THE POTENTIAL OF EVENT DATA RECORDERS TO IMPROVE IMPACT INJURY ASSESSMENT IN REAL WORLD CRASHES

Ada Hei-dat Tsoi

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Hampton C. Gabler
Stefan M. Duma
Andrew R. Kemper
Joel D. Stitzel
Pamela J. VandeVord

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ABSTRACT

Event data recorders (EDRs) are an invaluable data source that have begun to, and will increasingly, provide novel insight into motor vehicle crash characteristics. The “black boxes” in automobiles, EDRs directly measure precrash and crash kinematics. This data has the potential to eclipse the many traditional surrogate measures used in vehicle safety that often rely upon assumptions and simplifications of real world crashes. Although EDRs have been equipped in passenger vehicles for over two decades, the recent establishment of regulation has greatly affected the quantity, resolution, duration, and accuracy of the recorded data elements. Thus, there was not only a demand to reestablish confidence in the data, but a need to demonstrate the potential of the data. The objectives of the research presented in this dissertation were to (1) validate EDR data accuracy in full-frontal, side-impact moving deformable barrier, and small overlap crash tests; (2) evaluate EDR survivability beyond regulatory crash tests, (3) determine the seat belt accuracy of current databases, and (4) assess the merits of other vehicle-based crash severity metrics relative to delta-v.

This dissertation firstly assessed the capabilities of EDRs. Chapter 2 demonstrated the accuracy of 176 crash tests, corresponding to 29 module types, 5 model years, 9 manufacturers, and 4 testing configurations from 2 regulatory agencies. Beyond accuracy, Chapter 3 established that EDRs are anecdotally capable of surviving extreme events of vehicle fire, vehicle immersion, and high delta; although the frequency of these events are very rare on U.S. highways. The studies in Chapters 4 and 5 evaluated specific applications intended to showcase the potential of EDR data. Even single value data elements from EDRs were shown to be advantageous. In particular, the seat belt use status may become a useful tool to supplement crash investigators, especially in low severity crashes that provide little forensic evidence. Moreover, time-series data from EDRs broadens the number of available vehicle-based crash severity metrics that can be utilized. In particular, EDR data was used to calculate vehicle pulse index (VPI), which was shown to have modestly increased predictive abilities of serious injury compared to the widely used delta-v among belted occupants. Ultimately, this work has strong implications for EDR users, regulatory agencies, and future technologies.

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List of Abbreviations

AAAM	Association for the Advancement of Automotive Medicine
AACN	Advanced Automatic Crash Notification
AASHTO	American Association of State Highway and Transportation Officials
ACM	Airbag Control Module
AIC	Akaike Information Criterion
AIS	Abbreviated Injury Severity
AR	Agreement Rate
ASI	Acceleration Severity Index
ATD	Anthropomorphic Test Device
AUC	Area Under the Curve (of the receiver operator characteristic)
CAN	Controller Area Network
CDR	Crash Data Retrieval
CEN	European Committee for Standardization
CFC	Channel Frequency Class
CG	Center of Gravity
delta-v	Change in vehicle velocity
EBS	Equivalent Barrier Speed
EDR	Event Data Recorder
EES	Equivalent Energy Speed
ES-2re	EuroSide2 with Rib Extensions
ETS	Equivalent Test Speed
EUROCAE	European Organization for Civil Aviation Equipment
FARS	Fatality Analysis Reporting System
FEMA	Federal Emergency Management Agency
FMVSS	Federal Motor Vehicle Safety Standard
FSM	Flail Space Model
GAD	General Area of Damage
GIT	Global Information Technologies
GM	General Motors
HL	Hosmer-Lemeshow test
HIC	Head Injury Criterion
IIHS	Insurance Institute for Highway Safety
ISO	International Organization for Standardization
kph	Kilometers Per Hour
MAIS	Maximum Abbreviate Injury Severity
MASH	Manual for Assessing Safety Hardware
MDB	Moving Deformable Barrier
mph	Miles Per Hour
MY	Model Year
NASS-CDS	National Automotive Sampling System - Crashworthiness Data System
NCAP	New Car Assessment Program
NCHRP	National Cooperative Highway Research Program

NHTSA	National Highway Traffic Safety Administration
NMVCCS	National Motor Vehicle Crash Causation Survey
OBD-II	Onboard Diagnostic Port
OEM	Original Equipment Manufacturer
OIV	Occupant Impact Velocity
ORA	Occupant Ridedown Acceleration
Part 563	Title 49 Code of Federal Regulations Part 563
PDOF	Principal Direction of Force
PHD	Post-impact Head Deceleration
PSU	Primary Sampling Unit
RMDB	Research Moving Deformable Barrier
RMS	Root Mean Square
ROC	Receiver Operator Characteristic
SAE	Society of Automotive Engineers
SDM	Sensing and Diagnostic Module
SDOF	Single Degree of Freedom
SID	Side Impact Dummy
SIR	Supplemental Inflatable Restraint
SINCAP	Side Impact New Car Assessment Program
SISAME	Structural Impact Simulation and Model Extraction
THIV	Theoretical Head Impact Velocity
VPI	Vehicle Pulse Index
VSR	Vehicle Safety Research

1 INTRODUCTION

The retrospective assessment of passenger vehicle crashworthiness in the real world relies upon the analysis of crash outcomes, currently determined by physical investigation of the post-crash vehicle. For instance, the maximum vehicle change in velocity (delta-v) is a widely adopted crash severity metric used to estimate occupant injury risk in real world crashes (Kononen et al 2006; Gabauer and Gabler 2008). Delta-v is currently estimated by an algorithm, WinSMASH, which correlates variables of vehicle deformation and stiffness through conservation of energy principles (Sharma et al 2011). The algorithm has been shown to underestimate delta-v in the real world by 23% on average (Niehoff and Gabler 2006; Hampton and Gabler 2010) and furthermore cannot be used in crashes involving rollovers, sideswipes, non-horizontal forces, severe over-ride/under-ride, undercarriage impacts, multiple impacts to the same area, and towed trailers or vehicles (Sharma et al 2006). Crashworthiness assessment of restraint systems is also a challenge. Estimates of seat belt use are currently based upon forensic evidence that must distinguish between crash loading and occupant wear with normal, prolonged use (Heydinger et al 2008). Crashes of high severity create greater occupant loading marks that aid investigator determination of seat belt use (Raymond et al 2006); however, the assessment becomes highly subjective during low severity cases or other crash scenarios exhibiting indistinct characteristics (Tanner et al 2006).

One alternative to these traditional methods was the use of event data recorders (EDRs), which are capable of recording crash characteristics prior to and during a collision. These devices were estimated to be equipped in 96% of model year 2013 passenger cars according to the National Highway Traffic Safety Administration (NHTSA 2012d). EDRs were first installed in model year 1994 General Motors (GM) passenger vehicles. Those early EDRs, referred to as Sensing and Diagnostic Modules (SDMs), only stored the longitudinal delta-v and the driver seat belt buckle status (Chidester et al 1999; Gabler et al 2008a). In the past two decades, most other original equipment manufacturers (OEMs) have equipped their vehicles with these devices, which now record much greater amounts of data.

1.1 REGULATION

EDRs are now equipped in most newly manufactured vehicles, but throughout the majority of their two-decade fleet permeation no standards existed and formats varied widely across OEMs (Gabler et al 2004b). Not until September 1, 2012 was Title 49 Code of Federal Regulations Part 563: Event Data Recorders (Part 563) made effective. The regulation sought to achieve 5 primary objectives: specify a minimum set of data, standardize the data set, increase the survivability of the data, require data retrievability by a commercially available tool, and require a standard statement in the vehicle owner's manual (NHTSA 2008b; SAE 2013).

As seen in Table 1.1, Part 563 requires that 15 data elements be recorded by any passenger vehicle equipped with an EDR. The Part 563 Table I required elements include longitudinal delta-v, precrash speed, driver seat belt buckle status, time to first stage frontal airbag deployment, and complete file recorded. Other data elements regulated, but not required, were included in Part 563 Table II (Table 1.2). This table includes acceleration, passenger seat belt buckle status, time to side torso airbag deployment, time to side curtain airbag deployment, and time to pretensioner airbag deployment. Standardization specifically referred to the recording duration, recording frequency, sampling frequency, and accuracy.

Although the majority of the current EDR dataset was not affected by this regulation, EDRs offer promising potential to obtain data measured directly before, during, and after the passenger vehicle collision. The data from these devices can provide a wealth of information to improve assessment of crashworthiness.

Table 1.1 Data elements required for all vehicles equipped with an EDR (Table I; Reproduced from Title 49 Code of Federal Regulations Part 563)

Data element	Recording interval/time (relative to time zero)	Data sample rate (samples per second)
Delta-V, longitudinal	(whichever is shorter) 0 to 250 ms or 0 to end of event time + 30 ms	100
Maximum delta-v, longitudinal	(whichever is shorter) 0 to 300 ms or 0 to end of event time + 30 ms	N/A
Time, maximum delta-v	(whichever is shorter) 0 to 300 ms or 0 to end of event time + 30 ms	N/A
Speed, vehicle indicated	−5.0 to 0 sec	2
Engine throttle or accelerator pedal	−5.0 to 0 sec	2
Service brake, on/off	−5.0 to 0 sec	2
Ignition cycle, crash	−1.0 sec	N/A
Ignition cycle, download	At time of download	N/A
Safety belt status, driver	−1.0 sec	N/A
Frontal air bag warning lamp	−1.0 sec	N/A
Frontal air bag deployment, time to deploy, driver	Event	N/A
Frontal air bag deployment, time to deploy, passenger	Event	N/A
Multi-event, number of event	Event	N/A
Time from event 1 to 2	As needed	N/A
Complete file recorded	Following other data	N/A

Table 1.2 Data elements required for all vehicles under specified minimum conditions (Table II; Reproduced from Title 49 Code of Federal Regulations Part 563)

Data element name	Recording interval/time (relative to time zero)	Data sample rate (per second)
Lateral acceleration	N/A	N/A
Longitudinal acceleration	N/A	N/A
Normal acceleration	N/A	N/A
Delta-V, lateral	(whichever is shorter) 0 to 250 ms or 0 to end of event time + 30 ms	100
Maximum delta-v, lateral	(whichever is shorter) 0 to 300ms or 0 to end of event time + 30 ms	N/A
Time maximum delta-v, lateral	(whichever is shorter) 0 to 300ms or 0 to end of event time + 30 ms	N/A
Time for maximum delta-v, resultant	(whichever is shorter) 0 to 300ms or 0 to end of event time + 30 ms	N/A
Engine rpm	−5.0 to 0 sec	2
Vehicle roll angle	−1.0 up to 5.0 sec	10
ABS activity	−5.0 to 0 sec	2
Stability control	−5.0 to 0 sec	2
Steering input	−5.0 to 0 sec	2
Safety belt status, passenger	−1.0 sec	N/A
Frontal air bag suppression switch status, passenger	−1.0 sec	N/A
Frontal air bag deployment, time to n^{th} stage, driver	Event	N/A
Frontal air bag deployment, time to n^{th} stage, passenger	Event	N/A
Frontal air bag deployment, nth stage disposal, driver	Event	N/A
Frontal air bag deployment, nth stage disposal, passenger	Event	N/A
Side air bag deployment, time to deploy, driver	Event	N/A
Side air bag deployment, time to deploy, passenger	Event	N/A
Side curtain/tube air bag deployment, time to deploy, driver side	Event	N/A
Side curtain/tube air bag deployment, time to deploy, right side	Event	N/A
Pretensioner deployment, time to fire, driver	Event	N/A
Pretensioner deployment, time to fire, passenger	Event	N/A
Seat track position switch status, driver	−1.0 sec	N/A
Seat track position switch status, passenger	−1.0 sec	N/A
Occupant size classification, driver	−1.0 sec	N/A
Occupant size classification, passenger	−1.0 sec	N/A
Occupant position classification, driver	−1.0 sec	N/A
Occupant position classification, passenger	−1.0 sec	N/A

1.2 RESEARCH APPROACH

The aim of this dissertation was to characterize the potential effect of EDR data on passenger vehicle crashworthiness. The specific aims were to (1) validate EDR accuracy in full-frontal, side-impact moving deformable barrier, and small overlap crash tests; (2) evaluate EDR survivability beyond regulatory crash tests, (3) determine the seat belt usage accuracy of current databases, and (4) assess the merits of vehicle pulse index as an alternative to delta-v in crash tests and real world collisions.

1.2.1 Specific Aim 1: Validation of Event Data Recorders

The objective of this specific aim was to establish the accuracy of EDR measurements recorded during full-frontal, side-impact, and small overlap crash tests. EDRs offer a unique method of reconstructing passenger vehicle crashes that improve upon traditional methods. Many studies could rely upon EDRs, which provide data such as delta-v, precrash speed, seat belt status, and airbag deployment time, measured throughout the event. However, before EDR data can be fully utilized, it is important to first establish the accuracy of the data elements. Although Part 563 standardizes EDRs, the regulation only applies to vehicles that were manufactured after September 1, 2012. This leaves much of the EDR data available from modules manufactured between 1994 and 2012, which must be evaluated for accuracy. Moreover, newer modules should also be evaluated to establish their compliance with the regulation.

