or technicians will not have the software or even know of its existence. Without Cummins PowerSpec, the event-related data cannot be imaged.

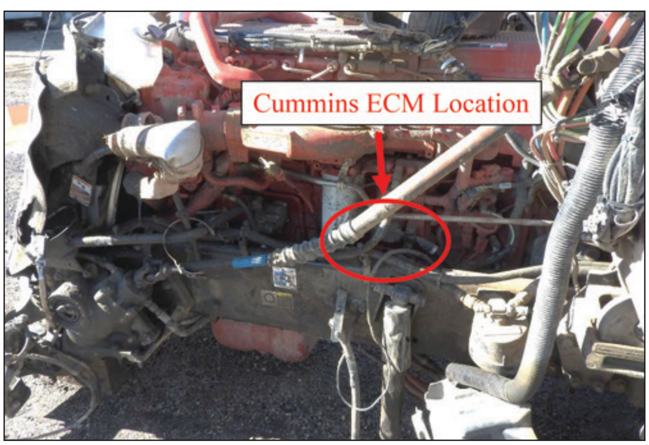

Figure 3
Typical Cummins ECM location.

Cummins ECMs built after the firmware upgrade — and ECMs from 2002 to 2005 with updated firmware — can record up to three *Sudden Deceleration Records,* which are accessed using Cummins PowerSpec and contain data for 59 seconds prior to the trigger and 15 seconds after the trigger, reported at a 1 Hz sampling rate. To trigger a *Sudden Deceleration*, the vehicle must slow at a default rate of 9 mphps (≈0.41*g*) or greater. *Sudden Deceleration Records* report vehicle speed, engine speed (RPM), throttle position, engine load, brake status, clutch status, cruise control status, and Malfunction Indicator Lamp (MIL) status at a reporting rate of 1 Hz. A few words of caution with Cummins *Sudden Deceleration Records*:

- *Sudden Deceleration Records* are recorded on volatile memory and then written to non-volatile memory at vehicle key-off. This means if a power interruption occurs during the collision, the *Sudden Deceleration Record* will not be recoded. Fault code snapshots, on the other hand, are recorded to non-volatile memory as they occur and may be correlated to a collision[5].

- Certain Cummins ECMs have a calibration error where the *Sudden Deceleration Record* is recorded at 5 Hz (0.2 second intervals), but reported at 1 Hz (1 second intervals)[6]. To account for this calibration issue, the forensics engineer must adjust the recorded data from the *Sudden Deceleration Record* of an affected ECM so that reported data intervals are spaced at 0.2 seconds from the trigger point, effectively compressing the data fivefold[6].

One notable difference with Cummins ECMs compared with other engine manufacturers is that setting a fault snapshot requires a fault to be active, go inactive, and then go active once more. This implies that the forensic engineer performing a Cummins ECM benchtop download with just a reprogramming harness should not generate any new fault code snapshots if the imaging is completed in a forensically sound manner (i.e., properly trained methods)[1].

Cummins equipped vehicles may also be fitted with Cummins RoadRelay, which is an in-dash trip and driver computer. RoadRelay 3, 4, and 5 are downloadable by the forensic engineer and can store *Panic Stops*. RoadRelay 3 requires special software (Cummins InRoads) while RoadRelay 4 and 5 can be imaged using Cummins PowerSpec. *Panic Stop* records on a RoadRelay 4 and 5 contain 59 seconds of pre-trigger data and 15 seconds of post-trigger data recorded at 1 Hz. The trigger threshold for a *Panic Stop* is a deceleration rate of 9 mphps (≈0.41*g*) — the same as a *Sudden Deceleration Record*. On a RoadRelay 3, the *Panic Stop* record reports 45 seconds prior to the trigger and 15 seconds post-trigger. The trigger threshold on a RoadRelay 3 is user programmable.

Figure 4
Cummins Road Relay.

Detroit Diesel

Detroit Diesel has been manufacturing ECUs with hardware to store event-related data since 1994. It currently has six generations of ECU-equipped engines capable of recording event-related data. Each generation of ECU has differences between the recorded data. The six generations of recording ECUs are DDEC III, DDEC IV, DDEC V, DDEC VI, DDEC 10, and GHG14. In 1997/1998, Detroit Diesel released a software update, allowing DDEC III ECUs to record data. However, the recorded data did not include *Hard Brake* records or *Last Stop* records. The functionality to record *Hard Brake* and *Last Stop* records was first introduced with the DDEC IV in 1998, and continues on to the latest generation of ECUs[1]. DDEC III, IV, and V are all single ECU systems, whereas DDEC VI consists of two modules, DDEC 10 consists of three modules, and GHG14 is either a three- or four-module system, depending on transmission configuration (manual vs automatic transmission).

To image data contained in a Detroit Diesel ECU, the forensic engineer must use two software suites: two versions of Detroit Diesel Diagnostic Link (DDDL), depending upon the ECU being interrogated, and Detroit Diesel Electronic Controls Reports (DDEC Reports). DDEC Reports accesses most of the incident-related data, but both pieces of software must be used to obtain a complete image of a Detroit Diesel ECU.

Detroit Diesel's one module ECUs have the module located on the left side of the engine block. The two-module ECUs consist of a Motor Control Module (MCM) and a Common Powertrain Controller (CPC). The MCM is located on the left side of the engine block and contains most of the engine parameters. The CPC is located in the tractor cab and contains most of the event-related data. The location of the CPC varies by tractor make and model, but is most often centered in the cab behind the dashboard. The three module Detroit Diesel ECUs consist of the MCM, CPC, and after-treatment control module (ACM) located on the underside of the tractor, most often by the diesel exhaust fluid (DEF) tank. The ACM retains data mainly related to the engine exhaust after-treatment. On four module ECUs, in addition to the three previously discussed modules, a Transmission Control Module (TCM01T) controls the Detroit Diesel automatic transmission when equipped.

