

Accuracy of Event Data in the 2010 and 2011 Toyota Camry During Steady State and Braking Conditions

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ABSTRACT

Independent verification of the accuracy of data from Event Data Recorders (EDRs) is useful when using the information to help reconstruct a crash. To this end, the accuracy of the EDR function of the Airbag Control Module (ACM) was tested on 2010 and 2011 Toyota Camry sedans during straight line operation. During steady state operation, and maximum ABS-braking runs starting from approximately 80 km/h (50 mph), and 113 km/h (70 mph), non-deployment events were artificially induced to store event data. Following each run, the EDR was imaged using the Bosch Crash Data Retrieval (CDR) system. The CDR reported speed values were compared to Racelogic VBox differential GPS speed records. Data recorders were also used to monitor the vehicle Controller Area Network (CAN) bus traffic, including the indicated speed, brake pressure, engine RPM, and accelerator pedal position. The speed and RPM reporting algorithms stated in CDR Data Limitations were confirmed. Exemplar graphs of EDR-reported speed/brake/RPM/accel pedal data versus GPS speed and CAN bus data are presented and discussed. The timing of the reported data with respect to the event is also discussed. The difference between vehicle speed recorded by the EDR and the GPS speed during steady state operation varied from +0.4 to -2.3 km/h, with the EDR typically reporting lower than the GPS. During heavy braking the difference in speed was observed to be from -7 to +15 km/h, with wheel slip causing negative differences, and time delay since the last CAN bus update causing positive differences.

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INTRODUCTION

While the Bosch Crash Data Retrieval (CDR) Tool has been publicly available since 2000 (first built and sold by Vetronix) and has historically provided access to General Motors, Ford and Chrysler line vehicles, the ability to access data which may be found in Toyota vehicles was only added to the tool's capabilities in 2011 (starting with CDR software version 4.0). With that public release, independent testing of Toyota event data recorder (EDR) data such as that reflected in this paper became possible. Prior to that, the only way to recover Toyota EDR data was to use the internal, proprietary Toyota EDR "Read Out Tool" (ROT).

Toyota began to phase in event data recording capabilities with precrash speed data in some 2001 and later models. In the Toyota Camry, the event data recorder function is housed in the airbag control module (ACM). Toyota EDR's in production as of this writing are either Generation 1 which includes 00EDR and 02EDR styles, or Generation 2 which includes 04EDR and 06EDR styles. The data recorded varies with generation. The 2010 and 2011 Camrys are equipped with the second generation 04EDR-style ACM.

According to the Data Limitations of the CDR software, the 04EDR ACM records brake status, accelerator pedal position, engine RPM, vehicle speed, and other status switches. The Data Limitations documentation also explains that some of the information stored in the airbag control

module comes from the vehicle's Controller Area Network (CAN) bus. As such, the analysis of CAN data is an important aspect of assessing accuracy of the stored data. Since a CAN may be asynchronous, timing information for the various signals is also of interest.

The remainder of the paper is structured as follows. A literature review gives some background, context, and precedent for the research. Following the review, some theory of operation is explained. A detailed testing procedure is described for the tests conducted on two Toyota Camry sedans. Following the procedure, the data is presented and discussed in four sections: 1) CAN bus data, 2) steady-state vehicle speed data, 3) speed during heavy braking, 4) theoretical vehicle speed difference, 5) speed message timing, 6) timing from trigger to first data point, and 7) other ACM recorded precrash values. Finally, a summary with concluding remarks is given.

LITERATURE REVIEW

While the CDR tool help file and the Data Limitations section in CDR reports contain useful information about accuracy limitations, actual test data is needed to quantify it. EDR precrash speed data was first recorded by General Motors beginning with some 1999 models and the first paper to address precrash EDR speed data accuracy was by Chidester in 1999 [1]. Chidester's team included General Motors personnel, and the paper listed the accuracy of speed as $\pm 4\%$. This paper was written before the start of 1999 model-year production, and the 4% articulated a design tolerance that could include tread wear, tire pressure variations, and other design variations. Test data was not yet available. The paper noted that the various data elements were recorded asynchronously, raising the issue that the timing labels associated with precrash data may not be precise regarding when the data was actually recorded. Data points labeled “-1” may actually be recorded any time during the second before algorithm enable (AE).

