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Event Data Recorder Performance during High Speed Yaw Testing Subsequent to a Simulated Tire Tread Separation Event

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Abstract

This paper presents event data from the Sensing and Diagnostic Module (SDM) of a 2004 Chevrolet Malibu during high speed yaw testing. Yaw tests were performed using tires that were intact and tires that had the tread removed. The tires that had the tread removed were placed at various wheel positions on the vehicle (e.g. leading side - front, leading side -rear, trailing side - rear). This testing simulates the loss of control phase subsequent to a tread separation. Speeds up to 117 km/h (72.9 mph) were achieved. A simple electro-mechanical device was incorporated to the dynamic testing to simulate a low-severity non-deployment event that triggered the recording of pre-crash data by the SDM. The SDM data from the tests was imaged and compared to reference data from vehicle-mounted instrumentation recording wheel speed, steering angle, measured vehicle sideslip angle and GPS calculated over the ground speed. This paper examines the dynamic effect of high sideslip angles and changes to tire rolling radius, as a result of a tread separation, as it pertains to the accuracy of EDR reported vehicle speed.

Introduction

In 2016, a literature review compiled numerous studies involving EDR pre-crash speed validation testing [1]. Absent from the literature were any studies involving tire tread belt separations.

In 2006, Reust and Morgan tested twelve different General Motors vehicles on a dry, level roadway and compared vehicle reported speed, measured with a Tech 2 scan tool, to VBOX reference instrumentation [2]. Acceleration, deceleration (braking) and yaw conditions were tested with vehicles equipped with intact tires. Reust and Morgan also examined effects of tire wear and the operation of a "space-saving" spare tire. The reduction of rolling radius of the space saving tire resulted in the over-reporting of vehicle speed by the EDR. Reust and Morgan found that in tests in which the vehicle was yawing, the vehicle reported speed underreported the vehicle's true over the ground speed by 3 to 18% at speeds of 30 mph or greater.

In 2008, Reust, et al. tested the performance of Powertrain Control Modules installed in a 2005 Ford Crown Victoria Police Interceptor and a 2007 Ford F-150 [3]. Original equipment sized, inflated tires were used for this testing. These vehicles were tested in steady state operation, acceleration, braking and while yawing. Reust et al. found that in a pure yaw, the PCM-reported vehicle speed underestimated the vehicle's true over the ground speed by 0.02 to 2.9%. In tests that combined braking and yaw, Reust et al. found that the PCM-reported vehicle speed underestimated the vehicle's true over the ground speed by 0.11 to 5.15%.

In 2010, Ruth, et al. examined the accuracy of EDR reported speeds during rotation on low friction surface using a 2009 Ford Crown Victoria with intact tires [4]. Tests were conducted on a skid pad that had been wetted with high capacity sprinklers. Ruth et al. reported discrepancies between the vehicle-reported speed and the vehicle's true over the ground speed. Ruth, et al. concluded that the discrepancy between vehicle over the ground speed and vehicle-reported speed, which are based on wheel speed measurements, for rotating vehicles may be explained by examining sideslip.

The vehicle used in this study was a 2004 Chevrolet Malibu, equipped with the SDM Epsilon airbag control module. The accuracy of EDR data for this vehicle was published in a 2008 study sponsored by the National Highway Traffic Safety Administration (NHTSA), authored by Gabler, et al. [5]. In an offset pole crash test, the pre-crash vehicle speed for this test was found to have an absolute error of 1.1 km/h (0.7 mph), or 2%; 39.7 mph (reference instrumentation) versus 39 mph (EDR reported).

The goal of this study was to examine any effects of tires with the tread removed and high side-slip on the EDR reported vehicle speed.

FIGURE 1 EVOC Test Facility

Test Site

Testing was conducted on September 28, 2018 at the Douglas County (Colorado) Emergency Vehicle Operation Center (EVOC). The test facility includes a test track and several skid pads. The larger of the two skid pads was used and measures 800 by 500 feet. The test pad was generally flat and level, and free of any pavement defects. The pavement was dry at the time of testing. Figure 1 is a photograph of the EVOC test facility. The tire to roadway friction was measured to be 0.766 with four intact tires and 0.488 with four tires with the tread removed.