A *Hard Brake* record recorded by a Detroit Diesel ECU consists of 60 seconds of data prior to the trigger and 15 seconds of data past the trigger, reported at 1 Hz. The trigger for Detroit Diesel ECUs is factory set at a speed drop of 7 mphps (≈0.32*g*), with a technician-changeable trigger. To trigger a *Hard Brake* event, the vehicle must be traveling a minimum of 10 mph prior to the speed drop, and the speed drop cannot be followed or proceeded by a speed gain of 4 mphps (≈0.18*g*) or greater[1]. Detroit Diesel ECUs can store up to two *Hard Brake* events and a single *Last Stop* record, reflecting the most previous operation of the vehicle. *Last Stop* records report 1 minute and 44 seconds prior to the vehicle's speed dropping to zero and 15 seconds thereafter. In order to trigger a *Last Stop* record, the vehicle must travel at a speed greater than 1.5 mph with the engine speed greater than 0 RPM. Then, the vehicle's speed must drop to 0 mph or the ignition turned off. Lastly, the vehicle must remain stopped for a minimum of 15 seconds[5].

Detroit Diesel ECUs record diagnostic snapshots that contain one minute of data prior to the diagnostic fault code becoming active at a 0.2 Hz (1 record every 5 seconds) interval. A note to the forensics engineer: If an ECU is imaged using a programming harness only, a high probability exists that new diagnostic snapshots will be written that will overwrite those previously existing. But, even if active fault codes exist on the vehicle after an event, no new diagnostic snapshots should be written if the forensic engineer images the ECUs directly through the in-cab Deutsch connector.

Another commonly useful data set obtained from Detroit Diesel ECUs is the *Daily Engine Usage* reports, which provide the following detail: drive time, idle time, and off time for the last 30 days. The data imaged can be useful when checked against a driver's logs and when investigating potential hours-of-service violations.

Testing demonstrates that in order for a DDEC IV or V ECU to write a *Hard Brake* record, the vehicle must have continuous power for at least 20 seconds and a key-off condition prior to the vehicle losing power. The DDEC VI generation of ECUs requires only a key-off condition prior to the vehicle losing power to write a *Hard Brake* event. On DDEC VI, X and GHG14 ECUs, the *Last Stop* is written immediately after the trigger event[5].

Similar to Cummins RoadRelay, Detroit Diesel offered the ProDriver computer. ProDriver can contain up to 5 *Hard Brake* records and a *Last Stop* record. For a *Hard Brake* event, ProDriver reports 90 seconds prior to and 30 seconds after a trigger event. The driver can manually trigger a snapshot for ProDriver by pressing a button. When a Snapshot is manually triggered, a record of the 2 minutes prior to activation of the snapshot button will be recorded[1]. ProDriver was discontinued in 2010, and is not widely equipped on vehicles.

Figure 5
Detroit Diesel ProDriver.

International/Navistar

Many International engines have accessible event-related data since 2010 and downloadable parameter data since 2007. The downloadable parameter data in pre-2007 International engines includes diagnostic trouble codes, vehicle events, and engine and vehicle parameters. Generally, the single ECM on International engines is located on the left side of the engine block. Starting in 2010, newly built International MaxxForce engines started to record event-related data. Access to these engines is made possible using International's ServiceMaxx software.

International MaxxForce engines that have the ability to record event-related data can record up to two *Hard Accel/Decel* records and up to two *Last Stop* records. *Hard Accel/Decel* records are triggered when the vehicle either accelerates or decelerates at a user-programmable rate. A *Hard Accel/Decel* record will store 105 seconds of data at 1 Hz prior to the trigger, a snapshot of engine and vehicle parameter at the time of the trigger, and 15 seconds after the trigger. *Last Stop* records are recorded once the vehicle comes to a stop and the engine is shut off — or the vehicle comes to a stop and idles for at least 2 minutes. A *Last Stop* record contains the same amount of data as a *Hard Accel/Decel* record at the same recording frequency of 1 Hz.

International engines can record diagnostic snapshots when fault codes are set. These snapshots contain data from a single point in time and do not record a time series of the data surrounding the trigger. International engines can also contain vehicle activity reports, vehicle event reports, diagnostic trouble codes, parameters, and vehicle information[1].

Mack

Starting in 1998, vehicles equipped with Mack engines can contain event-related data. However, the software necessary to access the data in a forensically sound manner is available only to Mack/Volvo-authorized providers. Three options exist for the forensic engineer to obtain the EDR data on a Mack-equipped vehicle. The first option is to have the Mack/Volvo-authorized provider directly download data from the vehicle. The second option requires the Mack/Volvo-authorized provider to use a surrogate vehicle with the ECUs swapped. The third is to remove the ECUs and send them to the authorized provider to attempt a benchtop download. More information on authorized providers and costs for data downloads can be found at www.hvedr.com.

Mack uses a two-ECU or three-ECU system — each consisting of a Vehicle Electronic Control Unit (VECU) and an Engine Electronic Control Unit (EECU) — and the three-ECU system having the addition of an Instrument Cluster ECU in 2006 and later

Mack trucks. The EECU is located on the left side of the engine block, whereas the VECU is located within the cab, generally near the passenger-side kick panel. The Instrument Cluster ECU is usually integrated into the instrument cluster, and the entire instrument cluster must be removed and sent to the authorized provider for a benchtop download (**Figure 6**).

Figure 6
Mack/Volvo instrument cluster ECU.

Mack ECUs either contain two deceleration-triggered events or one deceleration-triggered event and one last stop event, depending on the software revision. Most Mack engines built from 1998 to 2007 record 15.8 seconds of data prior to the trigger for either a deceleration event or a last stop event, and 16 seconds after the trigger event at a reported interval of 5 Hz (one data point per 0.2 seconds). These same modules require a default 10 mphps speed increase or drop (±0.46*g*) and a change in engine speed of 50 rpm/second to set a deceleration trigger event, although the speed change is user programmable. In order to set a last stop event, a Mack-equipped vehicle must have traveled faster than 45 mph prior to coming to a stop, and the parking brake must be set prior to the vehicle's ignition key being switched to the off position.