In 2003, Lawrence created artificial crash signals during normal driving and published data finding the GM EDR speed to be under reported by 1.5 kph (about 1 mph) at low speeds and over reported by 3.7 kph (about 2.3 mph) at high speed when compared to reference instrumentation, under steady state conditions [2]. This paper raised the issue that differences between recorded speed values and speeds obtained with external instruments may have some relationship to vehicle speed.

In 2005, Niehoff reported the recorded pre-crash speed from NHTSA crash tests of GM, Ford, and Toyota vehicles [3]. This was the first known publication of any Toyota EDR accuracy. Only one Toyota model was equipped with an EDR that could record precrash speed data that could be read, a 2004 Toyota Sienna from NHTSA Test #4846. The measured impact speed was 56.6 km/h (35.2 mph), while the EDR recorded 56 km/h (34.8 mph). The Sienna used the first

generation Toyota EDR and the data was read by a proprietary Read Out Tool (ROT).

In 2006, Wilkinson reported on the timing of EDR data in General Motors sensing and diagnostic modules, indicating that the actual time between labeled data points may vary from the interval suggested by the labels [4]. In 2011, Bare reported on precrash data timing of the GM SDM-DS module, indicating that the timing of the last data point recorded can vary from the label “-1” that is placed on that last data point [10]. This work addresses some of the same type of timing issues as Wilkinson but used more sophisticated instrumentation and was on a more recently designed EDR. Bare, et al also suggested that data timing was far closer to the reported “1 second” interval than reported by Wilkinson.

In 2008, Gabler reported on a number of NHTSA tests [5]. The only Toyota test for which a speed was reported was NHTSA Test #5269. It was a 56.3 km/h (35.0 mph) frontal barrier test of a 2005 Toyota Sienna (00/02 EDR). Gabler reported the EDR-recorded speed to be 54 km/h (33.8 mph). Data was obtained using the Toyota ROT.

Takubo and Ishikawa et al reported on Japanese New Car Assessment Program (NCAP) tests and additional tests intended to mimic real world crashes [6, 7, and 8]. They published two SAE papers and one Enhanced Safety of Vehicles (ESV) paper, with each successive paper including some additional tests. As such, the most complete data set as of this writing can be found in the latest, though the earlier papers contain some minor details which are not reproduced in the most recent paper. They reported that the cars were mostly 2007 and 2008 Toyota Corollas (00/02 EDR), and that “the pre-crash velocities [reported by the] EDR were highly accurate and reliable but generally lower than the optically derived velocities.” EDR speed records from 14 full overlap barrier tests were averaged and a percent difference was calculated from reference instrumentation. The average of the EDR speed data was -2.0% different than the reference instrumentation, with a range of -6.3 to $+1.9\%$, and an RMS of 2.6% . For the 14 Offset Deformable Barrier (ODB) tests, the EDR averaged -2.1% different than the reference instrumentation, with a range of -4.1% to 0.0% and an RMS of 2.7% . The negative average value is consistent with the CDR Data Limitations which state the speed data is truncated to the next lower even km/h value.

In 2010, Ruth reported on the accuracy of the 2009 Ford Crown Victoria Powertrain Control Module (PCM) EDR in steady state and heavy braking [16]. The Crown Victoria vehicle speed sensor is on the transmission output shaft, and during heavy ABS controlled braking wheel slip results in the speed being under reported by an average of 5% at 97 km/h. This recognized that the vehicle indicated speed on the speedometer or CAN bus obtained may not represent the true speed of the vehicle center of mass under heavy braking conditions.