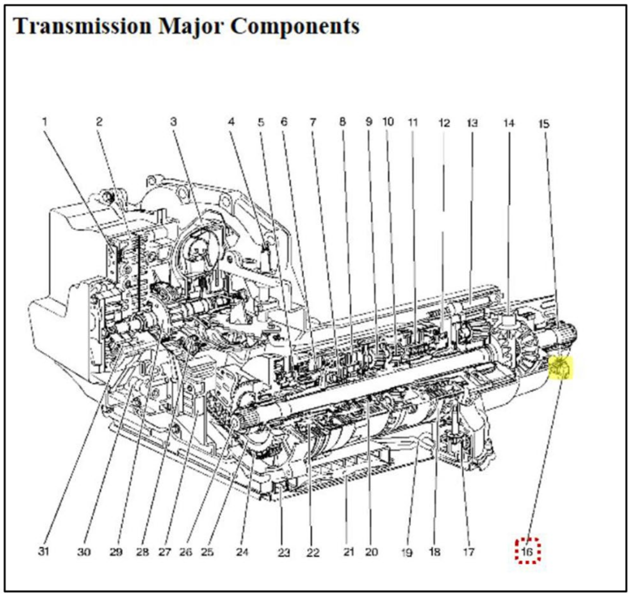
Test Vehicle: 2004 Chevrolet Malibu

The test vehicle was a four-door, 2004 model year Chevrolet Malibu LT (VIN - 1G1ZU54854F135916). The vehicle was equipped with a 3.5-liter, 6-cylinder gasoline engine and a four-speed, front-wheel-drive automatic transmission. Safety features include four-wheel anti-lock brakes and traction control. The Malibu has electric, power-assisted variable-speed rack and pinion steering. The Malibu was equipped with independent front and rear suspension. The vehicle was outfitted with 215/60R16 tires, which match the original equipment size specification. The tires used in this study had been previously driven with relatively low mileage. The airbag control module in this vehicle was an SDM Epsilon. At the time of testing, the vehicle with instrumentation and driver weighed 3,298 lbs (Driver A) and 3,262 lbs (Driver B). The Malibu had a 64% front axle weight distribution. Figure 2 is a photograph of the test vehicle.

The output speed sensor for this vehicle is located on the output of the transmission on the passenger (right) side of the vehicle. The output speed sensor of the vehicle measured the rotation of the half-shaft attached to the right front wheel. Figure 3 is a diagram from the rear of the transmission depicting the location of the output speed sensor (highlighted) on the right side of the vehicle.

FIGURE 2 Test Chevrolet Malibu

FIGURE 3 Vehicle Output Speed Sensor (Image courtesy of Identifix)



Full Scale Vehicle Testing

Instrumentation

The test vehicle was instrumented with the Racelogic VBOX VB20SL3 + data acquisition equipment. The sampling rate was 20Hz. The speed data was not filtered, and the accuracy of the speed data is 0.1 km/h (0.062 mph) averaged over 4 samples. The VBOX recorded yaw, pitch, and roll angles in addition to the vehicle's speed. The Malibu's CAN Interface was connected to the VBOX system which allowed for the recording of wheel speeds, and steering position from the vehicle. Figure 4 contains photographs showing the installation of the VBOX and GPS antennas.

Multiple video cameras were used to document the testing. A video camera was mounted in the vehicle's interior to document the driver. External vehicle-mounted cameras documented the subject tire. Stationary external cameras and cameras from unmanned aerial vehicles were used to document the general motion of the vehicle.

FIGURE 4 Test Chevrolet Malibu: Instrumentation Installation

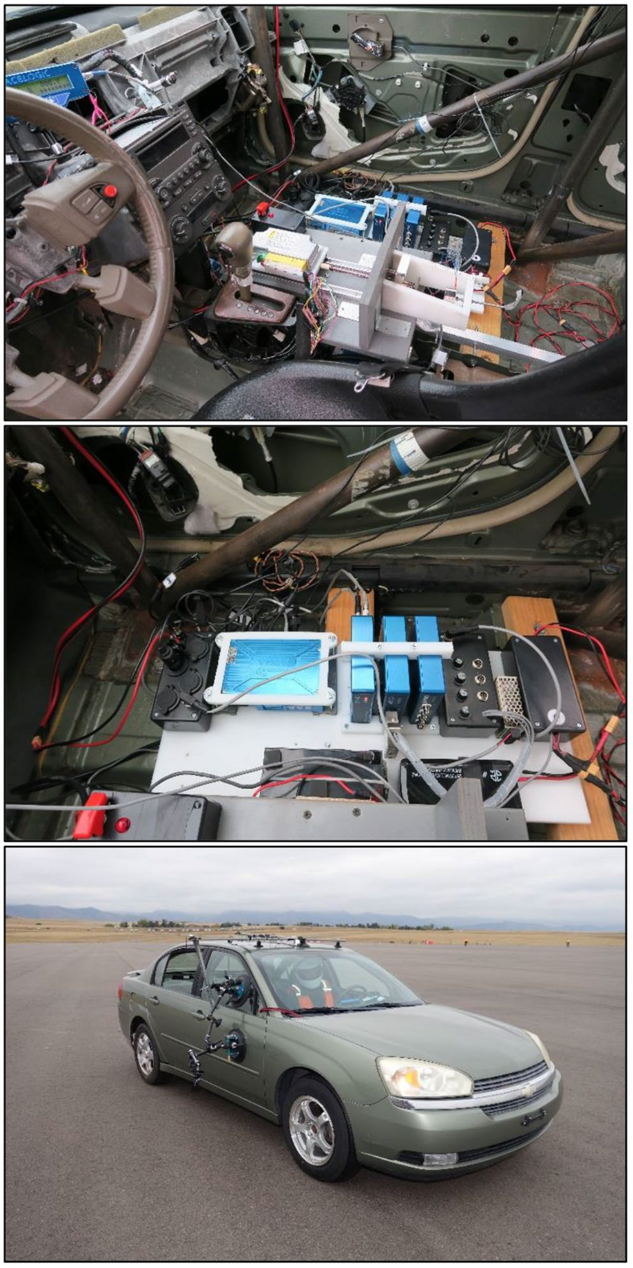
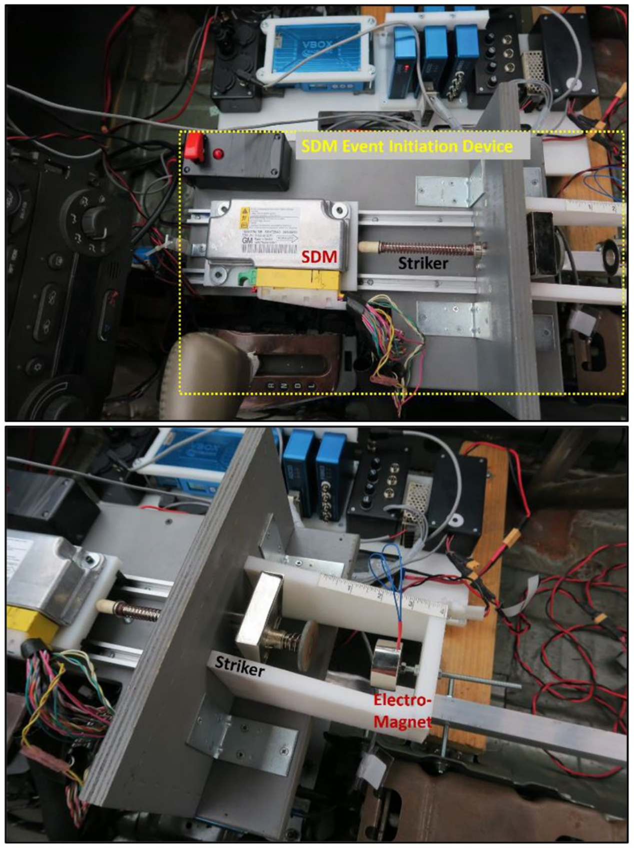