1.2.2 Specific Aim 2: Survivability of Event Data Recorders

The objective of this study was to determine the survivability of EDRs in real world fire, immersion, and high severity crashes. Specific objectives were to identify the frequency of fire, immersion, and high severity scenarios in which the EDR could still be imaged and to identify any vehicles in which the EDR could not be read after fire, immersion, or high severity. As more and more EDRs were collected and read, interest in their accuracy and survivability has arisen. Many papers have been published describing the ability of an EDR to collect accurate data (Niehoff et al 2005; Gabler et al 2008), but little research has been performed in the area of survivability. The U.S. Motor Vehicle Safety Act of 2010 proposed EDR survivability far beyond Part 563 requirements, in response to concerns over EDR operation in crashes which involved fire or immersion. This initiative was likely motivated by existing aviation standards which specify that similar devices (*i.e.* flight data recorders) should survive these events (EUROCAE 2003; EUROCAE 2009). Little was known, however, about whether current EDRs were capable of surviving these events or whether the data received by the EDRs can be recovered after these events. In addition, a study was needed to determine whether these events were sufficiently common to justify the expense of increasing survivability in EDRs.

1.2.3 Specific Aim 3: Accuracy of Seat Belt Usage Estimates

Seat belt use was a critical factor in occupant injury prediction in passenger vehicle crashes. Previous studies have used investigator estimates in a national database as the gold-standard in checks on the accuracy of police-reported seat belt usage (Schiff and Cummings 2004; Viano Parenteau 2009; Moore et al 2009). However, no study has quantified the accuracy of the National Automotive Sampling System–Crashworthiness Data System (NASS-CDS) seat belt use estimates. EDRs provide objective insight into seat belt use in a passenger vehicle collision, making them ideal for seat belt use determination. A study of real-world seat belt buckle status on 9 early GM EDRs showed that one was inaccurate (Chidester et al 1999). However, more recent studies evaluating EDR seat belt buckle status in crash tests indicated 100% accuracy when reported (Niehoff et al 2005; Gabler et al 2008). EDRs were already collected and downloaded in conjunction with the NASS-CDS investigation and the data was available online. However, NASS-CDS investigators relied on vehicle inspection, medical records, and interviews to determine seat belt use (Zhang and Chen 2013). Belt use assessment could be improved if EDR data were used. This specific aim examined the accuracy of NASS-CDS seat belt usage observations and the factors which control this measurement's accuracy.

1.2.4 Specific Aim 4: Evaluation of an Alternative to the Delta-V Risk Metric

The purpose of this specific aim was to (1) evaluate the vehicle pulse index (VPI) injury metric's predictive aptitude in standardized crash tests and (2) to compare the ability of delta-v and VPI to predict injury in real world collisions. In passenger vehicle crashes, delta-v was a widely used impact severity metric used to estimate occupant injury risk (Kononen et al 2006; Gabauer and Gabler 2008). Despite its conventional use, delta-v has several limitations. Delta-v does not consider the (acceleration) crash pulse shape, as two dissimilar crash pulses can produce identical delta-v. Additionally, it does not consider the usage of occupant restraints, *e.g.* airbags and seat belts. These inadequacies have prompted the development of other impact severity metrics. In particular, the International Organization for Standardization (ISO) has proposed the VPI as an alternative (ISO 2013). VPI was a metric based upon a mass-spring model that incorporates restraint use in its estimates of occupant motion. Previous studies have shown the aptitude of VPI to predict head and chest injuries in crash tests (Prasad and Weston 2011). However, no study has evaluated VPI or compared the metric with respect to the traditional delta-v metric in real world collisions.

1.3 DATA SOURCES

Many of the specific aims relied upon national databases of real world passenger vehicle collisions and crash tests. In the sections that follow, a brief description is provided, accompanied by an indication of which specific aims each database was utilized in.

1.3.1 National Automotive Sampling System – Crashworthiness Data System (NASS-CDS)

The NASS-CDS is a publicly available probability sample of passenger vehicle crashes, where at least one passenger vehicle, light truck, or van was towed due to damage. Since 1988, NASS-CDS collects approximately 5,000 crashes each year. There were 24 primary sampling units (PSUs) from which the data was collected. Each PSU was a geographical location with a population size close to 50,000 individuals (Zhang and Chen 2013). Data was gathered by trained investigators on the occupants, vehicles, and overall crash from police accident reports, witness interviews, medical records, and thorough investigations of the site and involved vehicles. This additionally includes retroactive photographs, damage measurements, interviews, as well as EDR information when available. Beyond the data itself, NASS-CDS further provides a weighting factor from which the dataset to be extrapolated as national numbers (NHTSA 2012c). This database was utilized for specific aims 2, 3, and 4.

1.3.1.1 Event Data Recorders

In conjunction with the NASS-CDS investigation, EDR data was downloaded with the Bosch Crash Data Retrieval (CDR) Tool. Investigators possess a series of cables that allow the tool to interface with the EDR through the Onboard Diagnostic (OBD-II) port or by connecting direct-to-module. The output is a *.CDR or *.CDRx file which contains encrypted HEX, which can also be converted to PDF or CSV. Since case year 2000, the NHTSA has annually provided the CDR files to Virginia Tech to produce and sanitize the PDFs, which were then uploaded to the NHTSA website for public use. The database currently contains over 9,000 EDR files collected from case years 2000 through 2013.

First available in 2000, the Bosch CDR Tool was the only publically available EDR download tool, until recently. As GM vehicles were the earliest implementers of EDRs in passenger cars (Chidester et al 1999), early versions of the Bosch CDR Tool supported primarily GM vehicles. As a result, the NASS-CDS EDR database is largely composed of EDRs extracted from GM vehicles. The tool now supports most OEMs and their subsidiaries including Bentley, BMW, Chrysler, Ford, Honda, Lamborghini, Maserati, Mazda, Mitsubishi, Nissan, Rolls-Royce, Smart, Suzuki, Toyota, Volkswagen, and Volvo (version 16.0, Bosch CDR Tool, Santa Barbara, CA). Although these OEMs are supported, it should be noted that the Bosch CDR Tool supports specific model years. Also, support by the tool does not equate to having all such vehicles present in the NASS-CDS database. Additionally, the CDR files also contain information about the module. A unique identifier, described as the "module type" in the following studies, can be found in the second line of the CDR file when opened from a plain text editor. EDRs of identical module type record the same data elements for identical durations and sampling frequencies. Module types may span various model years and vehicle models, but do not mix between OEMs.

1.3.2 National Motor Vehicle Crash Causation Survey (NMVCCS)

The National Motor Vehicle Crash Causation Survey (NMVCCS) includes a total of 6,949 crashes that were investigated between January 1, 2005 and December 31, 2007. This database utilized the existing infrastructure of NASS to collect a nationally representative sample of 5,470 passenger vehicles. Similar to NASS, NMVCCS uses case weights to allow weighted extrapolation of results to a national scale. Unlike NASS, however, NMVCCS data collection begins on-scene as soon as possible after the crash occurs (NHTSA 2008a). As photographs and descriptions were taken immediately, this database was useful for specific aim 2, survivability of EDRs.

1.3.3 Fatality Analysis Reporting System (FARS)

The Fatality Analysis Reporting System (FARS) is a nationwide census of passenger vehicle traffic crashes including a fatality. This NHTSA database compiles fatal crashes that occurred throughout the United States, including Puerto Rico and the District of Columbia, since 1975. To be included in this database, a crash must occur on a public road and an individual involved in the crash (*i.e.* occupant or pedestrian) must be fatally injured and die within 30 days of the crash. Data sources of this survey include police accident reports, death certificates, state vehicle registration files, coroner/medical examiner reports, state driver licensing files, hospital medical reports, state highway department data, emergency medical service reports, vital statistics, and other state records. Over 100 data elements were coded and each case includes information describing the crash, the vehicle, and the people involved (NHTSA 2014). This database was utilized for specific aim 2, describing EDR survivability.

1.3.4 Vehicle Crash Test Database

The Vehicle Crash Test Database is a database of government crash tests. A variety of crash tests were included, but of interest to this dissertation were the full-frontal (NHTSA 2012a), side-impact moving deformable barrier (MDB; NHTSA 2012b), and small overlap crash tests (NHTSA 2011b). This database includes videos, instrumentation data, and a test report which includes photographs. Accompanied with this database were a suite of vehicle safety research (VSR) tools for analysis. The primary software utilized for this dissertation was PlotBrowser, which plots the channels for each crash test and provides channel frequency class (CFC) digital filtering. Select EDR Bosch CDR reports were also uploaded (NHTSA 2013a). This database was utilized for specific aim 1 and specific aim 4.

2 VALIDATION OF EVENT DATA RECORDERS

2.1 BACKGROUND

EDRs offer a unique method of reconstructing passenger vehicle crashes that improve upon traditional methods. Many studies could rely upon EDRs, which provide data such as delta-v, precrash speed, seat belt status, and airbag deployment time, measured throughout the event. However, before EDR data can be fully utilized, it was important to first establish the accuracy of the data elements. Although Part 563 standardizes EDRs, the regulation only applies to vehicles that were manufactured after September 1, 2012 (Event Data Recorders 2012). This leaves much of the EDR data available from modules manufactured between 1994 and 2012, which must be evaluated for accuracy.

2.1.1 Previous Delta-V Accuracy Validation Studies

EDR validation, of various data elements, has been conducted for well over a decade (Chidester et al 1999). These validation efforts have primarily focused upon delta-v, defined as the change in velocity over the duration of the crash event. This data element has been the traditional injury severity metric often used to predict occupant outcomes (Kononen et al 2006; Gabauer and Gabler 2008). If the vehicle was not equipped with an EDR, delta-v was reconstructed by WinSMASH, an algorithm that requires deformation inputs and vehicle stiffness. This method cannot be used in crashes involving rollovers, sideswipes, non-horizontal forces, severe over-ride/under-ride, undercarriage impacts, multiple impacts to the same area, and towed trailers or vehicles (Sharma et al 2011). As a result, EDR data would not only provide delta-v for the crashes excluded by WinSMASH, but it would offer a simpler method of obtaining delta-v for supported crash modes as well.

Previous validation studies of EDR delta-v focused primarily on full-frontal collisions. A few studies have additionally studyied offset frontal impacts, side impacts with moving deformable barriers, and side impacts with poles. EDR delta-v accuracy was first found to be ±10% of the true delta-v by Chidester et al (1999) for model year 1999 GM vehicles. In 2005, Niehoff et al (2005) reported errors averaging 5.75% of the true delta-v in full-frontal crash tests (n=21) for primarily model year 2000-2005 GM vehicles, but with some Toyota and Ford vehicles as well. In modules that recorded lateral delta-v (n=3) the reported average error was 18.56%. Additionally, Niehoff et al (2005) found that vehicles in frontal offset crashes (n=7) showed an average error of 6.04%. Later, Gabler et al (2008) reported on GM, Toyota, and Ford vehicles of model years between 2004 and 2007. They reported an average longitudinal delta-v error of 4.3% for full-frontal crashes (n=39), 30.3% for side impact crashes (n=5), and 3.6% for 40% frontal offset crashes (n=3) at 100ms. Most recently, Comeau et al (2011) reported on 14 model year 1998-2002 Toyota EDRs from crash tests. Those involved in an offset barrier (n=2) and full-frontal (n=4) crash tests typically showed errors less than the ±10% reported by Chidester et al (1999).

Although many results have been established for full-frontal impacts, the model years validated do not include modules manufactured more recently. As a result, the findings of these studies do not reflect the state of recent EDRs. Furthermore, Part 563.10 set retrievability requirements that require all EDRs to have a commercially available tool for data retrieval. This had led a number of OEMs, *e.g.* Chrysler, Honda, Mazda, Nissan, and Volvo, to introduce EDRs (Event Data Recorders 2012). More recently, NHTSA and Insurance Institute for Highway Safety (IIHS) have introduced a small overlap crash test for which EDR accuracy has not been validated.

Also needed is validation of EDR lateral delta-v. Many of the previous studies have primarily focused on frontal crashes, utilizing the longitudinal data integral to algorithms that determine frontal airbag deployment. Most early EDRs computed and recorded longitudinal delta-v using the frontal airbag accelerometer data (Chidester et al 1999). Vehicles with early EDRs were typically not equipped with lateral accelerometers or side airbags; and hence did not record lateral acceleration. However, with the increased prevalence of side airbags in recent model years, there has been a parallel increase in lateral accelerometers. EDRs from these vehicles can now compute and record lateral delta-v, providing an opportunity to validate EDRs in side crashes.