Starting in 2006, Mack released V-MACK IV to replace the earlier V-MACK III. V-Mack IV-equipped vehicles record 60 seconds of data prior to a deceleration triggered event and 30 seconds after, reported at 4 Hz (0.25 data points per second). The factory default for the deceleration trigger was changed to 10 mphps, but is user programmable. The last stop triggered events on a V-MACK IV records 90 seconds prior to the vehicle coming to a stop, reported at 4 Hz (0.25 second intervals) [1].

Mack ECUs can also record diagnostic snapshots when a fault code is first detected, which contains data from a single point in time. Mack ECUs also contain vehicle and engine parameters and various other information that may be useful to the forensic engineer.

Mercedes

Mercedes engines appeared in North American heavy vehicles from 2000 to 2010, and record essentially the same information as Detroit Diesel engines of the same vintage. Mercedes ECUs are accessed using the same software as Detroit Diesel engines; specifically, DDDL and DDEC Reports. From 2000 to 2006, Mercedes engines contained a two-module ECU system, consisting of a *Pumpe Liene Dusse* (PLD) located on the left side of the engine block and the Vehicle Control Unit (VCU) located in the cab of the tractor (**Figure 7**). After 2006, Mercedes engines switched to Detroit Diesel's DDEC VI ECU system.

One notable feature of pre-2007 Mercedes ECUs is that a *Last Stop* record is set when the engine rpm drops to 0, regardless of the vehicle's speed[5]. An equally

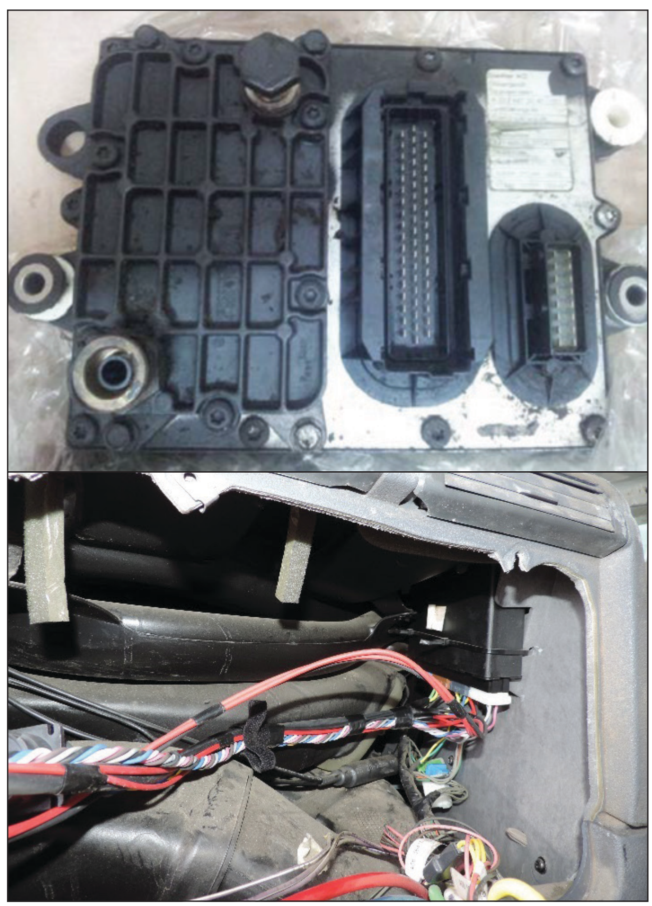

Figure 7
Mercedes ECUs.

notable difference between the data from Mercedes ECUs and Detroit Diesel ECUs is that Mercedes data does not contain an audit trail to monitor changes to the ECU's programming. A word of caution to the forensic engineer: Testing has found that if active faults are present on pre-2007 vehicles with Mercedes ECUs, accessing the modules through the Deutsch connector will result in the diagnostic records being overwritten[7].

Paccar

Paccar, the parent company of Kenworth, Peterbilt, DAF, and other vehicle manufacturers, started producing its own branded engines for the North American market in 2008. These engines (branded "PX" and "MX" series engines) are increasingly more common. The PX branded engines are manufactured by Cummins and contain Cummins ECUs. Accessing Paccar PX engines for imaging uses the same methods and contains the same data elements as outlined in the previous Cummins section of this paper.

The Paccar MX-13 engine was introduced into the North American market in 2013 and contains event-related data that the forensic engineer can access using Paccar's Software DAVIE4. A few notes: DAVIE4 requires an active Internet connection to properly function, and accessing Paccar MX engine parameters requires the use of the dealer-only software Paccar Engine Pro[1].

Paccar ECUs containing event-related data in Paccar MX series engines are the Paccar Multi-Control Injection (PMCI), the Emissions After-Treatment System (EAS), and the Cab Electronic Control Unit (CECU). The PMCI is located on the left side of the engine block (**Figure 8**), the EAS is generally located near the DEF tank under the cab, and the CECU is typically mounted in the dash within the interior of the tractor.

Paccar MX-13 engines can record *Fast Stops,* diagnostic trouble code freeze frames, trip data, and more. A *Fast Stop* record contains 5 seconds of data prior to the trigger for the *Fast Stop* and 5 seconds after the *Fast Stop* at 4 Hz (0.25 second intervals). Paccar ECUs store the last 3 *Fast Stops*, with the oldest of the three records overwritten by subsequent events. The recording of *Fast Stops* can be disabled by a technician by changing the factory default trigger. The default trigger to set a *Fast Stop* Record is 11.2 mphps (≈0.51*g*), but is user programmable[8].