FIGURE 5 Test Chevrolet Malibu: SDM Event Initiation Device



SDM Non-Deployment Event Initiation

A simple electro-mechanical device was used to initiate non-deployment events in the SDM for each test. A spring-loaded striker was used to accelerate the SDM, simulating a low-severity collision. This striker was held in an armed position by an electro-magnet and released with a trigger mounted to the steering wheel. The spring-loaded striker could be armed in position at variable displacements. Figure 5 contains photographs of the SDM event initiation device.

By increasing the displacement of the spring-loaded striker, successive non-deployments of increasing severity could be initiated in such a way that they would overwrite previous non-deployment events stored within the SDM. This allowed for the same SDM to be used for three consecutive test runs.

As seen in Figure 4, some of the interior had been removed from the vehicle to accommodate the roll cage and instrumentation. 3 Ω resistors were installed in the place of any supplemental restraints that had been removed, so the SDM would not generate fault codes during its diagnostic phase. A 12 volt Bosch style relay was wired in conjunction with the frontal collision sensors, mounted to the radiator supports in the front of the test vehicle. The crash sensor relay was wired in parallel with the release for the electro-magnet on the striker in the triggering circuit. Depressing the trigger would simultaneously release the striker and short, or close, the circuit containing the frontal crash sensors.

Between tests, data was imaged from the SDM using the Bosch Crash Data Retrieval (CDR) system. The crash sensor circuit was reset, and any diagnostic trouble codes were addressed and cleared using a scan tool.

Tire Preparation

Cuts were made to the tires so that the tread and top belt could be removed. First, a single cut was made across the tread, diagonally along the belt bias. This cut went through the top nylon belts. The shoulder on both sides of the tire were then cut around the entire circumference. The tread and top belt

FIGURE 6 Tire with tread and top belt removed.

were then pulled off the tire. Preparing the tire in this manner and removing the top belt causes the tire to bulge, or "balloon" out, and increase the unloaded rolling radius of the tire by approximately 6%, and the loaded radius increased by approximately 5%. A 5% increase in rolling radius of the prepared tire would decrease the tire revolutions per mile from approximately 771 to approximately 732.

Figure 6 contains photographs of a prepared tire with the tread and top belt removed.

Test Methodology

In total, five tests were performed in which an SDM triggering event was initiated; four high speed yaw tests and a steady-state baseline test.

For the four yaw tests, the vehicle was steered to the left to develop counterclockwise rotation. The right (passenger) side of the vehicle was on the leading side during a counterclockwise rotation. The tire configuration for the four yaw tests were as follows:

A. All tires intact
B. Prepared tire: Right (leading side) front
C. Prepared tire: Right (leading side) rear
D. Prepared tire: Left (trailing side) rear

The baseline test was conducted with all the tires intact.

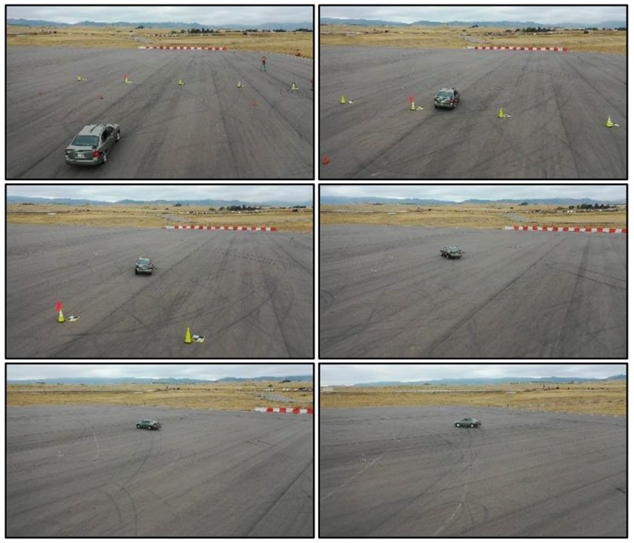
Table 1 summarizes the tests parameters.