2.1.2 Validation of Other Event Data Recorder Elements

In addition to delta-v, other data elements have also been evaluated for accuracy. For instance, precrash speed has been widely studied and the literature findings have been summarized in Table 2.1. As with delta-v, the first paper to address precrash EDR speed data accuracy was published by Chidester et al (1999) reporting error within ±4% of the true delta-v. On average, these results have been consistent in the following studies (Bare et al 2011; Bortolin et al 2010; Brown et al 2012a; Brown et al 2012b; Chidester et al 1999; Comeau J-L et al 2011; Diacon et al 2013; Lawrence et al 2003; NHTSA 2011a; Ruth et al 2008; Ruth and Reust 2009; Ruth and Brown 2010; Ruth et al 2012).

Seat belt buckle status has also been previously evaluated. Chidester et al (1999) found one out of nine real world EDRs was inaccurate. However, all following studies evaluating seat belt buckle status from crash tests have shown 100% accuracy when the data element was reported (Niehoff et al 2005; Gabler et al 2008).

2.2 OBJECTIVE

The objective of this study was to establish the accuracy of EDR measurements recorded during full-frontal, side-impact, and small overlap crash tests.

Table 2.1 Summary of precrash speed accuracy studies

OEM	Subsidiary	Author, Year
GM	—	Chidester et al 1999
	—	Lawrence et al 2003
	—	Bare et al 2011
Ford	—	Ruth et al 2008
	—	Ruth, Brown 2010
Chrysler	Jeep & Dodge	Ruth, Reust 2009
	Dodge Caravan	Bortolin et al 2010
Toyota	—	NHTSA 2011
	—	Ruth et al 2012
	—	Brown et al 2012
	—	Brown, White 2012
Honda	—	Diacon et al 2013

2.3 CRASH TESTS

The following analysis was based on EDRs extracted from vehicles that experienced either a NHTSA new car assessment program (NCAP) crash test or an IIHS crash test. Accelerometer data, testing center reports, and publicly available Bosch CDR reports were available on the NHTSA vehicle crash test database website. Table 2.2 indicates general crash test characteristics. EDRs were designed to capture and record data in these NHTSA crash tests. In the case of an airbag deployment, the EDR records and prevents overwriting of the characteristics described. In the following datasets, each of the test vehicles deployed at least one type of airbag. The coordinate system followed Society of Automotive Engineers (SAE) J1733 conventions: the positive (longitudinal) x-axis was forward movement, the positive (lateral) y-axis was right, and the positive (vertical) z-axis was down.

Table 2.2 Crash test characteristics of the sample

	Full-Frontal	Side-Impact MDB	Small Overlap	
Testing Agency	NHTSA	NHTSA	NHTSA	IIHS
Impact Object	Rigid Barrier	MDB	RMDB	Rigid Barrier
Impact Speed	35 mph (56 kph)	39 mph (62 kph)	56 mph (90 kph)	40 mph (64 kph)
Model Years	2012	2010-2012	2010-2012	2012-2014

2.3.1 Full-Frontal Crash Tests

The dataset included 41 EDRs extracted from model year 2012 passenger vehicles that had experienced a NHTSA NCAP full-frontal crash test. The distribution of OEMs and EDR module types is shown in Table 2.3. The protocol for this crash test requires that the test vehicle perpendicularly impacts a fixed, rigid, concrete barrier at 56.30 ± 0.80 kph, or approximately 35 mph (NHTSA 2012a). A schematic of the test is shown in Figure 2.1. Two anthropomorphic test devices (ATDs) were belted and placed in the front outboard positions: a 50th percentile male hybrid III ATD in the driver's seat and a 5th percentile female hybrid III in the right front passenger seat.

Table 2.3 Composition of OEMs and EDR module types in the full-frontal dataset

Variable	Number of Tests
Vehicle Manufacturer	
Chrysler	12
Ford	6
General Motors	7
Honda	5
Mazda	1
Toyota	9
Volvo	1
EDR Module Type	
CHRY0000	1
CHRY0305	5
CHRY0403	3
CHRY4005	2
CHRY4101	1
FordAB10	1
FordRC6_2011	2
FordRC62011CGEAD	3
Honda001	5
MAZDA002	1
SDM10	5
SDM10P	1
SDM11_AUTOLIVNEW	1
Toyota001	9
Volvo001	1
Total	**41**

Only crash test accelerometers mounted in the occupant compartment were used in the analysis. Crash test accelerometers mounted in either the crush zone or to non-rigid occupant compartment components, *e.g.* the instrument panel, were excluded from the study. Sensors mounted were be considered in order to avoid impact damaged accelerometers or compromised signals caused by localized crush. Our study used, four uniaxial accelerometers, measuring longitudinally (x-axis), were located in the rear of the passenger compartment. In general, two accelerometers were placed on the left and the remaining 2 were placed on the right. The specific location of the sensors were dependent upon the test laboratory. Vehicles tested at MGA Research placed the sensors in the rear floorpan, Karco Engineering placed them in the rear sill, and Calspan placed the sensors on the rear seats.

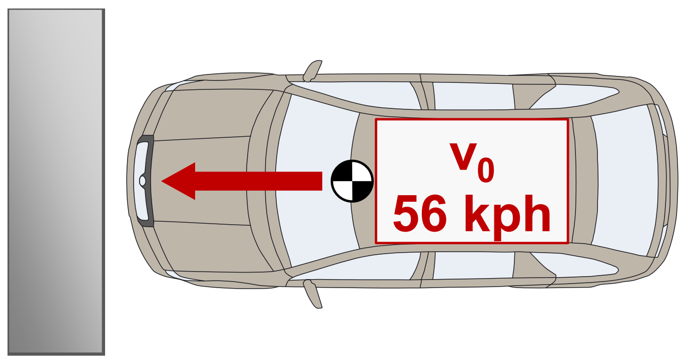

Figure 2.1 Schematic of the new car assessment program full-frontal crash test

2.3.2 Side-Impact Moving Deformable Barrier Crash Tests

As shown in Table 2.4, the dataset for this study was composed of 75 EDRs extracted from model year 2010-2012 passenger vehicles subjected to the side impact NCAP moving deformable barrier (SINCAP MDB) crash test conducted by NHTSA. SINCAP MDB tests involve a stationary test vehicle that was perpendicularly impacted on the driver (left) side by the MDB at 61.90 ± 0.80 kph (39 mph). The protocol for this crash test specifies a crabbed MDB angle of 27° to simulate an impact where both vehicles were moving, as seen in Figure 2.2. The MDB has a crushable block of aluminum honeycomb structure to simulate the stiffness (310 ± 17 kpa) of the front end of a striking vehicle. In this crash test, two belted side impact dummies (SIDs) were seated in the driver and left rear (or middle) row passenger positions, depending upon the vehicle type. The driver was a 50th percentile male EuroSID2 with rib extensions (ES-2re) and the rear passenger was a 5th percentile female SID (SID-IIs). The right front passenger seat was usually unoccupied and unbuckled (NHTSA 2012b).

Sensors for this study were limited to the triaxial accelerometers mounted within the occupant compartment of the test vehicle. Similar to the sensor exclusion criteria of the full-frontal crash tests, sensors mounted to the struck side of the vehicle were not be considered in order to avoid impact damaged accelerometers or compromised signals caused by localized crush. After these constraints were applied, four accelerometers were considered in the analysis: the right front sill, right rear sill, center trunk floor, and vehicle center of gravity (CG). Figure 2.3 gives the approximate mounting location of these accelerometers within the test vehicle. The data quality of the longitudinal and lateral channels was manually scrutinized and if unusual behavior was observed, the channel was not used in the proceeding analysis.

Table 2.4 Composition of OEMs, model years, and EDR module types in the side-impact dataset

Variable	Number of Tests
Vehicle Manufacturer	
Chrysler	16
Ford	17
GM	16
Honda	4
Mazda	2
Toyota	20
Model Year	
2010	12
2011	28
2012	35
EDR Module Type	
CHRY0000	2
CHRY0305	7
CHRY0403	3
CHRY4005	2
CHRY4101	1
Epsilon2006	1
FordAB10	1
FordRC6_2010	6
FordRC6_2011	5
FordRC62011CGEAB	1
FordRC62011CGEAC	2
FordRC62011CGEAD	2
HONDA001	4
MAZDA001	1
MAZDA002	1
SDM10	12
SDM10P	1
SDM11_AUTOLIVNEW	1
SDMC2008V	2
TOYOTA001	20
Total	**75**

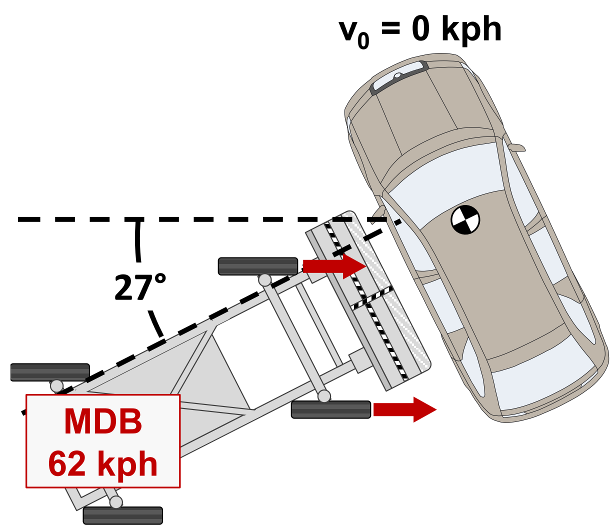

Figure 2.2 Schematic of the new car assessment program side-impact moving deformable barrier crash test

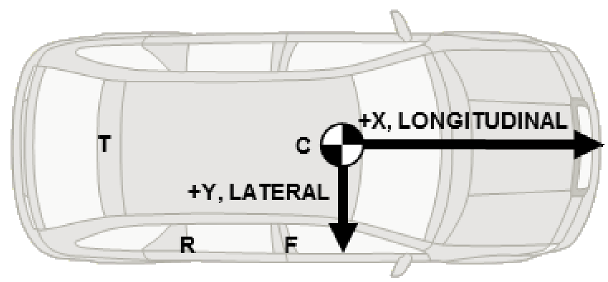

Figure 2.3 Vehicle-fixed reference frame orientation with approximate accelerometer locations: (F) right front sill, (R) right rear sill, (T) trunk floor center, and (C) vehicle center of gravity.

2.3.3 Small Overlap Crash Tests

As seen in Table 2.5, 11 EDRs were extracted from NHTSA small overlap crash tests, which do not have a formal protocol document as they were still in the research and development phase. Crash test characteristics were gathered from Saunders et al (2011, 2012) and the testing house reports. This sample includes an array of model years from 2010 through 2012. In these crash tests, a research moving deformable barrier (RMDB) impacts the front of the stationary test vehicle at 90 kph (56 mph). The RMDB was a modified MDB, such that the face plate was widened and heightened; and the honeycomb block was bi-layered and stiffer (inner: 1,710 kpa, outer: 724 kpa; Saunders et al 2011, 2012) than the MDB used in FMVSS 214 tests (310 kpa; NHTSA 2012b). The impact occurred at an impact angle of 7° with a 20%

overlap of the vehicle width. A schematic is shown in Figure 2.4. In these tests, two ATDs were belted at the front outboard seat positions: a 50th percentile THOR ATD was placed in the driver's seat and a 5th percentile hybrid III was placed in the passenger seat. Among the various sensors located on the vehicle and ATDs, there were 3 accelerometers of interest: 2 biaxial accelerometers located at the left and right rear sills and 1 triaxial accelerometer located approximately at the vehicle CG.

Table 2.5 Composition of OEMs, model years, and EDR module types in the NHTSA small overlap dataset

Variable	Number of Tests
Vehicle Manufacturer	
Chrysler	2
Ford	3
General Motors	4
Toyota	2
Model Year	
2010	3
2011	7
2012	1
EDR Module Type	
CHRY0000	1
CHRY0403	1
FordRC6_2010	1
FordRC6_2011_EU	1
FordRC62011CGEAD	1
SDM10	4
TOYOTA001	2
Total	**11**

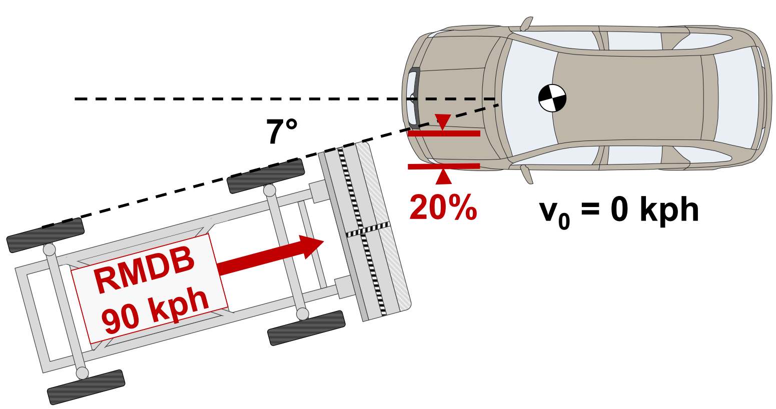

Figure 2.4 Schematic of the NHTSA small overlap crash test

Table 2.6 Composition of OEMs, model years, and EDR module types in the IIHS small overlap dataset

Variable	Number of Tests
Vehicle Manufacturer	
Chrysler	6
Ford	3
General Motors	8
Honda	7
Kia/Hyundai	5
Mazda	7
Nissan	3
Toyota	8
Volvo	2
Model Year	
2012	5
2013	23
2014	21
EDR Module Type	
CHRY0000a	1
CHRY0305	1
CHRY6001	2
FordAB10BEV	1
HONDA001	2
HONDA002	4
MAZDA001	1
MAZDA002	3
NISSAN02	1
NISSAN02B	1
SDM10P_1	8
TOYOTA001	2
VOLVO001	1
Unknown	21
Total	**49**

In addition to the NHTSA crash tests, IIHS small overlap crash tests were also used. As seen in Table 2.6, 49 EDRs were extracted from model year 2012-2014 passenger vehicles subjected to the IIHS small overlap crash tests. The protocol for this crash test requires that the test vehicle perpendicularly impacted a fixed, rigid, steel barrier at 64.4 ± 1.0 kph (40 ± 0.6 mph; IIHS 2014). As shown in the schematic of the test Figure 2.5, the impact only overlaps 25% ± 1% of the vehicle width. Vehicle width, as defined by IIHS excluded exterior mirrors, flexible mud flaps, and marker lamps. The protocol dictates a 50th percentile male hybrid III ATD was placed in the driver's seat. The right front passenger seat was unoccupied and unbuckled. Sensors for this study were limited to one triaxial accelerometer mounted to a steel plate welded to the rear seating area of the test vehicle, located along the centerline. The location of the precrash CG and the accelerometer array were marked with photographic targets on the roof of the vehicle. The precrash CG was determined from the test vehicle's weight distribution (IIHS 2014).