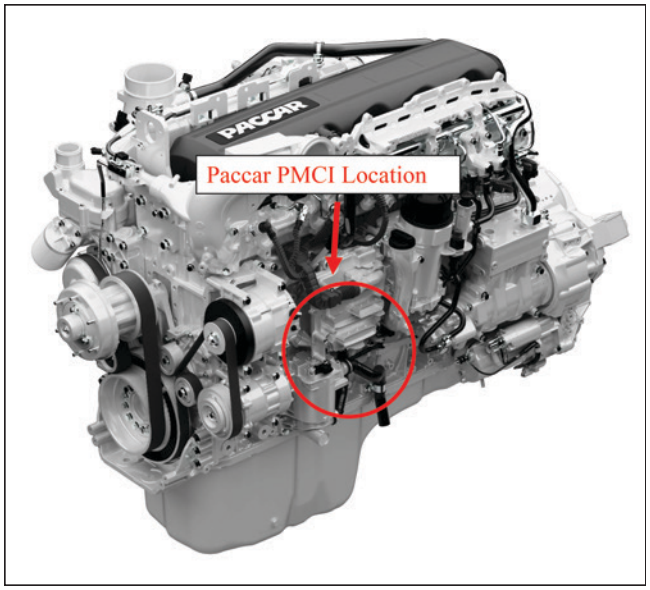

Figure 8
Typical Paccar PMCI location
(image courtesy of www.ccjdigital.com).

Paccar ECUs can store snapshots, which can be operator activated by toggling the cruise control "Resume" switch followed by the cruise control "Set" switch. Paccar ECUs can store up to three snapshots, each containing 10 seconds of pre-trigger and 5 seconds of post-trigger data at 2 Hz (0.5 second intervals). Certain diagnostic trouble codes, generally critical faults, can also trigger a snapshot report.

Diagnostic freeze frames most often contain only one data point in time when the diagnostic trouble code became active, but some diagnostic codes will trigger multiple freeze frame data sets surrounding when the diagnostic code became active. This data will encompass 5 seconds prior to the diagnostic code becoming active, the time of the diagnostic codes and the 4 seconds after the diagnostic codes — all at 1 Hz.

Volvo

From 2002 to 2010, Volvo heavy vehicle engines recorded *Freeze Frames* surrounding diagnostic trouble codes. The data surrounding a fault code consists of two data points prior to the fault, a data point at the time of the fault, and two data points after the fault code. The two data points recorded prior to the fault are spaced 30 seconds apart, but, due to the way Volvo stores data, the timing of the closest data point could be anywhere from 0 seconds prior to the fault to 30 seconds prior to the fault[1]. In order to image Volvo ECUs from 2002 to 2010, the forensic engineer must use the

Pro Tech Tool/Volvo Computer Aided Diagnostic System (Volvo PTT/VCADS). Starting in 2010, Volvo switched over to the same ECU controls as Mack engines. Although this enabled the recording of deceleration events and last stop records, the recorded data can only be imaged by Mack/Volvo-authorized service providers. The data on the post 2010 Volvo is the same as the data contained on the same vintage Mack ECUs and outlined in a previous section of this paper.

Volvo heavy vehicles may be equipped with supplemental restraint systems (SRS) that may have limited event-related data stored on the SRS ECU. An SRS ECU in a Volvo heavy vehicle must be sent to the manufacturer for retrieval of an event-related acceleration pulse.

Case Study

The following case study revolves around the analysis of *Sudden Stop* data imaged from a 2005 Kenworth T2000 equipped with a Caterpillar C15 heavy-duty diesel engine having a Caterpillar ADEM IV HVEDR. The Kenworth tractor/semi-trailer experienced a loss of control during a sudden heavy rain storm weather event in southern Wyoming. The collision event involved three tractor/semi-trailer units, and was initiated by the loss-of-control event for the Kenworth. The Kenworth semi-trailer came to rest along the inside median, partially blocking the inside traffic lane of the roadway. The right rear of the Kenworth's semi-trailer was subsequently sideswiped by a 2007 Peterbilt tractor pulling a loaded livestock semi-trailer and traveling in the inside traffic lane in the same direction as the Kenworth. The Peterbilt came to rest in the outside traffic lane approximately 50 feet beyond the final rest position of the Kenworth. After an extended time period, a 2004 Volvo tractor/semi-trailer entered the collision area while traveling in the outside traffic lane and collided with the rear of the stopped livestock semi-trailer of the Peterbilt, resulting in catastrophic damage to both the Volvo tractor and Peterbilt semi-trailer.

The authors were called upon to document the roadway evidence and post-collision condition of the Kenworth and Volvo within a two-week period following the collision date. The Peterbilt and its livestock semi-trailer were no longer available for inspection. The scene evidence was recorded using a total station survey as well as a high-resolution custom aerial of the scene flown specifically for this incident. The Kenworth was documented, the airbrake system was inspected to include push-rod adjustments and brake shoe/drum conditions, and the HVEDR was accessed and imaged for further analysis.

The Kenworth was traveling within the inside (left) traffic lane of a stretch of four-lane-two-way interstate highway having a 75-mph posted regulatory speed limit and a brushed concrete surface. The roadway section was on the downgrade side of an extended crest vertical curve of approximately -3%. The roadway geometry also consisted of an approximate 2,000-foot radius horizontal curve to the left at the centerline of the travel lanes for the Kenworth's travel direction, having an approximate 7% super-elevation toward the outside edge of the roadway. **Figure 9** provides a diagram of the collision scene, documented evidence, and final rest locations of the three tractor/semi-trailer combinations.