In total two SDMs were used during the testing; SDM 1 (Tests A-C) and SDM 2 (Test D, Baseline).

TABLE 1 Summary of Test Parameters

Test: Test Type	Vehicle/Tire Configuration	Driver	Test Speed km/h	Test Speed mph
A: Yaw	All Tires Intact	A	104.8	65.1
B:Yaw	Prepared Tire: Right Front (Leading Side, Front)	B	94.3	58.6
C:Yaw	Prepared Tire: Right Rear(Leading Side, Rear)	B	105.1	65.3
D:Yaw	Prepared Tire: Left Rear (Trailing Side, Rear)	A	117.3	72.9
0: Baseline	All Tires Intact	–	62.9	39.1

FIGURE 7 Yaw Test Dynamics



Yaw Test Procedure

For each of the yaw tests, the vehicle was driven onto the skid pad toward a predefined course as it was brought up to speed. As the vehicle approached a gate identified by a series of cones, the driver input a large left-hand steer. The photographs in Figure 7 depict this maneuver. Appendix A contains the larger versions of the photographs found in Figure 7.

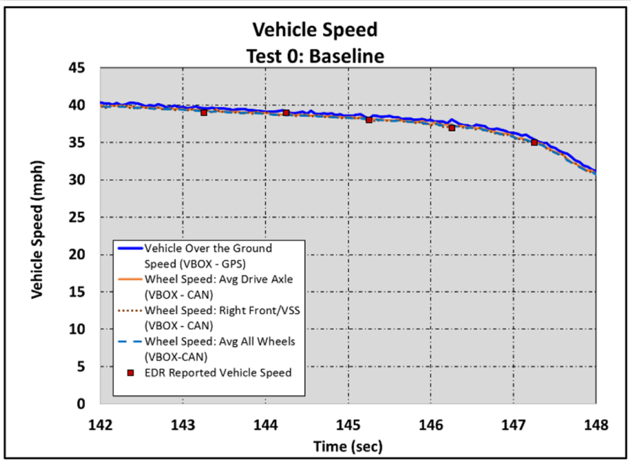
Approximately two seconds after the steering input, the driver initiated a non-deployment event by depressing the trigger; striking the SDM and closing the forward crash sensors.

Test Results

Test 0-Baseline (All Tires Intact)

For analysis of the EDR reported speed, a baseline test was run. The vehicle was equipped with intact tires that matched the original equipment size. The vehicle was accelerated up to

FIGURE 8 Test 0: Baseline - Speed Comparison



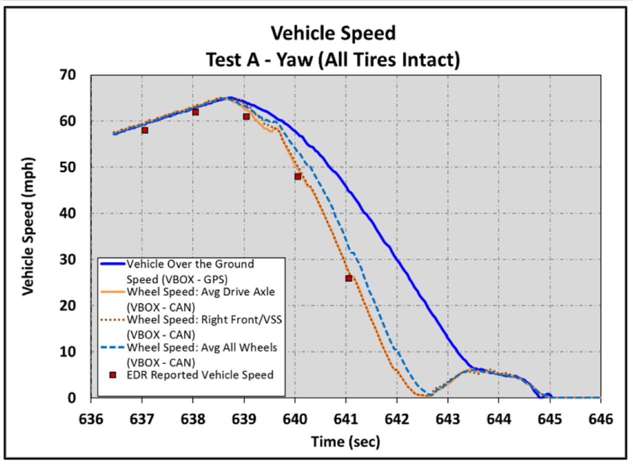
a speed of 40 mph in a straight line and a non-deployment event was initiated. Figure 8 contains a plot comparing the vehicle over the ground speed (reference instrumentation), the wheel speed from the right front tire/vehicle speed sensor, an average of front axle wheel speed measurements, an average of all four wheel speed measurements and the pre-crash vehicle speed data from the EDR. As seen in Figure 8, the vehicle speed from the EDR compared favorably with the reference instrumentation for over the ground speed and wheel speeds broadcast over the CAN.

Test A-Yaw (All Tires Intact)

The first yaw test performed was a test in which all the tires were intact. The vehicle was accelerated to a speed of approximately 65 mph and the driver input a left-hand steer of approximately 215 degrees. As a result, the vehicle rotated in the counter-clockwise direction with rear wheels tracking outside the front wheels. Figure 9 contains a composite aerial image of the vehicle dynamics from Test A. Figure 10 contains a plot comparing the over the ground speed of the vehicle compared to various wheel speeds and the EDR reported pre-crash speed.

FIGURE 9 Yaw Test A: Vehicle Dynamics

FIGURE 10 Test A: Yaw (All Tires Intact) - Speed Comparison



As seen in Figure 10, the wheel speeds and EDR reported pre-crash speed underreported the actual over the ground speed of the vehicle as the vehicle rotated and sideslip was developed. As sideslip angle approached 90 degrees, the wheel speeds approached zero despite an over the ground speed of the vehicle of approximately 20 mph. The EDR reported pre-crash speed compared favorably with the wheel speeds from the right front tire/vehicle speed sensor.