In 2011, NHTSA conducted an evaluation of Toyota pre-crash data accuracy [9]. The paper reports 28 staged events using two 2007 Camrys (04/06 EDR) and a 2008 Highlander (04/06 EDR) as bullet vehicles striking the back of a 2006 Tacoma (00/02 EDR) target vehicle with a 3 to 8 km/h (2-5 mph) closing speed in order to create a nondeployment event the EDR would capture. NHTSA defined the vehicle speed tolerance as ± 2.3 km/h (1.5 mph), and was aware that the recorder temporary buffer only refreshed speed data every 0.5 seconds. Around each EDR data point they created a “window of acceptance” of ± 2.3 km/h (1.5 mph) that extended back in time 0.5 seconds. If the GPS speed data crossed anywhere in the window, then it was deemed within the acceptable tolerance. NHTSA concluded that 100% of the precrash speed data fell within the tolerance and time window. The ± 2.3 km/h window was wider than the ± 0.2 km/h range expected from the data resolution cited in the CDR Data Limitations. Data was read using the ROT tool.

In 2011 Comeau reported on Toyota crash tests conducted by Transport Canada, comparing their measured impact speed to the EDR-recorded speed “at -1 s”, just prior to the impact [11]. They compiled data from 14 full frontal rigid barrier tests at 40, 48, and 56 km/h (25, 30 and 35 mph). The models tested included 3 from 2005 Camry (00/02 EDR), 5 from 2009-10 Corolla (00/02 EDR), 5 from 2009 Toyota Matrix (00/02 EDR), and 1 from a 2009 Venza (04/06 EDR). They showed that the EDR-reported speed ranged from 0.2 km/h higher than measured to as much as 2.27 km/h below the measured speed, with the reported speed consistent with the recording resolution of the next lower even km/h stated in the CDR Data Limitations. Data was obtained using the Toyota ROT.

This research contributes by testing over a wider range of speeds, gathering a larger sample size of events, checking both EDR data and its CAN bus data source versus differential GPS reference instrumentation, and by evaluating how CAN message timing and data refresh rates may affect accuracy. This research is limited to a single model.

THEORY OF OPERATION

Toyota uses the average of the two drive wheel speed sensors to calculate a vehicle speed in either the ABS or VSC module, which is then transmitted on the data bus. The transmitted speed is subsequently picked off the bus. Some airbag control modules decode this data and store it at some frequency and resolution. Therefore, the accuracy of speed data from an EDR depends on the accuracy of the signal sent over the data bus. This means that the EDR recorded speed signal can be no more accurate than the broadcast speed signal in terms of frequency and resolution.

The EDR within the ACM draws data from the vehicle's CAN bus. A Controller Area Network was invented by Bosch in the 1980s to be a robust and efficient method for communicating in harsh automotive environments. It is a multi-master implementation where message arbitration is

automatic based on the priority of the message identifier. Due to the arbitration scheme, some messages can be deferred to the next available opportunity if higher priority messages are present. The Toyota Camry uses an 11-bit ID at 500 kbps. The following messages are recorded by the ACM: indicated vehicle speed (0x610), accelerator pedal position (0x2C1), engine RPM (0x2C4), and brake switch status. The indicated vehicle speed value was found to update at a nominal rate of 2 Hz. The accelerator pedal position is also updated every 512 ms. The engine RPM is updated every 24 ms (42 Hz). The brake switch updates on change. In addition to those ID's monitored and recorded by the EDR, the CAN bus data includes four individual wheel speeds, brake pressure, and other parameters. Further details on collecting and interpreting CAN bus data from the 2010 Toyota Camry can be found online at <http://tucrrc.utulsa.edu/ToyotaCAN.html>.

According to the CDR Data Limitations, indicated vehicle speed is rounded down to the nearest 2 km/h. The speed is recorded in six intervals: one value is sampled approximately concurrent with an event trigger (indicated as “0.0 seconds”), the next chronologically older buffered value prior to that (indicated as “ $-0.x$ seconds prior to the trigger”), and four data sets stored at one-second intervals prior to that ($-1.x$, $-2.x$, $-3.x$, and $-4.x$ seconds prior to the trigger). The value of x is rounded down to the nearest 0.1 seconds.