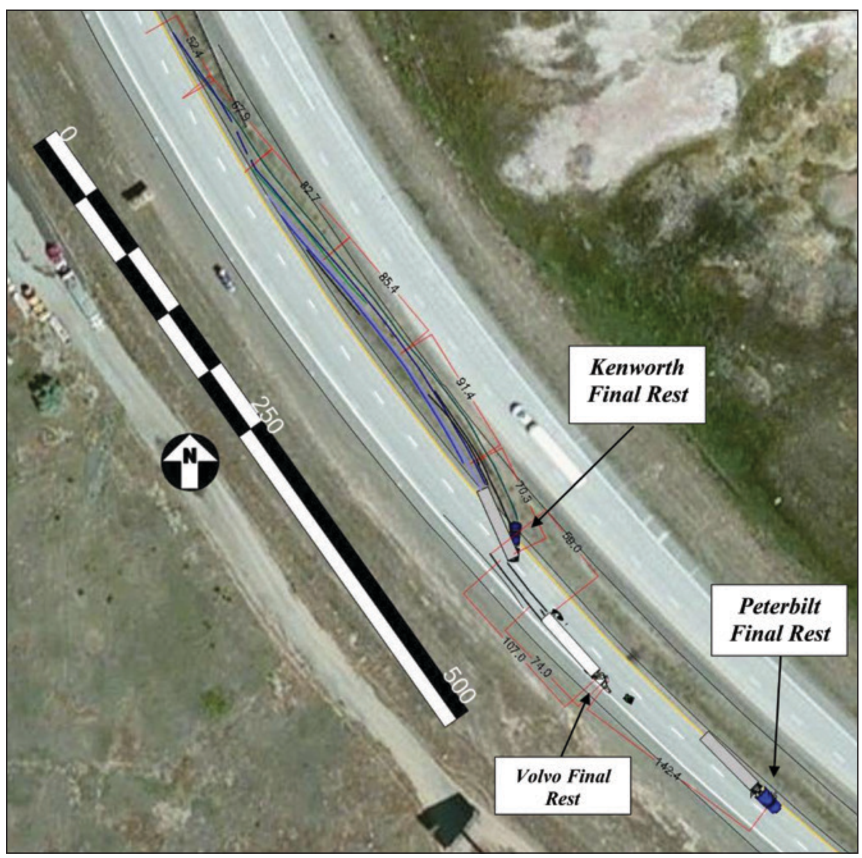

Figure 9
Collision scene evidence.

Emergency personnel cut the power supply cables from the service batteries of the Kenworth. However, the authors were able to provide power to the vehicle using a high-amperage jump box connected to the main power terminals located on the driver's side firewall inside the engine compartment, as shown in **Figure 10**. The Kenworth Caterpillar engine was equipped with an ADEM IV generation Caterpillar HVEDR, located on the driver's side of the engine block at frame rail height, also shown in **Figure 10**.

Figure 10
Power supplied through main power terminal; location of HVEDR.

The Kenworth's HVEDR was accessed using the preferred direct download method through the in-cab Deutsch Connector while using Caterpillar Electronic Technician software. Vehicle speed limit and cruise control settings, as well as trip parameters extracted from the download of the ADEM IV, provide the governed maximum speed limit, high cruise control speed limit, and *Quick Stop* trigger rate settings for the Kenworth, which is also shown in **Figure 11**.

The *Quick Stop* trigger rate for the Kenworth was set at a speed drop of 9 mph/second or greater for recording a *Quick Stop* event. During the loss-of-control event for the Kenworth, the driver had applied braking, and the event produced a speed loss of the vehicle with sufficient magnitude to trigger a *Quick Stop* occurrence consistent with the incident date and adjusted ECM clock time. The *Quick Stop* record indicates the cruise control system was active until service brake application at the record's time entries between -7 and -6 seconds. The initial speed range for the Kenworth ranged from 73 mph to 76 mph prior to brake application, followed by a speed drop to 7 mph at time entry 0-seconds, and a subsequent increase in vehicle speed up to 38 mph before decreasing toward final stop. **Figure 12** illustrates the *Quick Stop* record as recorded for the event.

Vehicle Speed Parameters		
Vehicle Speed Calibration	27526 P/mile	1
Vehicle Speed Cal (J1939-Trans)	Unavailable	
Vehicle Speed Cal (J1939-ABS)	Unavailable	
Vehicle Speed Limit	75 mph	5
VSL Protection	1398 rpm	1
Tachometer Calibration	113.0 PPR	1
Soft Vehicle Speed Limit	Yes	1
Two Speed Axle - Low Speed Range Axle Ratio	Unavailable	
Nominal Axle Ratio - High Speed Range Axle Ratio	Unavailable	
Cruise Control Parameters		
Low Cruise Control Speed Set Limit	30 mph	7
High Cruise Control Speed Set Limit	75 mph	5
Fuel Correction Factor	0 %	0
Dash - Change Fuel Correction Factor	No	0
Dash - PM1 Reset	No	0
Dash - Fleet Trip Reset	No	0
Dash - State Selection	Yes	0
Theft Deterrent System Control	No	0
Theft Deterrent Password	****	
Quick Stop Rate	9 mph/s	2
Vehicle Overspeed Threshold	73 mph	1

Figure 11
Kenworth Caterpillar engine ADEM IV parameters.