Test B-Yaw (Right Front Tire Prepared)

The second yaw test performed was a test in which the tread was removed from the front tire on the leading (right) side. The vehicle was accelerated to a speed of 59 mph and the driver input a left-hand steer of approximately 220 degrees. As expected, the prepared tire in the right front position resulted in an understeer condition (the vehicle "plowed out"). The large steering input caused the vehicle turn to the left, but vehicle did not rotate to the extent where the rear wheels tracked outside the front wheels. Figure 11 contains a composite aerial image of the vehicle dynamics from Test B. Figure 12 contains a plot comparing the over the ground speed of the vehicle compared to various wheel speeds and the EDR reported pre-crash speed.

As seen in Figure 12, the wheel speeds underreported the actual over the ground speed of the vehicle. Prior to the steering input, the first three EDR reported speeds were underreported by approximately 2 to 3 mph (approximately 3.8 to 6.0%). The final two EDR reported speed samples, which occurred after the large steering input, resulted in underreporting of 5 to 6 mph (9.5 to 10.8%).

Again, the EDR reported pre-crash speed compared favorably with the wheel speed from the right front tire.

FIGURE 11 Yaw Test B: Vehicle Dynamics

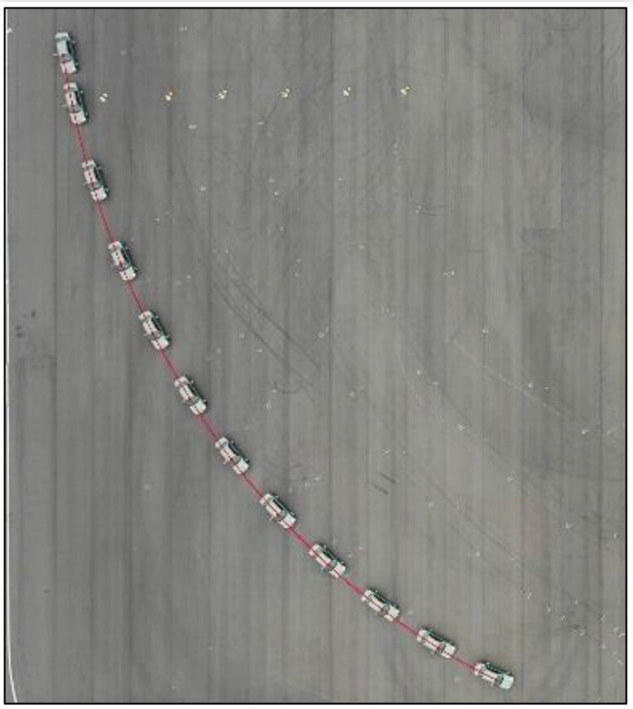
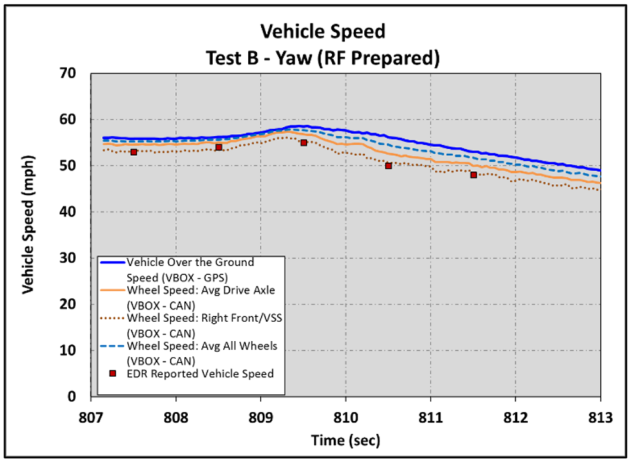


FIGURE 12 Test B: Yaw (Right Front Tire Prepared) - Speed comparison



Test C-Yaw (Right Rear Tire Prepared)

The third yaw test performed was a test in which the tread was removed from the rear tire on the leading (right) side. The vehicle was accelerated to a speed of approximately 65 mph and the driver input a left-hand steer of approximately 215 degrees. As expected, the prepared tire in the right rear position resulted in an oversteer condition. As a result, the vehicle rotated in the counter-clockwise direction with rear wheels tracking outside the front wheels. The vehicle ultimately traveled in reverse to its point of rest. As the vehicle traveled in reverse, the EDR reported positive values for vehicle speed. Figure 13 contains a composite aerial image of the vehicle dynamics from Test C. Figure 14 contains a plot comparing the over the ground speed of the vehicle compared to various wheel speeds and the EDR reported pre-crash speed.

As seen in Figure 14, the wheel speeds and EDR reported pre-crash speed underreported the actual over the ground speed of the vehicle as the vehicle rotated and sideslip was developed. The EDR reported a speed of 57 mph at first sample.