The 2010/11 Camry CDR Data Limitations state the upper limit for the recorded vehicle speed is 122 km/h (75mph). This research evaluated accuracy at speeds up to 113 km/h (70 mph) and does not address accuracy over 122 km/h (75 mph).

DATA COLLECTION PROCEDURE

Two Toyota Camrys were tested, one each from 2010 and 2011 model years. The 2010 and 2011 Camry sedans tested were equipped with second generation modules, capable of storing up to two frontal and two lateral events per report. As indicated by looking at the “System Status at Time of Retrieval” in the CDR report, the Camrys tested had the “04EDR” variant. These ACMs are capable of recording precrash data for both deployment and non-deployment events. Given that the modules in the test vehicles may store up to two frontal and two side events, during each test run, two attempts to trigger an event were made.

One of the authors observed a Toyota representative demonstrate a procedure to set a non-deployment event as follows: remove enough of the central dashboard panels to access the airbag ECU from the rear. Loosen the module's three hold-down bolts and pull the module rearward to create some slack between the module and the bolts. Place the end of a steel rod on the case of the module, and when a non-deployment event is desired, strike the other end of the rod with a hammer. For this research, the procedure was modified slightly to reduce the possibility of an unintended deployment: a wooden dowel and a rubber mallet were used. This procedure worked reasonably well, triggering either a

longitudinal or lateral event more often than not, and often triggering both at the same time. Not all mallet strikes resulted in triggering an event. No deployment events were triggered. The passenger manipulated the rod and the mallet to trigger recordings as the driver created the desired test conditions.

Two test series were conducted. The first test series evaluated a 2011 Camry, bearing VIN 4T1BF3EK1BUxxxxxx, a front wheel drive vehicle with a 2.5L 4 cylinder engine, 6 speed automatic transmission, and P215/60R16 tires. It was instrumented with a differential GPS Racelogic VBox SL20 to both record GPS-based speed and act as a data acquisition system for CAN data. For this test series the data acquisition system gathered accelerator pedal position, brake pressure, RPM, and 3 individual wheel speeds - the CAN bus vehicle speed signal was not yet identified. An auxiliary brake switch was taped to the brake pedal.

The second test series evaluated a 2010 Camry, bearing VIN 4T1BF3EK1AUxxxxxx, also front wheel drive with a 2.5L 4 cylinder engine, 6 speed automatic and P215/60R16 tires. It was instrumented with a differential GPS VBox-3i from Racelogic. An external Racelogic Inertial Measurement Unit (IMU) was mounted near the centerline of the car, just behind the center of mass. The VBox specifications claim accuracy of ± 0.1 km/h when averaged over 4 samples. For the 2010, all CAN bus communications were recorded in synch with the VBox file using a Dearborn Group Gryphon S3 [12] and Hercules software [13] over a wireless link. The data was buffered and saved on a host computer as a comma separated value (CSV) file. The data was imported into Excel for further analysis. Analyzing the Gryphon data permitted identifying the vehicle speed CAN bus channels which were then added to the VBox data acquisition system inputs in later runs.

During one series of tests in the 2010 Camry, an external accelerometer was mounted to the ACM case to provide a convenient trigger-event indicator in the VBox file. The mallet strike typically affected 3 or 4 acceleration data points in 100 Hz file. For analysis purposes, the first affected data point was used as the zero point for indexing the EDR file to the VBox data.

Test runs were conducted by accelerating from a stop to the intended speed and holding steady speed before pulling onto the paved shoulder and braking firmly to a stop, invoking ABS. A rapid accelerator pedal input followed by a brake pedal tap was conducted just prior to recording an event to help with data synchronization. Events were triggered during the steady state travel and during the hard brake event.