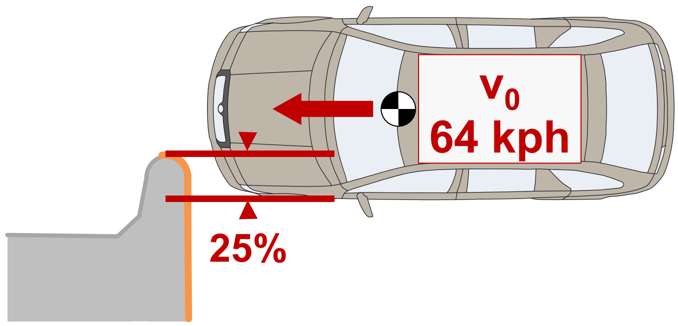

Figure 2.5 Schematic of the IIHS small overlap crash test

In addition to using the Bosch CDR tool to download Chrysler, Ford, General Motors, Honda, Mazda, Nissan, Toyota, and Volvo modules, IIHS was capable of downloading the data from Hyundai and Kia modules with the Global Information Technologies (GIT) tool (Ruth and Tsoi 2014). The output produces a PDF with the data elements, organized identically to Part 563 tables I and II.

2.4 METHODOLOGY

Table 2.7 Proposed EDR data elements for validation and characterization

Data Elements	Full-Frontal	Side-Impact MDB	Small Overlap	
			NHTSA	IIHS
Maximum Delta-V: Longitudinal	☑	☐	☑	☑
Maximum Delta-V: Lateral	☐	☑	☑	☑
Precrash Speed	☑	☐	☐	☑
Belt Status: Driver	☑	☑	☑	☑
Belt Status: R. Passenger	☐	☑	☑	☑
Airbag Deployment: Driver Frontal*	☑	☑	☑	☑
Airbag Deployment: Driver Torso*	☐	☑	☑	☑
Airbag Deployment: Driver Curtain*	☐	☑	☑	☑

*Time to fire was reported if the EDR provided this information

Each EDR report was examined for the data elements shown in Table 2.7 and the following section describes the validation approach. In addition to these crash characteristics, some EDRs also provide diagnostic information. In particular, the data element "complete file recorded" in the Bosch CDR report indicates whether the deployment event was successfully recorded. Some EDR reports (*e.g.* Toyota) provide additional recording statuses for subsections or pages of the report. If available, this data element was examined as an initial step to ensure data quality and, as one to identify the cause of unusual delta-v behavior or for an incorrectly reported status.

2.4.1 Delta-V Accuracy

The sensor data retrievable from the NHTSA vehicle crash test database was given in *.uds files, which can be read by the publicly available NHTSA VSR software, Plotbrowser. As the intention was to integrate the accelerometer data to obtain velocity, a 180 Hz CFC digital filter was first applied according to SAE J211-1 (2007). Author inspection, in addition to crash test specific procedures, was utilized to further ensure data quality. Two (2) EDR delta-v values were compared to the reference delta-v: (a) maximum delta-v as determined from the velocity versus time data and (b) the maximum delta-v data element. Quantification of error used 3 error metrics: arithmetic error (Equation 1), absolute error (Equation 2), and root mean square (RMS) error (Equation 3). Arithmetic and absolute error comparisons were made individually and within each OEM. RMS error was only computed for vehicles aggregated by OEM.

$$\text{Arithmetic Error} = \text{Maximum}\,\Delta V_{EDR} - \text{Maximum}\,\Delta V_{REF} \qquad \text{(Equation 1)}$$

$$\text{Absolute Error} = \left|\text{Maximum}\,\Delta V_{EDR} - \text{Maximum}\,\Delta V_{REF}\right| \qquad \text{(Equation 2)}$$

$$\text{RMS Error} = \sqrt{\frac{\sum_{i=1}^{n}\left(\text{Maximum}\,\Delta V_{EDR,i} - \text{Maximum}\,\Delta V_{REF,i}\right)^2}{n}} \qquad \text{(Equation 3)}$$

2.4.1.1 <u>Full-Frontal Crash Test</u>

The occupant compartment sensors were uniaxial and aligned with the longitudinal (x) axis. However, as the vehicle-barrier impact occurred perpendicularly, the primary movement of these vehicles in full-frontal crash tests was also along the longitudinal axis. Lateral and vertical movement were assumed to be negligible. The data quality of each channel was scrutinized for its relative shape compared with the other occupant compartment accelerometers to ensure consistency within the individual crash test. Among the 4 available accelerometers mounted in the occupant compartment of these full-frontal crash tests, those with the highest and lowest maximum delta-v were discarded and the remaining 2 accelerometers were averaged. In crash tests where only 3 accelerometers were available, any channels with unrealistic delta-v (*e.g.* near-zero rebound velocity) were discarded. The chosen channels for each crash test were reported for reproducibility.

2.4.1.2 Side-Impact Crash Test

As previously discussed, the reference accelerometers in a frontal crash tests can be simply integrated to obtain velocity that can be compared to the EDR velocity. Direct integration of this acceleration, however, was not immediately comparable to the vehicle-fixed EDR velocity if the vehicle experiences post-impact yaw motion. In SINCAP MDB crash tests, the crabbed angle of the MDB imparted both lateral and longitudinal components to the test vehicle, causing yaw rotation as illustrated in Figure 2.6. This rotation caused the velocity to be dependent on the location of the sensor, as seen in Figure 2.7. Although these effects could be overcome by a vehicle CG located accelerometer, the crash tests in our sample did not install an accelerometer at the true CG.

Figure 2.6 Still frames from an overhead video indicating rotation of a model year 2012 Fiat 500 (test no. 7507) during a side-impact new car assessment program moving deformable barrier test

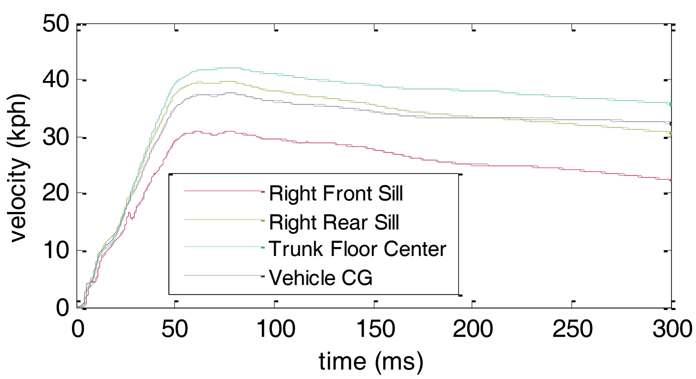

Figure 2.7 Directly computed velocity from accelerometers vary by sensor location in a rotating vehicle

2.4.1.2.1 Rotation Correction

Marine and Werner (1998) applied rotational concepts from rigid body dynamics using two bi-axial accelerometers to solve for the test vehicle's angular velocity (ω) and angular acceleration (α). This method was used to determine the acceleration of the CG within the vehicle-fixed coordinate system. This method ignored pitch and roll motion. Beyond the need for longitudinal and lateral accelerations from two sensors

(A and B), the relative distance of these accelerometers (r_A and r_B) were also needed with respect to the true vehicle CG. Sensor locations, as well as the location of the true vehicle CG as tested, were given in the test reports.

$$\alpha = \frac{(a_{A_x} - a_{B_x})(r_{B_y} - r_{A_y}) - (a_{A_y} - a_{B_y})(r_{B_x} - r_{A_x})}{(r_{B_x} - r_{A_x})^2 + (r_{B_y} - r_{A_y})^2} \qquad \text{(Equation 4)}$$

$$\omega^2 = \frac{(a_{A_x} - a_{B_x})(r_{B_x} - r_{A_x}) - (a_{A_y} - a_{B_y})(r_{B_y} - r_{A_y})}{(r_{B_x} - r_{A_x})^2 + (r_{B_y} - r_{A_y})^2} \qquad \text{(Equation 5)}$$

The components of linear acceleration at the true vehicle CG were solved from the addition of Equation 4 and Equation 5:

$$a_{CG_x} = \frac{1}{2}\left[a_{A_x} + a_{B_x} + \alpha\left(r_{A_y} + r_{B_y}\right) + \omega^2\left(r_{A_x} + r_{B_x}\right)\right] \qquad \text{(Equation 6)}$$

$$a_{CG_y} = \frac{1}{2}\left[a_{A_y} + a_{B_y} - \alpha\left(r_{A_x} + r_{B_x}\right) + \omega^2\left(r_{A_y} + r_{B_y}\right)\right] \qquad \text{(Equation 7)}$$

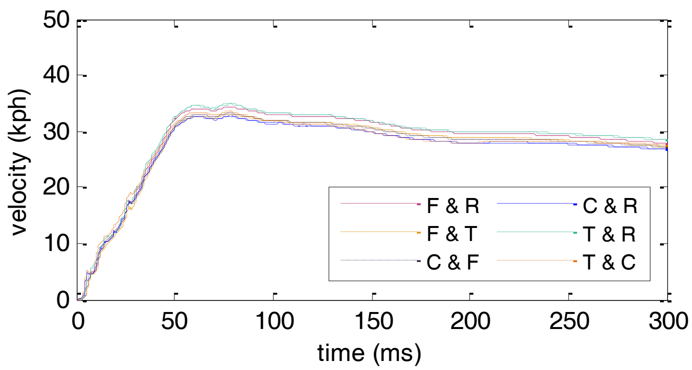

Figure 2.8 Six velocity pairs computed after rotation correction of four sensors: (F) right front sill, (R) right rear sill, (T) trunk floor center, and (C) vehicle center of gravity.

Prior to applying this approach, each channel was digitally filtered according to SAE J211-1 (2007) with a CFC 180 Hz filter. The SINCAP crash tests were equipped with 4 NHTSA sensors on the non-struck side yielding 6 possible accelerometer pairs, as shown in Figure 2.8. The velocity at the CG was then obtained through trapezoidal integration of these accelerations for each of the 6 accelerometer pairs. If all velocities exhibited normal behavior, then those with the 2 highest and 2 lowest maximum delta-v were discarded and the remaining 2 velocities were averaged. In instances where 3 sensors were available, only 3 accelerometer pairs were yielded. If the 3 pairs exhibited an assortment of maximum delta-v, the highest and lowest were discarded and only the middle was chosen. However, if two velocity pairs were similar, then those pairs were averaged and the third was discarded. Although the impact imparts both longitudinal and lateral components to the test vehicle, the primary component was along the lateral (y) axis, relative to the vehicle. Thus, the accuracy of EDR maximum lateral delta-v was the focus for this study on SINCAP MDB tests.

2.4.1.3 Small Overlap Crash Test - NHTSA

Similar to the SINCAP MDB crash tests, small overlap crash tests experience yaw motion, as shown in Figure 2.9. The approach by Marine and Werner (1998) described in the previous section was also applied in the NHTSA 7° angle / 20% offset configuration. However, as there were only 3 sensors measuring lateral and longitudinal acceleration components, only a maximum of 3 accelerometer pairs could be considered. The averaging approach defined for 3 SINCAP MDB accelerometer pairs was applied identically for these small overlap crash tests. Both the maximum lateral and longitudinal delta-v components were compared to the EDR maximum lateral and longitudinal delta-v, respectively.