Frame	Time		Engine Speed	Vehicle Speed	Cruise/Idle On-Off	Clutch Pedal	Service Brake	Accelerator Pedal	Cruise Mode
Unit	Seconds		rpm	mph				%	
Minimum Value			0	4				3	
Maximum Value			1630	76				85	
1	-44		1569	73	On	Off	Off	3	Active
2	-43		1567	73	On	Off	Off	3	Active
3	-42		1572	73	On	Off	Off	3	Active
4	-41		1565	73	On	Off	Off	3	Active
5	-40		1575	73	On	Off	Off	3	Active
6	-39		1571	73	On	Off	Off	3	Active
7	-38		1575	73	On	Off	Off	3	Active
8	-37		1577	74	On	Off	Off	3	Active
9	-36		1572	73	On	Off	Off	3	Active
10	-35		1578	74	On	Off	Off	3	Active
11	-34		1579	74	On	Off	Off	3	Active
12	-33		1584	74	On	Off	Off	3	Active
13	-32		1584	74	On	Off	Off	3	Active
14	-31		1581	74	On	Off	Off	3	Active
15	-30		1586	74	On	Off	Off	3	Active
16	-29		1591	74	On	Off	Off	3	Active
17	-28		1596	74	On	Off	Off	3	Active
18	-27		1594	74	On	Off	Off	3	Active
19	-26		1596	74	On	Off	Off	3	Active
20	-25		1597	75	On	Off	Off	3	Active
21	-24		1600	75	On	Off	Off	3	Active
22	-23		1605	75	On	Off	Off	3	Active
23	-22		1604	75	On	Off	Off	3	Active
24	-21		1609	75	On	Off	Off	3	Active
25	-20		1608	75	On	Off	Off	3	Active
26	-19		1607	75	On	Off	Off	3	Active
27	-18		1615	75	On	Off	Off	3	Active
28	-17		1616	75	On	Off	Off	3	Active
29	-16		1614	75	On	Off	Off	3	Active
30	-15		1615	75	On	Off	Off	3	Active
31	-14		1616	75	On	Off	Off	3	Active
32	-13		1618	75	On	Off	Off	3	Active
33	-12		1623	75	On	Off	Off	3	Active
34	-11		1624	76	On	Off	Off	3	Active
35	-10		1626	76	On	Off	Off	3	Active
36	-9		1630	76	On	Off	Off	3	Active
37	-8		1622	76	On	Off	Off	3	Active
38	-7		1611	75	On	Off	Off	3	Active
39	-6		1394	70	On	Off	On	3	Not Active
40	-5		1239	59	On	Off	On	3	Not Active
41	-4		1204	57	On	Off	On	3	Not Active
42	-3		1049	51	On	Off	On	3	Not Active
43	-2		807	40	On	Off	On	3	Not Active
44	-1		481	26	On	Off	On	3	Not Active
45	0		42	7	On	Off	On	3	Not Active
46	1		85	13	On	Off	Off	6	Not Active
47	2		34	19	On	Off	Off	6	Not Active
48	3		0	25	On	Off	Off	17	Not Active
49	4		0	32	On	Off	Off	18	Not Active
50	5		0	38	On	Off	Off	17	Not Active
51	6		0	36	On	Off	Off	23	Not Active
52	7		0	33	On	Off	Off	13	Not Active
53	8		0	27	On	Off	Off	12	Not Active
54	9		0	23	On	Off	Off	61	Not Active
55	10		0	19	On	Off	Off	85	Not Active
56	11		0	16	On	Off	Off	77	Not Active
57	12		0	11	On	Off	Off	74	Not Active
58	13		0	7	On	Off	Off	73	Not Active
59	14		0	5	On	Off	Off	73	Not Active
60	15		0	4	On	Off	Off	73	Not Active

Figure 12
Kenworth ADEM IV *Quick Stop* record.

The Kenworth was equipped with an ADEM IV generation ECM, which had a recording anomaly where each record was reported within the table shown in **Figure 12** as though at 1-second intervals (1Hz), when, in fact, the recordings were made every 0.5 seconds (2Hz). Accordingly, the data in **Figure 12** must be adjusted to reflect the recording anomaly in order to properly reflect the timing of the event for the Kenworth.

Additionally, in order to verify the *Quick Stop* record as related to the subject incident, the deceleration of the Kenworth and timing of the Kenworth's path after leaving the roadway were reconstructed using kinematic methods. The friction for the median and the wet roadway surface related to truck tires was obtained[9]. From the scaled diagram of the scene evidence, the incremental rotation and linear motion of the Kenworth to final rest were determined. Finally, the speeds and timing for each increment were calculated using kinematic methods as follows:

$$D3jk := \begin{pmatrix} 52.4 \\ 67.9 \\ 82.7 \\ 85.4 \\ 91.4 \\ 70.3 \end{pmatrix} \cdot ft \qquad \theta 3jk := \begin{pmatrix} 51.8 \\ 77.3 \\ 137.7 \\ 152.4 \\ 168.1 \\ 150.1 \\ 148.2 \end{pmatrix} \cdot deg$$

$\mu max := 0.50$ friction range of median (SAE830612 mud)

$$\Delta\theta 3_k := \frac{|\theta 3jk_k| + |\theta 3jk_{k+1}|}{2}$$

$\mu road := 0.50$ friction range of truck tire on wet concrete (SAE830612)

$$Vjk3max := \left[2 \cdot g \left[\sum_k \left(\mu max \cdot \sin(\Delta\theta 3_k) \cdot D3jk_k\right)\right]\right]^{\frac{1}{2}}$$

$\boxed{Vjk3max = 62.0 \cdot mph \quad \text{speed at start of jackknife to rest}}$

On-road rotation and braking:

$Dbrakeecm := 153 \cdot ft \qquad \theta := \theta 3jk_0$

$$Vinitial := \sqrt{Vjk3max^2 + 2 \cdot g \cdot (\mu road \cdot \sin(\theta)) \cdot Dbrakeecm}$$

$\boxed{Vinitial = 75.1 \cdot mph}$

The kinematic analysis produced a confirmation for the Kenworth's initial speed at the start of braking.

Finally, the corrected HVEDR data (corrected to 2 Hz from the reported 1 Hz within the *Quick Stop* record) from the initiation of braking by the Kenworth until final rest was plotted and compared to the previous kinematic analysis results, as shown in **Figure 13**, **Figure 14,** and **Figure 15**.

The case example presented provides a basic outline of general procedures for a forensic analysis of HVEDR data:

- Plot a scale diagram of the roadway evidence, placing the heavy vehicle on the diagram at regular intervals.
- Calculate the deceleration of the heavy vehicle across the evidence area.
- Determine if the HVEDR for the subject vehicle has any data recording anomalies.
- Adjust for HVEDR recording anomalies.
- Graph the HVEDR data and/or calculated deceleration and compare to roadway evidence.
- Interpret the data for vehicle dynamics.

Findings and Final Observations

Having an HVEDR record should never be the substitute for engineering analysis. Independent calculations for determining the speed of a heavy vehicle should be completed to verify the speeds recorded in an HVEDR record whenever appropriate physical evidence from the collision event is available. A proper engineering analysis will assist the forensic engineer in determining if anomalies in the data record exist, as well as confirm whether or not the record is related to the subject incident.

Graphical representations of the HVEDR data provide a visual means of presenting the timing of an incident involving a heavy vehicle to a jury. When coupled with a detailed scene diagram that places the heavy vehicle (and other involved vehicles) on a scaled diagram of the scene, a clear and effective presentation of the collision timing is achieved.