FIGURE 13 Yaw Test C: Vehicle Dynamics

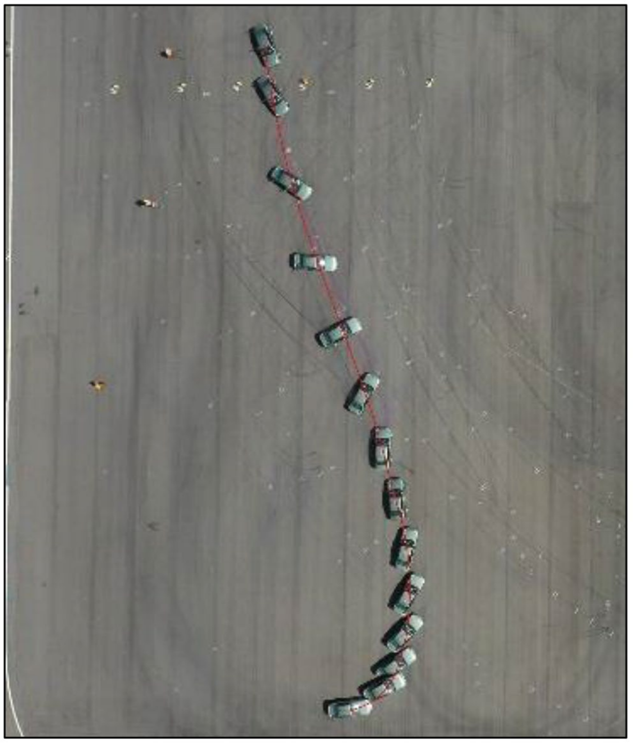
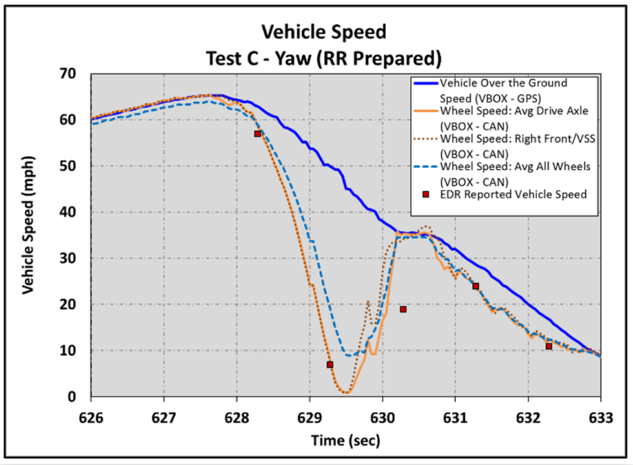


FIGURE 14 Test C: Yaw (Right Rear Tire Prepared) - Speed comparison



The next sample, the EDR reported a speed of 7 mph. This implies a deceleration of 50 mph in one second (>2.2 g). On its surface, this seems impossible for the vehicle to achieve. However, this time interval occurred as sideslip angle approached 90 degrees, the wheel speeds approached zero despite an over the ground speed of the vehicle of approximately 50 mph.

With the exception of a single pre-crash speed sample as the vehicle rotated in excess of 90 degrees sideslip and began traveling in reverse, the EDR reported pre-crash speed compared favorably with the wheel speed from the right front tire/vehicle speed sensor.

Test D-Yaw (Left Rear Tire Prepared)

The final yaw test performed was a test in which the rear tire on the trailing (left) side was prepared to simulate a tread separation. The vehicle was accelerated to a speed of approximately 73 mph and the driver input a left-hand steer of approximately 130 degrees. As a result, the vehicle rotated in the counter-clockwise direction with rear wheels tracking outside the front wheels. The overall vehicle dynamics were similar to Test A. Figure 15 contains a composite aerial image of the vehicle dynamics from Test D.

FIGURE 15 Yaw Test D: Vehicle Dynamics

FIGURE 16 Test D: Yaw (Left Rear Tire Prepared) - Speed comparison

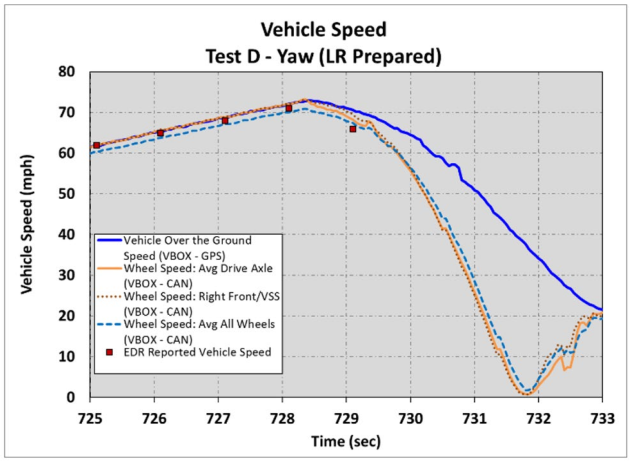


Figure 16 contains a plot comparing the over the ground speed of the vehicle compared to various wheel speeds and the EDR reported pre-crash speed. Unfortunately, the event was initiated early in the yaw sequence and most of the EDR reported pre-crash speeds were reported prior to the vehicle rotating significantly. However, similar trends can be seen in Figure 16 compared to the other tests. As the sideslip of the vehicle approached 90 degrees, the wheel speeds approached zero despite an over the ground speed of the vehicle of approximately 37 mph. The EDR reported speed prior to the steering input compared favorably with the wheel speed data. Subsequent to the steering input, the EDR reported pre-crash speed was underreported, likely due to steering induced sideslip of the front tires.

Analysis

The baseline test indicates that during normal operation, the EDR reported speed is a reliable indicator of the vehicle speed. The EDR reported vehicle speed was slightly underreported the vehicle's over the ground speed by approximately 1 mph or less (approximately 0.5 to 2.9% at 35 to 39 mph). This is consistent with previous literature [1] and appear to be the result of truncation [6].