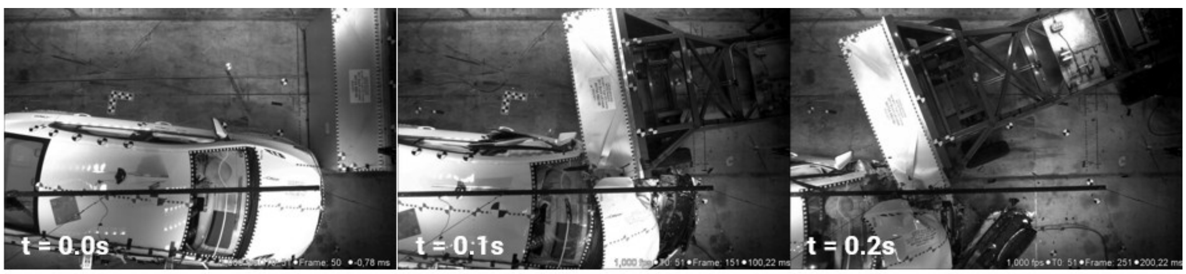

Figure 2.9 Frames from an overhead video indicating rotation of a model year 2011 Buick Lacrosse (RB0180) during a NHTSA small overlap impact by a research moving deformable barrier

2.4.1.4 Small Overlap Crash Test - IIHS

The IIHS small overlap crash tests also experienced yaw motion, but there was often only one available vehicle accelerometer located in the occupant compartment and the Marine and Werner (1998) approach could not be used to correct for vehicle rotation. Instead the motion of the photographic roof markers were analyzed from the high-speed (500 fps), overhead video using the TEMA Motion (Linköping, Sweden) software. The origin was established to be the CG marker at the first time of vehicle-barrier impact. Image scaling was provided by a 0.61m scale also located on the roof. As shown in Figure 2.10, the CG and accelerometer locations were tracked, giving the rotation of the centerline. The angle between the rotating centerline and original centerline were measured throughout the video to determine yaw motion. An example of the yaw motion, and resulting yaw rate, determined from this method is shown in Figure 2.11. The yaw rate observed from each test was similar in shape: an initial region of zero yaw rate, followed by a linear region, and concluded with a constant rotation. As the initial zero yaw motion region would suggest, negligible rotation was observed during the first few milliseconds, as shown in Figure 2.12.

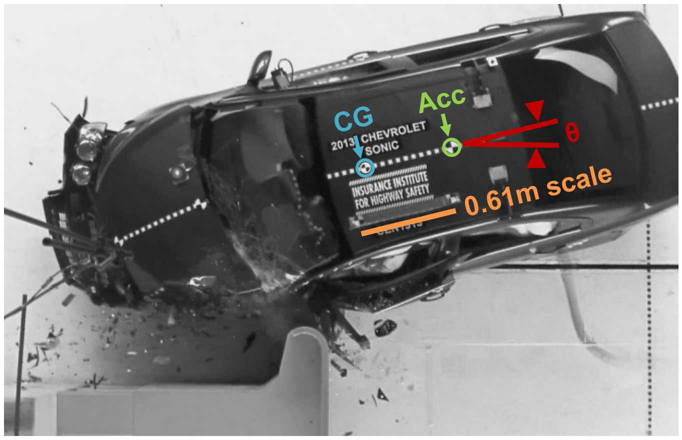

Figure 2.10 Landmarks (CG: Center of Gravity; Acc: Accelerometer) used in TEMA Motion video analysis of a 2013 Chevrolet Sonic (CEN1313)

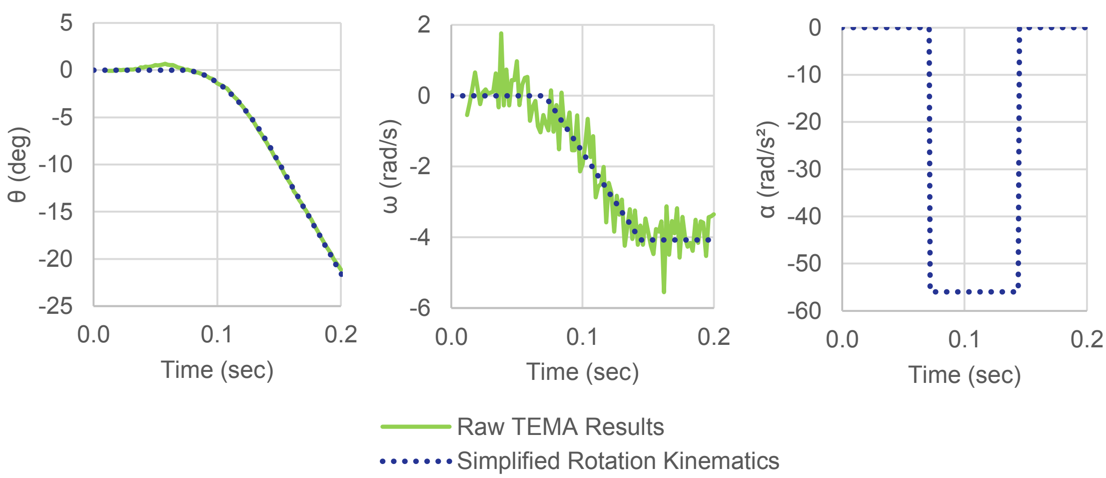

Figure 2.11 Simplified rotation kinematics for IIHS small overlap test on 2013 Hyundai Elantra (CEN1310) where t_1= 0.071 sec, t_2= 0.144 sec, and w = -4.074 rad/sec

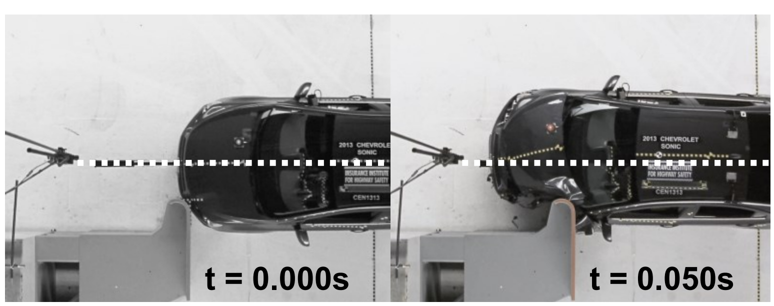

Figure 2.12 Negligible rotation observed immediately following barrier-impact of the IIHS small overlap test (2013 Chevrolet Sonic; CEN1313)

The similarity in yaw motion allowed for model simplification such that:

$$\theta = \begin{cases} \theta_{\max}\ , & t \le t_1 \\ 0.5\dfrac{w}{t_2 - t_1}t^2 - \dfrac{wt_1}{t_2 - t_1}t + 0.5\dfrac{wt_1^{\ 2}}{t_2 - t_1}, & t_1 < t \le t_2 \\ wt + 0.5\dfrac{wt_1^{\ 2}}{t_2 - t_1} \text{-} 0.5\dfrac{wt_2^{\ 2}}{t_2 - t_1}, & t < t_2 \end{cases} \qquad \text{(Equation 8)}$$

$$\omega = \begin{cases} 0, & t \le t_1 \\ \dfrac{w}{t_2 - t_1}t - \dfrac{wt_1}{t_2 - t_1}, & t_1 < t \le t_2 \\ w, & t < t_2 \end{cases} \qquad \text{(Equation 9)}$$

$$\alpha = \begin{cases} 0, & t \le t_1 \\ \dfrac{w}{t_2 - t_1}, & t_1 < t \le t_2 \\ 0, & t < t_2 \end{cases} \qquad \text{(Equation 10)}$$

A simulated annealing algorithm was used to determine t_1, t_2, and w and the best solution was chosen by the smallest sum of squares with a maximum number of 5,000 iterations. The result of the rotation simplification is shown in Figure 2.11. This simplification method ignores any positive (clockwise) yaw motion that occurs before t_1, which signifies the beginning of the rotation in the primary direction, seen as negative (counterclockwise) yaw motion. Only a few cases exhibited this behavior and the positive yaw motion was less than 5° in all instances. A constraint of this system of equations was that the initial yaw motion of the model was equivalent to the maximum raw, measured angle, or $\theta(0) = \theta_{max}$. Additionally, Equations 8-10 were derived under the constraint that the yaw motion was continuous.

In addition to determining the angular velocity and angular acceleration, the point of rotation was also assumed to be approximately at the front axle and laterally located at 25% overlap of the vehicle width. This is illustrated in Figure 2.13. With these assumptions, modified Marine and Werner (1998) equations could be rewritten as:

$$a_{CG_x} = \alpha(r_{Acc_y} - r_{CG_y}) + \omega^2(r_{Acc_x} - r_{CG_x}) + a_{Acc_x} \quad \text{(Equation 11)}$$

$$a_{CG_y} = \alpha(r_{CG_x} - r_{Acc_x}) + \omega^2(r_{Acc_y} - r_{CG_y}) + a_{Acc_y} \quad \text{(Equation 12)}$$

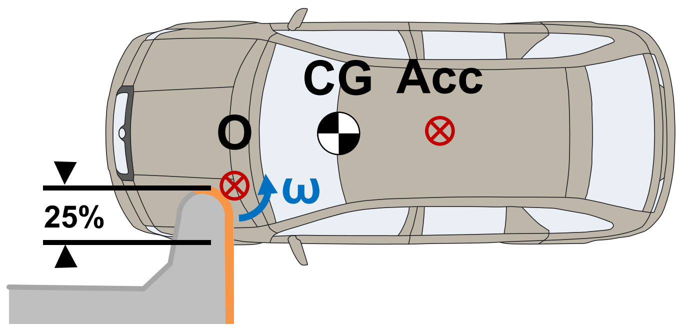

Figure 2.13 Schematic of the center of rotation

An example of the rotation corrected lateral and longitudinal velocities is shown in Figure 2.14.

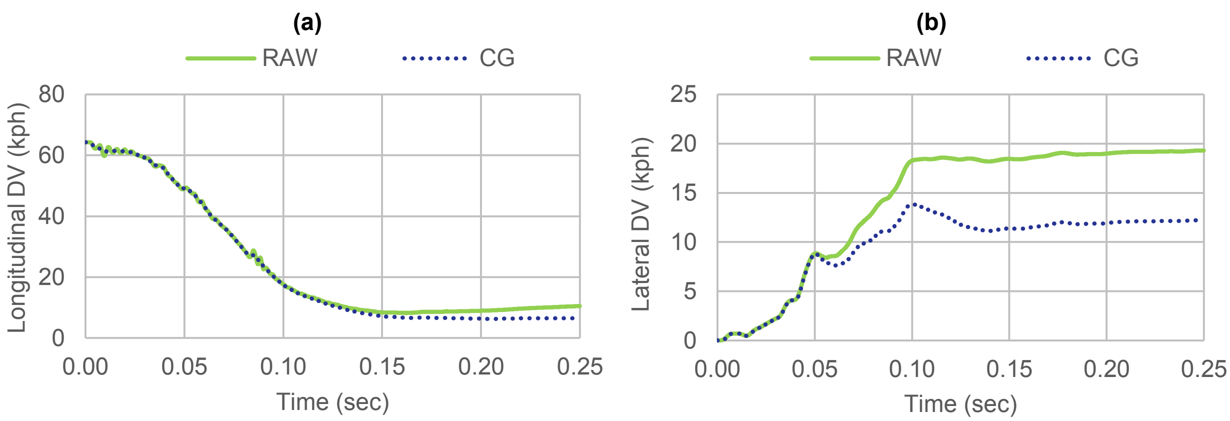

Figure 2.14 Effect of rotation correction on (a) longitudinal and (b) lateral delta-v for IIHS small overlap test on 2013 Hyundai Elantra (CEN1310)

2.4.1.5 Time-Zero Alignment

The time zero for the reference data was measured by a constant switch closure, intended to capture the instant of vehicle-MDB or vehicle-barrier first contact. For EDRs, the time zero was either be the time of algorithm wakeup or some other estimated time after impact, *e.g.* time of deployment. Thus, the velocity data of the reference and EDR may not have the same time zero.

Time-zero alignment first involved calculating the change in velocity between each of the time steps, referred to here as incremental delta-v, over the entire range of EDR and averaged reference values. To find the time when the EDR and reference incremental delta-v were most similar, the EDR incremental delta-v can be shifted in time by the reference time step (*i.e.* 0.1ms, 0.05ms, or 0.08ms). The reference incremental delta-v was then be summed in segments such that the time data matches the EDR incremental delta-v time data, shown in Figure 2.15a. With the EDR and reference incremental delta-v data lined up, an array of differences can be summed and squared to get a metric of best fit. This time shift allowed the EDR incremental delta-v to shift from -10ms to 30ms. An example of an optimized time shift of incremental delta-v is shown in Figure 2.15b. The original and time shifted EDR velocity are shown in Figure 2.16, along with the corrected reference. The time shift, and velocity shift for NHTSA full-frontal and IIHS small overlap crash tests, were only included for visualization of the reference and EDR velocity overlaid and had no effect on the analysis of delta-v accuracy. It should be emphasized that the time shift should not be interpreted as algorithm enable, wakeup, deployment time, or any other timing parameter related to airbags. The time shift was simply the outcome of time alignment of crash pulses. The airbag squib was not instrumented in these crash tests and no evaluation of airbag timing was possible for the studies.