DATA ANALYSIS AND DISCUSSION

CAN BUS DATA

For the 2010 model tests using the 100 Hz VBox 3i, a number of data elements pertaining to vehicle operation were identified in the CAN bus stream, including four wheel speed sensors, the ECU-reported vehicle speed, engine speed, brake pressure, steering wheel position, and accelerator pedal.

Each of the four wheel speed sensors updated on the CAN bus at 100 Hz. Recalling that this was a front-wheel-drive car, the signals from front and rear wheels would be expected to vary differently, depending on whether the vehicle was accelerating (causing overspeed slip on just the front wheels) or braking (causing slip on all four wheels, reflecting slower than actual speed). The front and rear signals were, in fact, observed to vary as expected. The additional testing necessary to isolate left and right data was not conducted. The vehicle speed sensor signal should be proportional to the average of the two drive (front) wheel speeds. Individual wheel speeds were monitored to understand the ABS function during hard braking.

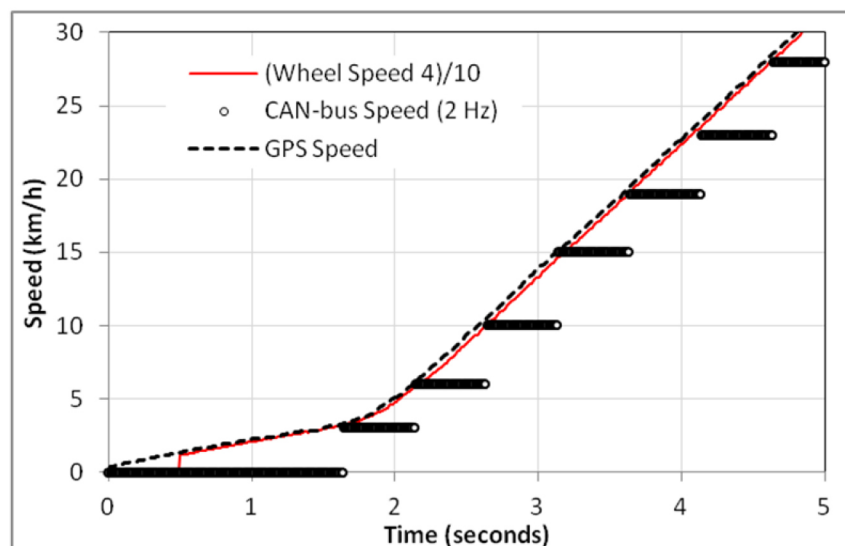


Figure 1. CAN bus vehicle speed and data from a rear wheel speed sensor during firm acceleration.

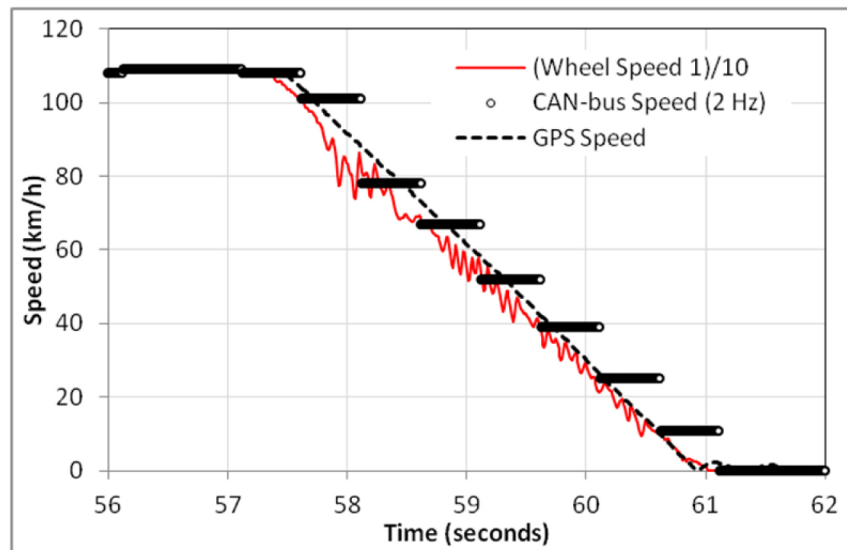


Figure 2. CAN bus vehicle speed and data from one front wheel speed sensor during ABS-braking on dry pavement.