During the yaw tests, as the vehicle was being accelerated, but prior to the large steering input, the EDR was a reliable indicator of vehicle speed prior to the yaw. While yawing, the EDR underestimated the over-the-ground speed of the vehicle. Front wheel drive vehicles in which the vehicle speed sensor is coupled to a steered tire, like the vehicle involved in this testing, exhibit additional steering contributions at the tire which may also effect the EDR reported speed.

The "Data Limitations" section contained in the EDR report lists factors that will affect the accuracy of the EDR reported vehicle speed. Two of these factors are relevant to this testing:

- Significant changes in the tire's rolling radius
- Wheel slip (sideslip)

As discussed earlier, there was a systematic underreporting of vehicle speed in Test B, the test in which the tire coupled to the vehicle speed sensor had the tread removed and was bulged [7]. This prepared tire was approximately 5% larger in rolling radius compared to intact tires matching the OEM size. As a result, the larger prepared tire would experience a corresponding 5% reduction in revolutions per mile. In Test B, the EDR underreported the vehicle's over the ground speed by a similar percentage, as seen in Figure 12.

Figure 17 through Figure 20 contain plots in which calculations have been performed to determine the longitudinal vehicle speed (the speed parallel to the vehicle heading) and longitudinal steered tire speed (the speed parallel to the tire heading) based on the VBox reported over the ground speed and reconstructed vehicle sideslip. As seen in these plots, by considering the effects of sideslip, the EDR reported pre-crash speed compared favorably to the longitudinal tire speed. For Test B, a calculation was also performed to adjust for the tire size change, as seen in Figure 18.

FIGURE 17 Test A: Speed Calculations Considering Slip vs. EDR Reported Speed

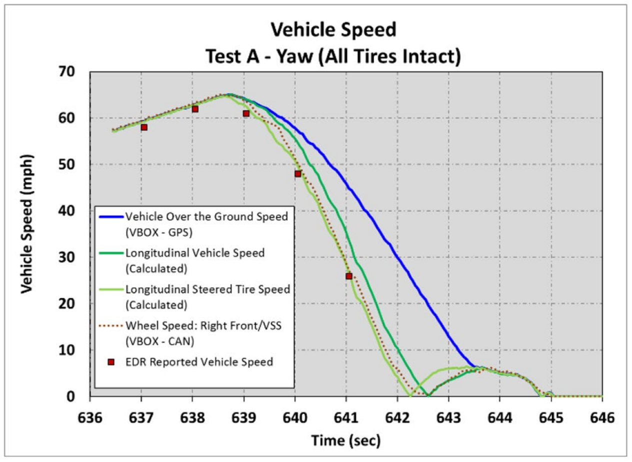


FIGURE 18 Test B: Speed Calculations Considering Slip vs. EDR Reported Speed

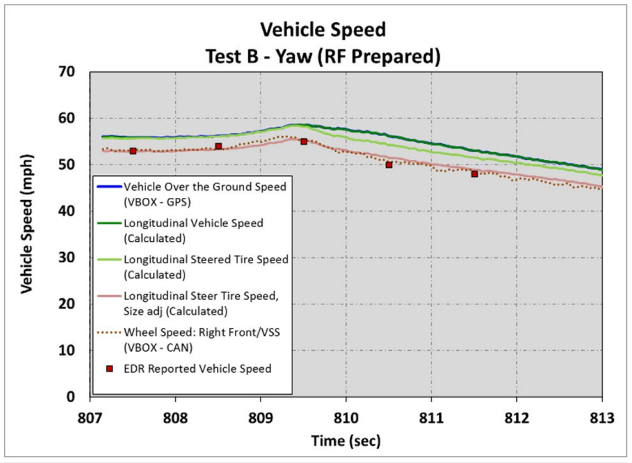


FIGURE 19 Test C: Speed Calculations Considering Slip vs. EDR Reported Speed

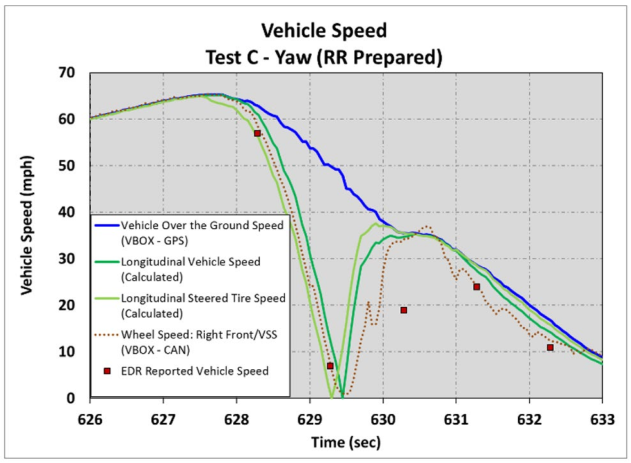
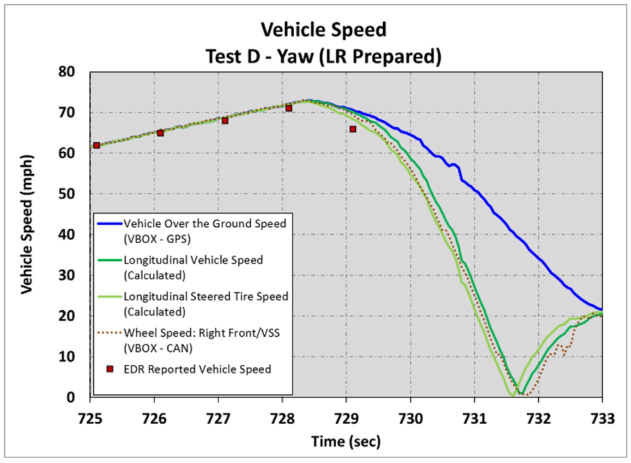