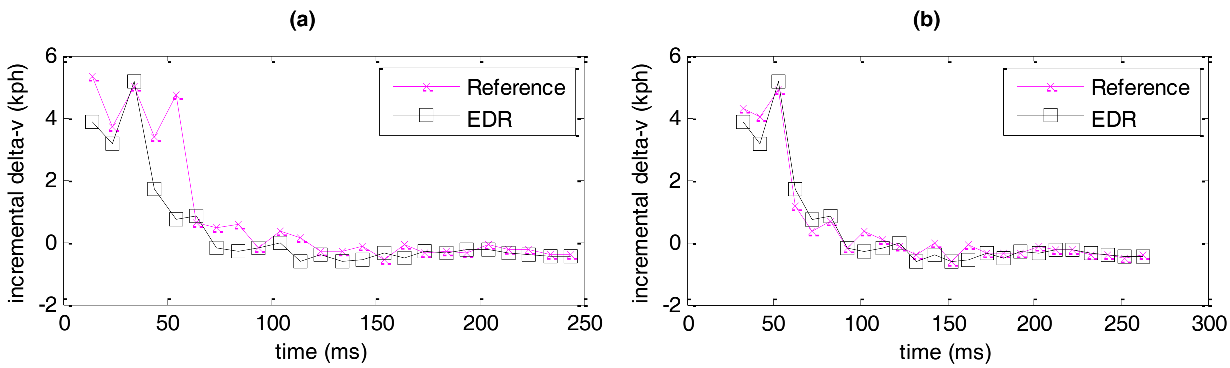

Figure 2.15 Incremental delta-v (a) prior to time shift and (b) after optimization at a time shift of 12.5ms for test 6798}, a side-impact crash test of a 2010 Ford Taurus

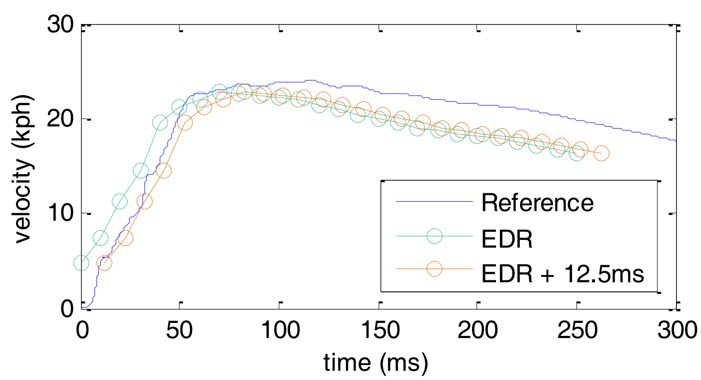

Figure 2.16 Sample time zero alignment shift where an EDR shift of 12.5ms resulted in the smallest sum of squares for test 6798, a side-impact crash test of a 2010 Ford Taurus

2.4.1.6 Velocity Alignment

In the crash tests where the test vehicle collided with a barrier, the delta-v recorded by the EDR at time zero was zero. In contrast, the impact speed given by reference instrumentation would be: 56 kph for NCAP full-frontal and 64 kph for the IIHS small overlap crash tests. Therefore, for alignment purposes, the vehicle-barrier impact speed from the reference instrumentation was added to the EDR delta-v values to allow comparison of EDR and reference velocity versus time for each test. In many cases, a small amount of delta-v was not recorded by some EDRs between the time of impact and the EDR time zero. Thus, for these cases, we will use the reference delta-v to compute the velocity of the vehicle when the EDR began recording. This computed velocity was incorporated into the EDR velocity (*i.e.* downward shift). For those cases in which the EDR recorded data prior to impact, the impact speed was also incorporated into the EDR velocity. An example of this operation is shown in Figure 2.17.

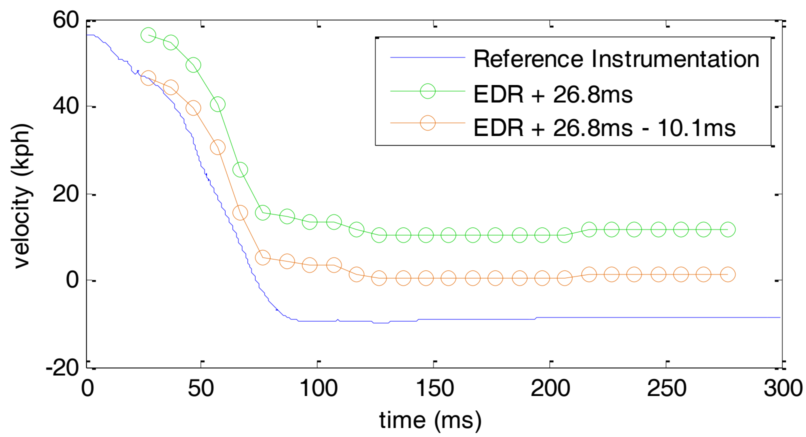

Figure 2.17 Example of EDR velocity shifted applied after time shift (test 7566, full-frontal)

2.4.2 Precrash Speed Accuracy

The speed at barrier impact for the full-frontal crash test can be determined from the NHTSA vehicle crash test database *.uds files and was utilized as the reference. For the IIHS small overlap tests, the reference speed was extracted from test reports. The EDRs, in our sample, recorded precrash speed for 5 seconds before the time zero at either 1 or 2 samples per second. The last precrash vehicle speed value recorded in the EDR, *i.e.* given at time zero, was compared with the crash test impact speed. As the SINCAP MDB and NHTSA small overlap crash test protocols required a stationary test vehicle, no precrash speed was reported in the EDRs and this comparison was not made.

2.4.3 Seat Belt Buckle Status Accuracy

This portion of the study examined seat belt buckle status accuracy. The study asked two questions: (a) was seat belt buckle status recorded and, (b) if recorded, was the status correct?

All test vehicles were equipped with seat belts for the front outboard occupants; however, not all EDRs report this information. Some EDRs included the data element, but were not configured to report a buckle status. The accuracy of seat belt buckle status was only penalized in these instances if the module was manufactured before the Part 563 effective date. Forty-four (44) of the 49 modules from the IIHS small overlap crash tests were required to meet Part 563.

Post-crash photographs from the test reports were manually inspected to confirm the seat belt buckle status and used as the reference value. The EDRs in the sample only recorded buckle information for the front occupants, *i.e.* seat belt buckle status was only determined for the driver and right front passenger. Recall, in the full-frontal crash test, the driver and right front passenger were occupied and belted. In the SINCAP MDB and small overlap crash tests (NHTSA and IIHS), the driver was buckled and occupied and the right front passenger seat was unoccupied and typically unbuckled.

2.4.4 Airbag Deployment Status Accuracy

This portion of the study examined airbag deployment accuracy. As in the seat belt status analysis, this section asked two questions: (a) was an airbag deployment status recorded and, (b) if recorded, was the status correct?

For all 3 crash modes, post-crash photographs from the test reports were inspected manually to determine whether the frontal airbag had deployed for both the driver and right front passenger. In addition, curtain and/or torso airbags deploy were examined for both the SINCAP MDB and small overlap tests as these airbags were not deployed in any of the full-frontal crash tests.

All EDRs which recorded an airbag deployment status, with the exception of Honda modules, reported a “Yes” or “No” deployment status. Some EDRs, however, recorded the time to deployment or time to criteria met for deployment. Note that time to frontal airbag deployment, or time to first stage deployment in multi-stage airbags, is a Part 563 Table I data element, *i.e.* a required element in EDR subject to the regulation. Side torso and curtain airbag time to deployment are Table II elements, *i.e.* not required. For the Honda modules, a non-zero number was assumed to imply an airbag deployment. The Honda Fit (7576) and the Honda Civic IMA (7713) EDR reports recorded a zero time to deployment without any accompanying data elements that specifically indicated deployment status. Honda was contacted regarding these cases and Honda determined that the EDR recorded a deployment after analysis of the HEX data.

For side airbags, the terminology used in the testing house reports did not necessarily match the terminology given in the EDR Bosch reports. Part 563 and the test reports use the terms “side torso” and “side curtain” airbags, which were the convention for the results. Thus, EDRs that described “thorax” airbags and “seat” airbags were included in the “torso” airbag classification. If a report only provided a “side airbag” deployment data element this was assumed to apply to all side airbags, *i.e.* “torso” and “curtain” airbags if equipped.

2.5 RESULTS

2.5.1 Full-Frontal Crash Tests

A description of the dataset is provided in Table A.1. All EDRs in our dataset contained a flag which indicated whether the event recording was complete. The event recording complete status of the EDRs is reported in Table A.2. Of the 41 modules, 39 EDRs reported indicated that the recording was successfully completed at the time of their original readout. The Dodge Journey (7471) recorded an interrupted status and had several precrash data elements display as “SNA” (signal not available) from t = –4.3 seconds to impact. The speed and delta-v data appeared to be recorded properly and were used in the analysis. The Dodge Durango (test 7585) reported an interrupted status but all data appeared to be recorded completely and has been used in this analysis.

2.5.1.1 Precrash Vehicle Speed

As shown in Table 2.8 and Table A.4, the EDR precrash vehicle speed was very close to the crash test speed in all 41 frontal crash tests. The differences ranged from –2.67 kph to +0.80 kph. On average, the EDRs in our sample underestimated crash test precrash speed by 0.58 kph (1.0% of the nominal impact speed of 56 kph). Only 5 EDRs differed from the test speed more than 1 kph.

Speed errors can be affected by truncation, resolution, and rounding of the values before being output to the Bosch CDR report. For example, the data limitations section of the Bosch CDR report for Toyota001 modules states “Resolution is 2km/h (1.2mph) and the value is rounded down and recorded.” Compared to the nominal 56 kph impact speed of NCAP full-frontal tests, an error of 2 kph is approximately 3.6%.

Similarly, the Bosch CDR reports for several Chrysler modules state in the data limitations section that “…the resolution is 1 kph,” which is 1.8% of the nominal impact speed. Most vehicles calculate speed in kph, but when the EDR records them it truncates to the next lower whole kph (GM, Ford, Chrysler, Honda), except Toyota which records to the next lower even kph. For example, in Table A.4, the Toyota RAV4 (test 7744) EDR reported a vehicle speed of 54 kph. Although Toyota EDRs recorded vehicle speed at a resolution of 2 kph, the Bosch report for Toyota EDRs reported precrash speed to the nearest tenth of a mph. Some Ford EDRs reported precrash speed to a resolution of the nearest tenth of a mph after unit conversion from kph. In contrast, the EDRs installed in GM, Chrysler, Honda, and some Ford vehicles only reported precrash speed to a resolution of the nearest integer.

Table 2.8 Comparison of EDR and crash test precrash speed by vehicle make

Vehicle Make	n	Avg. Test Speed(kph)	Avg. EDR Speed(kph)	Avg. Arithmetic Error (kph)	Avg. Absolute Error (kph)	RMS Error (kph)	Avg. Arithmetic Error (%)	Avg. Absolute Error (%)	RMS Error (%)
Chrysler	12	56.34	56.17	-0.17	0.41	0.46	-0.30%	0.72%	0.81%
Ford	6	56.41	55.85	-0.56	0.56	0.69	-0.98%	0.98%	1.22%
GM	7	56.21	56.43	0.22	0.44	0.53	0.40%	0.79%	0.95%
Honda	5	56.39	56.20	-0.19	0.36	0.37	-0.34%	0.64%	0.66%
Mazda	1	56.44	55.00	-1.44	1.44	1.44	-2.55%	2.55%	2.55%
Toyota	9	56.29	55.33	-0.96	0.96	1.37	-1.71%	1.71%	2.42%
Volvo	1	56.53	56.00	-0.53	0.53	0.53	-0.94%	0.94%	0.94%
Overall	41	56.32	55.95	-0.37	0.58	0.82	-0.66%	1.03%	1.45%

For the –2.67 kph largest error reported by the Toyota RAV4, up to 2 kph may be due to truncation to the next lower even kph value. The percentage (–4.7%) reported for this vehicle at 56 kph should not be applied to other manufacturers or to Toyotas at higher speeds, and it should be recognized that this error is in the negative direction and is not symmetrical about zero.

As shown in Table 2.8, the accuracy of the EDR precrash speed varied somewhat by vehicle manufacturer. The Honda EDRs in our sample had the lowest absolute difference between EDR and crash test (0.36 kph, or 0.6% of the nominal test speed of 56 kph). Mazda had the largest absolute difference (1.44 kph, or 2.6% of the nominal test speed of 56 kph).

2.5.1.2 Delta-V

Of the 41 EDRs, only one did not record delta-v (test 7460, a 2012 Chrysler Town & Country). For all other crash tests, the EDR delta-v values were time shifted to adjust for time zero differences between the EDR and the reference instrumentation. The time shifts are shown in Table A.2. Most EDRs in our sample defined time zero to be the time of algorithm enable, wakeup, or recording trigger. For 6 GM EDRs (test 7488, 7494, 7509, 7521, 7564, and 7582), the time zero in the Bosch report was defined to be the time of deployment. To align these tests with the balance of the data set, the time of first stage deployment was subtracted from the algorithm derived time shift.