In addition to 100 Hz wheel speed data, the CAN bus carried a 2 Hz speed element found in message 0x610. [Figure 1](#) shows one of the rear wheel speed data elements along with the 2 Hz speed data from the CAN bus and the GPS-based speed during firm acceleration of about 0.35 g (Run 28, TGR 52). [Figure 2](#) shows the 2 Hz speed data from the CAN bus, a front wheel speed data element from the CAN bus and the 100 Hz GPS derived vehicle speed during ABS-invoked braking. The front wheel speed shows 10-14 Hz speed cycling resulting from the cycling of hydraulic pressure in the ABS system.

Note: The CAN bus speed, represented in the legend by circles, comes out as a heavy horizontal bar when graphed because it is overlaying one circle over another over another, with the actual circle visible only at the right edge of the bar. The speed was first received at the left edge of the heavy horizontal bar (the same is true for [figures 2, 3, 5, 7, 8 and 9](#) that follow).

STEADY STATE VEHICLE SPEED

The Data Limitations section in version 4.3 of the Bosch CDR software states, “Resolution is 2 km/h (1.2 mph) and the value is rounded down and recorded.” Six nominally steady-speed tests were conducted with the 2010 Camry at each of two speeds: 80 and 113 km/h. [Figure 3](#) shows an example of one such test conducted at a nominal speed of 113 km/h (Test 21, TRG 30). The 2 Hz speed element from the CAN bus was observed to be always reported as a whole number (not necessarily an even whole number). The EDR-recorded speed was observed to be the next lower even whole number, consistent with the 2 km/h resolution cited in the CDR Version 4.3 Data Limitations for this test vehicle. Where the GPS speed in km/h was close to a whole number at the

moment the CAN bus updated the 2 Hz signal, the reported value was often within 0.1 km/h of the GPS speed.

The difference between the GPS-speed and the EDR-recorded speed was calculated for all steady-state test EDR data points where the brake was not engaged. [Figure 4](#) shows the difference as a function of GPS-speed.

For the 2011, steady state runs were made at nominal speeds of 48, 64, 80, 97, and 113 km/h (30, 40, 50, 60 and 70 mph). A best fit line was calculated for the data, $y = -0.0103x + 0.6244$, with the negative slope indicating the difference grew more negative at higher speeds. The average difference at 48 km/h (30 mph) was -1.1 km/h (-0.7 mph) with a range of 0 to -1.9 km/h (0 to -1.2 mph), and the average difference at 113 km/h (70 mph) was -1.8 km/h (-1.1 mph) with a range of -0.4 to -3.0 km/h (-0.2 to -1.9 mph). The differences for speeds in between 48 and 113 km/h (30 and 70 mph) are shown in [Figure 4](#). No EDR data points overestimated the speed.

For the 2010, steady state runs were made at nominal speeds of 80 and 113 km/h (50 and 70 mph). For the 80 km/h nominal tests, the average difference was -0.61 km/h (-0.4 mph) with a standard deviation of 0.63 km/h (0.4 mph). The average difference for the 113 km/h (70 mph) tests was -0.85 km/h (-0.5 mph) with a standard deviation of 0.67 km/h (0.4 mph). The best fit line is $y = -0.0062x - 0.1367$.

When analyzing data by fitting a line, the value of the slope may be non-zero only due to the randomness of the observed data. To test this hypothesis, a statistical T-test can be performed on the slope of the best-fit line. The null hypotheses for this test is that the slope = 0, which means there are no measureable differences based on vehicle speed. The null hypothesis should be accepted if the T statistic is less than the critical T value.