FIGURE 20 Test D: Speed Calculations Considering Slip vs. EDR Reported Speed



Longitudinal speed of the right front (steered) tire is calculated by equation 1:

$$S_l = S_o * \cos(\alpha + \delta) \tag{1}$$

Where

S_l is the speed of the vehicle along it's longitudinal axis,

S_o is the speed over the ground of the vehicle with respect to the path of the center of gravity,

α is the vehicle side-slip angle, and

δ is the steering angle of the steered tire/axle.

S_o, α and δ were recorded by the VBOX GPS antenna.

As $(\alpha + \delta)$ approaches 90 degrees the longitudinal speed approaches zero. This is reflected in the EDR data recording a near zero speed in Figure 19.

Discussion

The vehicle speed reported by EDR's is recorded by output shaft speed sensors and individual wheel speed sensors - devices that sense the rotation rate (e.g. of a transmission output shaft or axle) by measuring pulses per unit time of that rotating object. From this rotational speed, longitudinal wheel speed can be calculated based on the radius of the tire. It is this longitudinal wheel speed that is reported by the EDR as vehicle speed.

Under normal steady-state vehicle operation (i.e. negligible slip, $(\alpha + \delta) \sim 0$), the longitudinal wheel speeds are equal to the over-the-ground speed of the vehicle. Under these circumstances, the EDR reported vehicle speed is a reliable indicator of vehicle speed. This is also true for the initial speed of a vehicle prior to a yaw.

As vehicle sideslip develops during a yaw, the longitudinal wheel speeds and the over-the-ground speed of the vehicle diverge. The longitudinal wheel speeds of the front wheels can also be affected by steering.

When considering EDR data within the context of a crash investigation or reconstruction, vehicle sideslip angle must be considered. In the case of high sideslip after a loss of control, the authors recommend the following procedure when incorporating EDR data into the reconstruction of a crash:

1. Reconstruct the speed of the vehicle, using the physical evidence and all other available data, starting from the rest position and working back to the start of physical evidence. This process will typically yield speeds at several positions at different times defined by the physical evidence.
2. Calculate the longitudinal speed of the vehicle at each position based on the sideslip angle.
3. Plot the reconstructed longitudinal speed of the vehicle versus time for the vehicle positions.
4. Verify that the vehicle was equipped with OEM-sized tires. If the tires on the vehicle at the time of the crash are different than OEM sized, or EDR calibration, correct the EDR-reported speeds for the actual tire size.
5. Plot the speeds from the EDR on the same graph as the reconstructed longitudinal speeds.
6. Align the reconstructed longitudinal speed to EDR-reported data, in time, until there is a reasonable agreement between the two data sets.

Some front wheel drive vehicles, like the Malibu used in this study, the EDR may rely on a front wheel speed for monitoring vehicle speed. Under these conditions, increased accuracy may be achieved by estimating the magnitude of any steering contributions to front tire slip angles. Many modern EDRs are capable of reporting steering inputs that can be used for this purpose. If the documentation of the physical evidence allows, steering inputs may also be reconstructed based on striation angle [8, 9]. If this is the case, increased accuracy may be achieved by modifying step 2; reconstruct the longitudinal speed of the front wheels using equation 1. Use this reconstructed front wheel longitudinal speed for comparison to the EDR speed in the remaining steps.

Changes in rolling radius of a tire, if the rotational speed of that tire is being monitored by the EDR, is inversely proportional to accuracy effects. If the subject tire is 5% larger than the baseline tire, the tire's revolutions per mile will decrease by 5% and the EDR will underreport speed. Conversely, smaller tires will result in an increase of revolutions per mile and therefore overreport speed.

Conclusions

1. EDR reported vehicle speed is a reliable indicator of a vehicle's over-the-ground speed when side slip is negligible; during straight line driving or at the onset of an event if the EDR speed samples correlate to a point in time to prior to high side-slip condition (i.e. the beginning of a crash event, prior to a loss of control).
2. The EDR will underreport a vehicle's over-the-ground speed during a yaw. The magnitude of underreporting increases as the total slip of the tire(s) being monitored by the speed sensor approaches 90°.
3. Changes in a tire's rolling radius is inversely proportional to accuracy effects. In this case the tire tread detachment caused the tire to bulge. This bulging increased the rolling radius of the tire, decreased the number of revolutions per mile and caused the EDR to underreport the vehicle's over-the-ground speed. Intact, oversized tires would have same effect.

This data presented in this paper was limited to one vehicle over the four tests. However, the findings in this paper were consistent with the findings of Reust [2, 3] and Ruth [4] for similar testing involving yawing vehicles, and general vehicle dynamics [10].

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Appendix A

FIGURE 21 Yaw Test Dynamics

FIGURE 22 (Continued) - Yaw Test Dynamics

FIGURE 23 (Continued) - Yaw Test Dynamics

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