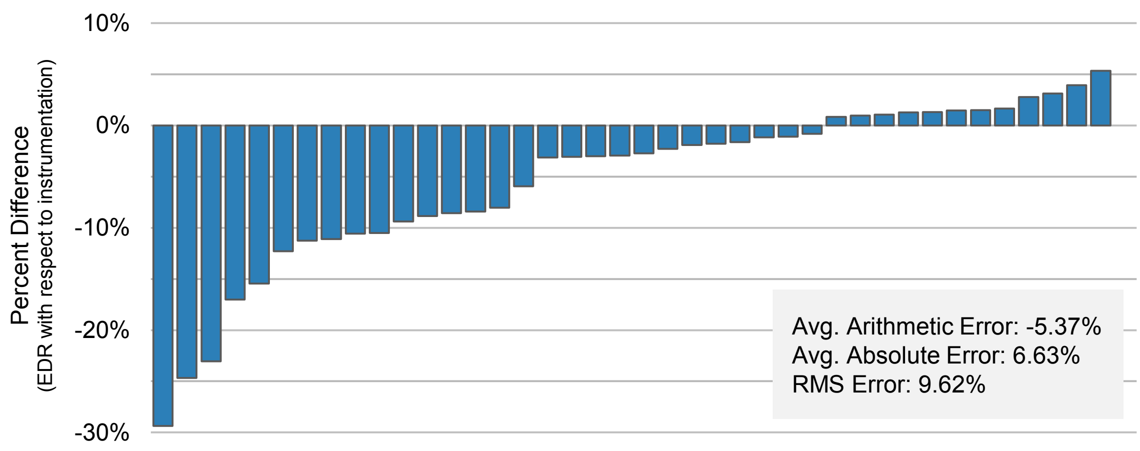

Figure 2.18 Distribution of EDR time series final delta-v percent difference with respect to reference instrumentation

The time shifted velocity graphs are shown in Figure A.1 and incremental delta-v graphs are shown in Figure A.2. As shown in this table, the alignment algorithm appears to properly time align the EDR data with reference instrumentation. In a small number of cases, the time shift was negative. In these cases, the first reported time point in the EDR Bosch report time series was not zero.

Table 2.9 Comparison of reference instrumentation and EDR final delta-v by vehicle make among full-frontal crash tests

Vehicle Make	n	Avg. Test Delta-V (kph)	Avg. EDR Delta-V (kph)	Avg. Arithmetic Error (kph)	Avg. Absolute Error (kph)	RMS Error (kph)	Avg. Arithmetic Error (%)	Avg. Absolute Error (%)	RMS Error (%)
Chrysler	12	62.15	61.27	-0.94	1.79	2.63	-1.53%	2.88%	4.20%
Ford	6	63.23	62.74	-0.49	1.24	1.68	-0.78%	1.96%	2.66%
GM	7	62.40	59.14	-3.26	4.41	4.97	-5.16%	7.05%	7.94%
Honda	5	63.28	58.40	-4.88	6.54	8.70	-7.60%	10.28%	13.65%
Mazda	1	64.98	50.00	-14.98	14.98	14.98	-23.05%	23.05%	23.05%
Toyota	9	63.25	56.68	-6.58	6.71	8.36	-10.34%	10.55%	13.13%
Volvo	1	62.97	61.00	-1.97	1.97	1.97	-3.13%	3.13%	3.13%
Overall	41	62.82	59.44	-3.42	4.20	6.13	-5.37%	6.63%	9.62%

A table of delta-v measurements for each test is shown in Table A.5. The distribution of final delta-v percent difference for longitudinal data is shown graphically in Figure 2.18. Further accuracy metrics are presented in Table 2.9. On average, the EDRs in our sample underestimated reference final delta-v by 4.20 kph (6.6% error). The largest observed error was 19 kph for the 2012 Toyota Sienna (test 7615). In our dataset, Ford EDRs had the lowest average absolute error (1.24 kph or 2.0%) with reference instrumentation. The Mazda EDR (test 7566) had the highest average absolute difference (14.98 kph or 23.1%).

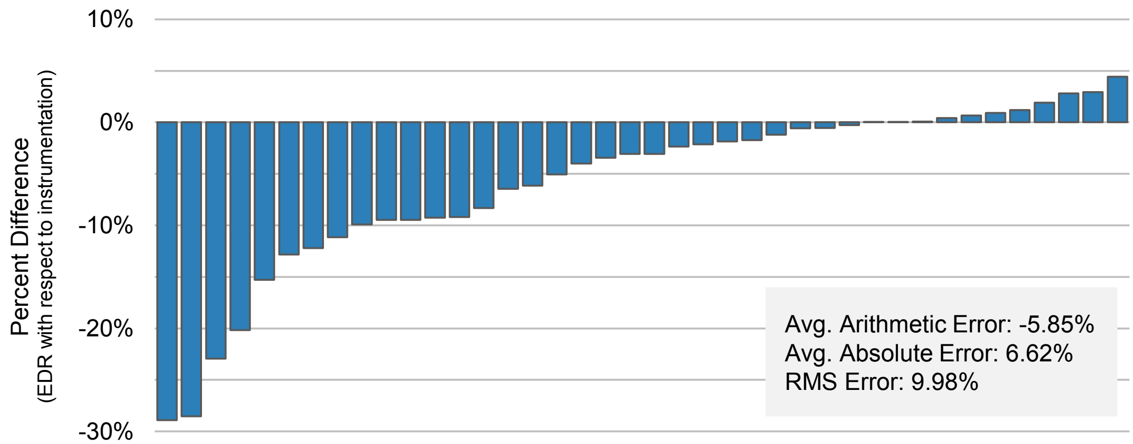

Figure 2.19 Distribution of EDR time series maximum delta-v percent difference with respect to reference instrumentation

Figure 2.19 and Table 2.10 present a comparison of maximum delta-v for EDR versus reference instrumentation. The average absolute error between the reference and the EDR was 4.32 kph (6.6%). The 2012 Honda CR-Z (test 7622) had the greatest error, 19.16 kph (28.5%). Across OEMs, the average absolute error for maximum delta-v ranged between Ford's 1.23 kph (1.9%) and Mazda's 15.19 kph (23.0%).

Table 2.10 Comparison of reference instrumentation and EDR time series maximum longitudinal delta-v by vehicle make among full-frontal crash tests

Vehicle Make	n	Avg. Test Delta-V (kph)	Avg. EDR Delta-V (kph)	Avg. Arithmetic Error (kph)	Avg. Absolute Error (kph)	RMS Error (kph)	Avg. Arithmetic Error (%)	Avg. Absolute Error (%)	RMS Error (%)
Chrysler	12	64.50	64.00	-0.70	1.89	2.52	-1.08%	2.93%	3.91%
Ford	6	65.72	64.66	-1.07	1.23	1.80	-1.63%	1.88%	2.77%
GM	7	64.01	60.71	-3.29	4.09	4.82	-5.15%	6.42%	7.61%
Honda	5	66.20	59.20	-7.00	7.00	10.49	-10.46%	10.47%	15.68%
Mazda	1	66.19	51.00	-15.19	15.19	15.19	-22.95%	22.95%	22.95%
Toyota	9	65.33	58.30	-7.03	7.03	8.65	-10.79%	10.79%	13.29%
Volvo	1	64.58	62.00	-2.58	2.58	2.58	-3.99%	3.99%	3.99%
Overall	41	65.03	61.27	-3.83	4.32	6.54	-5.85%	6.62%	9.98%

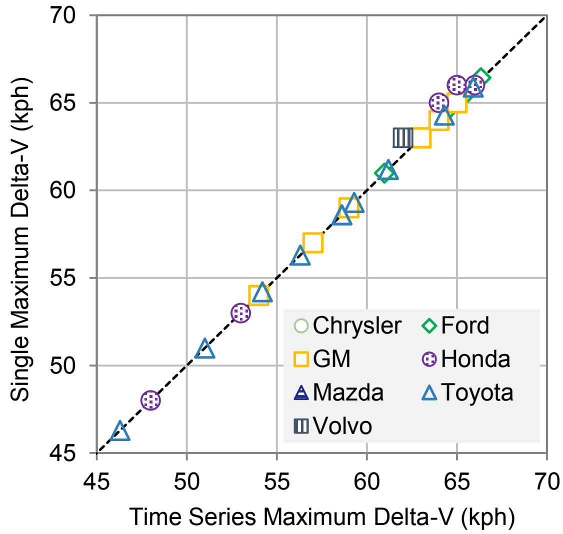

Figure 2.20 Comparison of calculated and reported maximum EDR delta-v by vehicle make

Figure 2.20 compares the EDR maximum delta-v determined from the time series to that reported by the Bosch report. Note that the EDR maximum delta-v on the Bosch report may be different than that observed in the table of delta-v values versus time. The largest error seen was only 1 kph (1.6%). This can be due to calculating at an intermediate point in time, or by using the NHTSA definition of the end of a crash to calculate the "maximum" value. Table 2.11 compares the single maximum delta-v value, as listed on the Bosch report, against the test maximum delta-v. Due to the similarity of the single CDR reported maximum to the maximum found from the time series data, the accuracy metrics are also similar. The average absolute error between the reference instrumentation and the EDR was 4.67 kph (7.2% error).

Table 2.11 Comparison of reference instrumentation and EDR reported single maximum delta-v by vehicle make

Vehicle Make	n	Avg. Test Delta-V (kph)	Avg. EDR Delta-V (kph)	Avg. Arithmetic Error (kph)	Avg. Absolute Error (kph)	RMS Error (kph)	Avg. Arithmetic Error (%)	Avg. Absolute Error (%)	RMS Error (%)
Chrysler	12	64.50	63.29	-0.99	2.27	2.96	-1.54%	3.53%	4.62%
Ford	6	65.72	64.72	-1.01	1.21	1.77	-1.54%	1.84%	2.72%
GM	7	64.01	60.71	-3.29	4.09	4.82	-5.15%	6.42%	7.61%
Honda	5	66.20	59.60	-6.60	7.25	10.51	-9.85%	10.85%	15.70%
Mazda	1	66.19	51.00	-15.19	15.19	15.19	-22.95%	22.95%	22.95%
Toyota	9	65.33	58.30	-7.03	7.03	8.65	-10.79%	10.79%	13.29%
Volvo	1	64.58	63.00	-1.58	1.58	1.58	-2.45%	2.45%	2.45%
Overall	41	65.03	60.92	-4.14	4.67	6.87	-6.33%	7.15%	10.48%

In 39 of 41 cases, EDR recording duration was clearly sufficient to capture the entire crash pulse. In the remaining 2 cases (test 7622, a Honda CR-Z, and test 7732, a Honda CR-V), the ACM deployment algorithm appears to have gone back to sleep and stopped recording new values at 130ms and 100ms respectively. While the reference crash pulse in these two cases appears to be complete, the ACM algorithm crash pulse does not appear to be complete at the time that the ACM stopped recording.

2.5.1.3 Seatbelt Buckle Status

In all of the crash tests in our sample, both the driver and right front passenger were belted. All EDRs which recorded driver belt buckle status (37 of 41 cases) correctly recorded the status as buckled. In the remaining four vehicles, all Chrysler vehicles, the Bosch report stated that the module was not configured to store driver buckle status. These results are seen in Table A.3.

Likewise, all EDRs which recorded right front passenger belt buckle status (34 of 41 tests) correctly recorded the status as buckled. In the remaining 7 tests, the Bosch report stated that the module was not configured to store passenger buckle status (5 Chrysler EDRs), the passenger buckle status was not active (1 Ford EDR), or the passenger buckle status was not available (1 GM EDR). These results are seen in Table A.3.

2.5.1.4 Airbag Deployment

The frontal airbag of both the driver and right front passenger deployed in all crash tests. In 100% of full-frontal crash tests (41 vehicles) the EDR correctly reported airbag deployment of a driver airbag and right front passenger airbag. The results are shown in Table A.3.

2.5.2 Side-Impact Crash Test

Of the 75 EDRs in our dataset, 70 had an event recording complete flag. All 70 indicated that the event was successfully recorded, as shown in Table A.6. Five (5) Toyota EDRs did not have recording status flags: the 2011 Tacoma (7103), 2011 Tundra Double Cab (7343), 2011 Corolla (7353), 2012 Tundra (7586), and 2012 Corolla (7749). None reported any diagnostic trouble codes which would indicate EDR recovery problems. However, the EDR reports did indicate that much of the HEX data was not imaged from the EDR into the report. Additionally, the report identified these modules to be from the "02EDR" ECU generation, among one of the oldest EDR families offered by Toyota. In addition to not reporting a recording status flag, these modules did not report any information regarding seat belt buckle status or frontal airbag deployment. The remaining Toyota EDRs in this analysis contain modules from later generations ("04EDR" and "06EDR"), suggesting that these data elements were either not recorded or not reported in these early modules.