Actual Time @2htz (seconds)	ECM time increm	ECM Time Value	distance	Velocity (fps)	Ave drag factor	Ave Calced Speed MPH	Brake Status	ECM Reported MPH	
12			0.0	0.0	0.294	0.0			Final rest
11.5	60	15	1.2	4.7		3.2	off	4	
11	59	14	4.7	9.5		6.5	off	5	
10.5	58	13	10.7	14.2		9.7	off	7	
10	57	12	18.9	18.9		12.9	off	11	
9.5	56	11	29.6	23.7		16.1	off	16	
9	55	10	42.6	28.4		19.4	off	19	
8.5	54	9	58.0	33.1		22.6	off	23	
8	53	8	75.8	37.9		25.8	off	27	
7.5	52	7	95.9	42.6		29.0	off	33	
7	51	6	118.4	47.3		32.3	off	36	
6.5	50	5	143.2	52.1		35.5	off	38	Strike median cables
6	49	4	170.4	56.8		38.7	off	32	
5.5	48	3	200.0	61.5		42.0	off	25	
5	47	2	232.0	66.3		45.2	off	19	
4.5	46	1	266.3	71.0		48.4	off	13	
4	45	0	303.0	75.8		51.6	on	7	Cab rotates to maximum angle
3.5	44	-1	342.1	80.5	Dist time 0.5	54.9	on	26	
3	43	-2	383.5	85.2	to 2 seconds	58.1	on	40	
2.5	42	-3	427.3	90.0		61.3	on	51	
2	41	-4	473.4	94.7	153.0	64.5	on	57	start jackknife on median
1.5	40	-5	522.0	99.4		67.8	on	59	
1	39	-6	572.9	104.2		71.0	on	70	
0.5	38	-7	626.4	110.0		75.0	off	75	In lane
0	37	-8	681.8	111.5		76	off	76	
-0.5	36	-9	737.5	111.5		76	off	76	
-1	35	-10	793.3	111.5		76	off	76	
-1.5	34	-11	849.0	111.5		76	off	76	
-2	33	-12	904.4	110.0		75	off	75	
-2.5	32	-13	959.4	110.0		75	off	75	
-3	31	-14	1014.4	110.0		75	off	75	
-3.5	30	-15	1069.4	110.0		75	off	75	

Figure 13
Corrected HVEDR data.

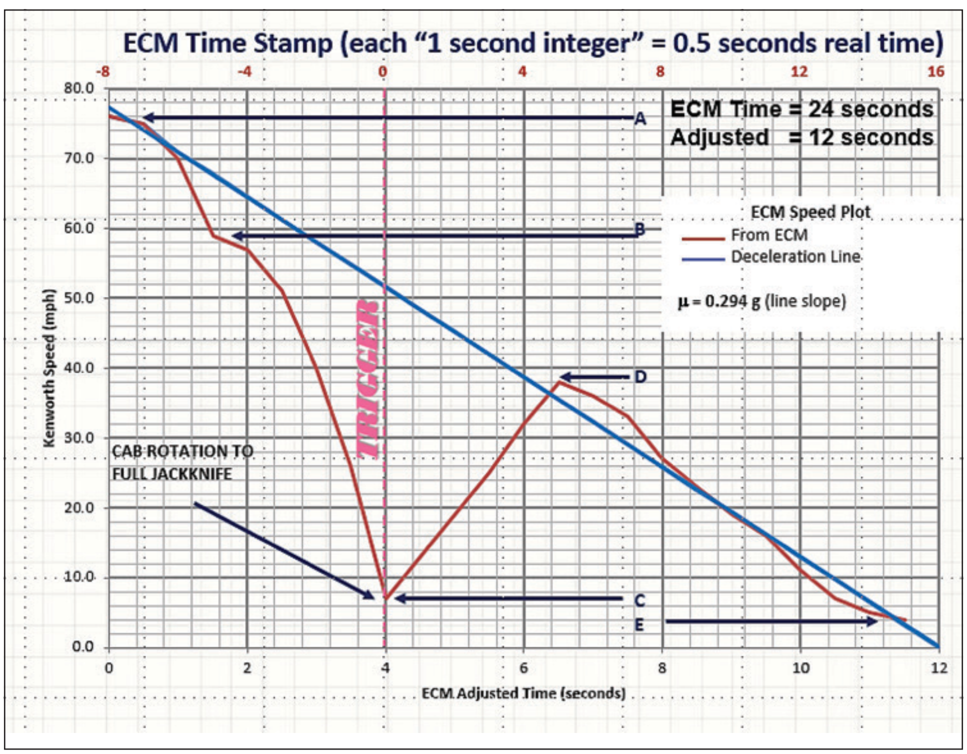

Figure 14
Graphical analysis of HVEDR data.

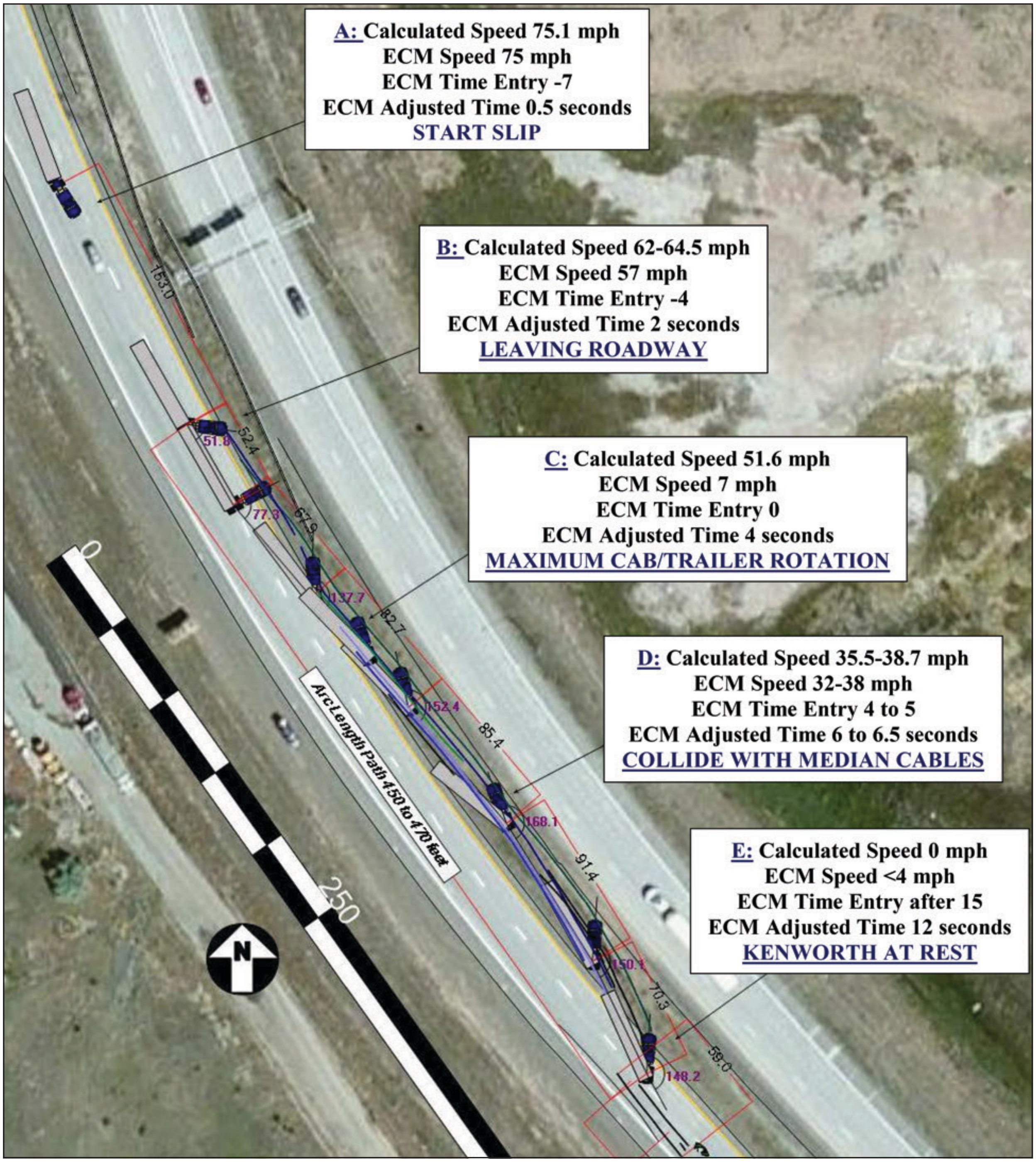

Figure 15
Diagram of Kenworth Dynamics.

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Appendix A

Possible EDR Data by Engine Manufacturer

Caterpillar

Years	ECM	Sudden Deceleration	Last Stop	Snapshots	eLog
1994	ADEM II	Not recorded	Not recorded	Not recorded	Not recorded
1995-2006	ADEM II & 2000/III	Can be recorded if programed	Not recorded	Diagnostic and user triggered	Not recorded
2007-2010	ADEM IV	Up to 2 recorded	Not recorded	Diagnostic and user triggered	Not recorded

Cummins

Years	Engine	Sudden Deceleration	Last Stop	Snapshots	eLog
1998-2001	IS-series	Not recorded	Not recorded	Not recorded	Not recorded
2002-2004	IS-series	Can be recorded if ECM updated	Not recorded	Diagnostic	Not recorded
2005+	IS-series	Up to 3 recorded. Trigger 9 mphps	Not recorded	Diagnostic	Not recorded

Detroit Diesel

Years	ECM	Sudden Deceleration	Last Stop	Snapshots	eLog
1997	DDEC III	Not recorded	Not recorded	Not recorded	Not recorded
1998-2006	DDEC IV & V	Up to 2 recorded Trigger 7 mphps	Recorded	Diagnostic last 3	Recorded
2007-2009	DDEC VI	Up to 2 recorded. Trigger 7 mphps	Recorded	Limited diagnostic	Recorded
2010+	DDEC 10, GHG 14	Up to 2 recorded. Trigger 7 mphps	Recorded	Diagnostic last 3	Recorded

International

Years	Engines	Sudden Deceleration	Last Stop	Snapshots	eLog
2010+	MaxxForce 11, 13, 15	Up to 2 recorded Trigger programmable	Recorded	Diagnostic	Not recorded

Appendix A

Continued

Mack

Years	ECM	Sudden Deceleration	Last Stop	Snapshots	eLog
1998-2007	V-MACK III	Up to 2 recorded Trigger 10 mphps	Can be recorded	Diagnostic	Not recorded
2006+	V-MACK IV	Up to 1 recorded Trigger 10 mphps	Recorded	Diagnostic	Not recorded

Mercedes

Years	Engines	Sudden Deceleration	Last Stop	Snapshots	eLog
2000-2006	MBE 900 & 4000	Up to 2 recorded Trigger 7 mphps	Recorded	Diagnostic Last 3	Recorded
2007-2010	MBE 900 & 4000	Up to 2 recorded Trigger 7 mphps	Recorded	Limited diagnostic	Recorded

Paccar

Years	Engines	Sudden Deceleration	Last Stop	Snapshots	eLog
2008+	PX-6,7,8,9	Up to 3 recorded Trigger 9 mphps	Not recorded	Diagnostic	Not recorded
2013+	MX-13	Up to 3 recorded Trigger 11.2 mphps	Recorded	Diagnostic and user triggered	Not recorded

Volvo

Years	Engines	Sudden Deceleration	Last Stop	Snapshots	eLog
2002-2010	D-11,12, 13,16	Not recorded	Not recorded	Diagnostic	Not recorded
2010+	D-11,12, 13,16	Up to 1 recorded Trigger 10 mphps	Recorded	Diagnostic	Not recorded