2.5.2.1 Delta-V

Of the 75 extracted EDRs, all 75 recorded lateral delta-v and 55 recorded longitudinal delta-v. The 20 EDRs that did not record longitudinal delta-v were Toyota modules. None of the Toyota EDRs in this study recorded longitudinal delta-v.

The sensor pair used to compute the velocity at the CG, as well as the velocity at the CG, are reported in Table A.7. Likewise, the time shifts are shown in that same table. For 6 EDRs, the final time shifts were negative: 2011 Toyota Camry (6952), 2011 Toyota Tacoma (7103), 2011 Ford Edge (7151), 2011 Buick Lucerne (7363), 2011 Toyota Scion tC (7364), and 2012 Dodge Journey (7473).

Table 2.12 shows several error metrics by vehicle make for a comparison between the reference and maximum EDR lateral delta-v taken from the time series data. GM showed the lowest average absolute error with 2.07 kph (8.9%) and Toyota showed the greatest average absolute error with 6.34 kph (24.4%). As shown in Table A.6, Toyota modules also represent the OEM with the shortest EDR recording duration, less than 100ms, with rarely more than 70ms recorded after algorithm enable.

Overall, the average absolute error was 4.05 kph (15.9%). Considering the EDRs individually, the 2011 Ram 1500 Crew (7111) showed the greatest lateral absolute error 8.5 kph (37.6%). The 2012 Toyota Tundra (7586) and the 2012 Scion iQ (7733) also showed absolute errors greater than 35%. The 2010 Chevrolet Camaro (6746), 2011 Jeep Grand Cherokee (7036), 2012 Ford Explorer (7492), and 2012 Chrysler 300 (7593) showed the smallest lateral arithmetic errors, less than 1%. Out of the 75 EDR reports that provided lateral delta-v, 66 under-predicted the rotation-corrected reference velocity, shown in Figure 2.21.

Table 2.12 Comparison of reference instrumentation and EDR time series maximum lateral delta-v by vehicle make among side-impact moving deformable barrier crash tests

Vehicle Make	n	Avg. Test Delta-V (kph)	Avg. EDR Delta-V (kph)	Avg. Arithmetic Error (kph)	Avg. Absolute Error (kph)	RMS Error (kph)	Avg. Arithmetic Error (%)	Avg. Absolute Error (%)	RMS Error (%)
Chrysler	16	20.59	25.31	-4.73	4.73	5.45	-18.6%	18.6%	21.6%
Ford	17	23.23	25.44	-2.21	2.61	3.37	-8.4%	9.9%	12.6%
GM	16	23.09	23.84	-0.75	2.07	2.54	-2.7%	8.9%	11.2%
Honda	4	22.84	25.89	-3.05	3.05	3.76	-12.0%	12.0%	14.8%
Mazda	2	24.54	26.84	-2.29	2.29	3.04	-8.7%	8.7%	11.6%
Toyota	20	20.06	26.40	-6.34	6.34	6.66	-24.4%	24.4%	25.9%
Overall	75	22.14	25.77	-3.59	4.05	4.88	-13.8%	15.9%	19.1%

Table A.7 shows the arithmetic error for both delta-v comparisons. Figure A.3 shows the overlay of corrected, averaged reference and EDR velocity and Figure A.4 shows the overlay of incremental delta-v at the optimized time shift.

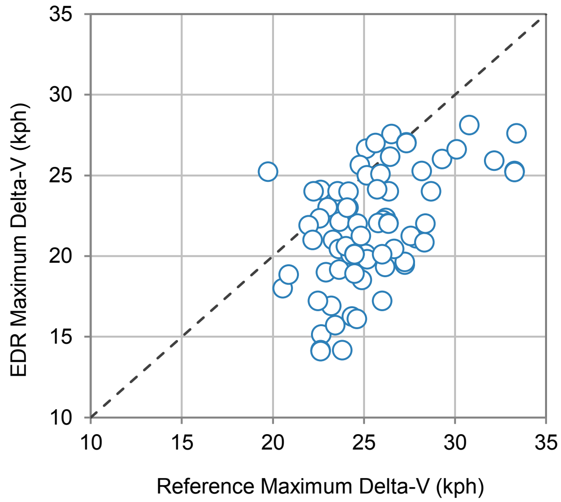

Figure 2.21 Distribution of EDR maximum delta-v with respect to the reference maximum delta-v, where the dotted line represents identical maximum values

2.5.2.2 <u>Seatbelt Buckle Status</u>

In all cases, if the driver seat belt buckle status was recorded, then it was reported correctly. For the driver position, 70 out of 75 EDRs reported seat belt buckle information. The remaining 5 EDRs did not report any information about seat belt status. Of the 70 EDRs, 65 reports correctly recorded that seat belt buckle status for the driver was buckled. The 5 remaining EDRs indicated that the module was not configured to record seat belt buckle status for the driver.

Similarly, in all cases, if the right front passenger seat belt buckle status was recorded, then it was recorded correctly. Out of the 75 EDR reports, 69 recorded seat belt buckle information and 6 did not report any information. Sixty-four (64) of the 69 EDRs that reported passenger seat belt buckle information correctly identified the seat belt status: 63 were unbuckled and 1 was buckled (2011 Ford Range, test no. 7341). The 5 remaining EDRs indicated that the module was not configured to record seat belt buckle status for the driver.

Of the 6 EDRs that did not report any information regarding seat belt buckle status, 5 were Toyota EDRs: the 2011 Tacoma (7103), 2011 Tundra Double Cab (7343), 2011 Corolla (7353), 2012 Tundra (7586), and 2012 Corolla (7749). The remaining EDR was a 2012 Ford F250 Super Crew (7650). For the EDR reports that did not provide a seat belt buckle status, 3 did not report for both the driver and the passenger, 2 reported only the driver status, and 2 reported only the passenger status. These results are shown in Table A.6. Although the model year (MY) 2010-2012 EDRs are not required to meet Part 563, seat belt buckle status is a data element that must be recorded by MY 2013 and later EDRs.

2.5.2.3 Airbag Deployment

For vehicles that reported frontal, side torso, or side curtain airbag deployment information, all vehicles recorded the correct status. Of the 75 vehicles analyzed in this study, all were equipped with a frontal airbag. All 75 vehicles were also equipped with either a side torso bag or side curtain bag, where 64 were equipped with both, 5 were equipped with only the curtain airbag, and 6 were equipped with only the side torso airbag. These results are shown in Table A.8.

The side torso airbag deployed in all 70 equipped test vehicles. Of these, 66 EDRs offered a deployment status and 4 did not offer any deployment information regarding side torso airbags. These 4 vehicles were the 2011 Toyota Tacoma (7103), 2011 Toyota Tundra Double Cab (7343), 2011 Scion tC (7364), and 2012 Mazda Mazda3 (7448). Thirty-five (35) out of 66 EDRs reported side time to deployment, a data element in Table II of Part 563. Although the regulation does not apply to the vehicles in this analysis, Part 563 requires "side airbag" time to deploy in MY 2013 EDRs "*if the data is recorded in non-volatile memory for the purpose of subsequent downloading.*"

The side curtain airbag deployed in all 69 equipped test vehicles. Sixty-five (65) out of 69 EDRs reported a deployment status. The remaining 4 EDRs did not offer any deployment information regarding curtain airbags. These 4 EDRs were the same modules that also did not report side torso airbag information even though they were equipped and deployed. Time to deploy was reported by 30 out of 65 EDRs that offered curtain airbag information. Curtain airbag time to fire is also a Part 563 Table II data element for MY 2013 vehicles.

For both the torso and curtain airbags, the Honda Fit (7576) and the Honda Civic IMA (7713) reports recorded 0ms for the time to deployment data element. The Honda reports did not contain a specific data element describing deployment. It was unclear from the report whether 0ms time to deployment meant that the airbag did not deploy or that the airbag deployed at time zero (T0). The Bosch CDR report data limitations for Honda EDRs states:

> *T0 is established by whichever of the following occurs first: (1) the change in longitudinal velocity at the SRS control unit equals or exceeds 0.8km/h over a 20ms timeframe; (2) the change in lateral velocity at the SRS control unit equals or exceeds 0.8km/h over a 5ms timeframe; or (3) a commanded deployment of any type of non-reversible deployable restraint device (e.g. airbag or seatbelt pretensioner).*

Honda looked at the report HEX data and Honda determined that both driver side airbags, *i.e.* torso and curtain, were deployed and that T0 in these tests was the time at which the airbag deployed.

Only 5 driver frontal airbags were deployed in all 75 side impact tests. All 5 were Toyota vehicles. Of these 5, only the 2010 4Runner (6861) and 2012 4Runner (7753) offered information about the frontal airbag. Both 4Runner modules reported a frontal airbag status correctly identified as deployed and a 2ms time to deployment. The remaining 3 vehicles did not offer any frontal airbag deployment information: 2011 Tacoma (7103), 2011 Tundra Double Cab (7343), and 2012 Tundra (7586). Note, although the EDRs in this analysis do not need to meet Part 563, frontal airbag time to fire is a Table I required element.

2.5.3 Small Overlap Crash Tests

A description of the dataset is provided in Table A.9, including the event recording complete status of the EDRs. Neither a CDRx nor a PDF file was available for the two Acura TSX IIHS tests, but the IIHS documentation provided time-series delta-v data extracted from the EDRs and all data appeared to be recorded completely and were used in this analysis. Of the remaining 58 crash tests, 57 reported indicated that the recording was successfully completed at the time of their original readout. The Mazda CX-9 (CEN1408) recorded two events, both of which indicated an interrupted record status. For the event corresponding to the crash tests, the engine throttle and service brake precrash variables displayed "SNA" (signal not available) for all time points. The speed and delta-v data appeared to be recorded properly and were used in the analysis.

2.5.3.1 Precrash Vehicle Speed

Table A.10 provides the error in precrash speed for each crash tests and Table 2.13 summarizes the error by OEM. Note that these precrash speed results only include the IIHS crash tests as they involved the test vehicle impacting a rigid barrier, as opposed to the NHTSA tests which involved an RMDB impacting the stationary test vehicle. Across all crash tests, the error ranged from –3.3 kph (2013 Kia Soul CEN1317) to +0.80 kph (2013 Kia Rio CEN 1330 and 2014 Jeep Grand Cherokee CEN1404). The majority underestimated the reference instrumentation. On average, the EDRs in our sample underestimated crash test precrash speed by 0.60 kph (less than 1.0% of the 64 kph impact speed). Of the 47 EDRs, 15 (32%) differed from the test speed more than 1 kph. Lumped by manufacturer, Ford EDRs (n=6) showed the least arithmetic error (-0.10 kph; -0.2%) and Hyundai (n=5) EDRs showed the greatest arithmetic error (-1.50 kph; -2.3%), with respect to the reference instrumentation. In terms of absolute error, Honda EDRs (n=7) showed the lowest error (0.26 kph; 0.4%) and Hyundai EDRs (n=5) showed the greatest arithmetic error (1.82 kph; 2.8%), with respect to the reference instrumentation. RMS error was similar to absolute error.

Honda EDRs (n=7) showed the lowest RMS error (0.27 kph; 0.4%) and Hyundai EDRs (n=5) showed the greatest RMS error (2.03 kph; 3.2%), with respect to the reference instrumentation.

Table 2.13 EDR comparison to reference precrash speed for small overlap crash tests

Vehicle Make	n	Avg. Test Speed(kph)	Avg. EDR Speed(kph)	Avg. Arithmetic Error (kph)	Avg. Absolute Error (kph)	RMS Error (kph)	Avg. Arithmetic Error (%)	Avg. Absolute Error (%)	RMS Error (%)
Chrysler	6	64.2	64.5	0.29	0.44	0.54	0.5%	0.7%	0.8%
Ford	3	64.4	64.3	-0.10	0.50	0.51	-0.2%	0.8%	0.8%
GM	8	64.3	64.1	-0.18	0.35	0.39	-0.3%	0.5%	0.6%
Honda	5	64.3	64.0	-0.26	0.26	0.27	-0.4%	0.4%	0.4%
Hyundai	5	64.3	62.8	-1.50	1.82	2.03	-2.3%	2.8%	3.2%
Mazda	7	64.3	63.4	-0.90	0.90	0.99	-1.4%	1.4%	1.5%
Nissan	3	64.4	63.7	-0.73	0.73	0.84	-1.1%	1.1%	1.3%
Toyota	8	64.3	63.3	-1.08	1.08	1.36	-1.7%	1.7%	2.1%
Volvo	2	64.2	63.0	-1.24	1.24	1.24	-1.9%	1.9%	1.9%
Overall	**47**	**64.3**	**63.7**	**-0.60**	**0.79**	**1.05**	**-0.9%**	**1.2%**	**1.6%**

2.5.3.2 <u>Delta-V</u>

Of the 60 EDRs extracted from small overlap crash tests, all 60 recorded longitudinal delta-v and 49 recorded coupled lateral delta-v. The 11 EDRs which did not record lateral delta-v were composed of 1 Honda module, 8 Toyota modules, and 2 Volvo modules. The averaged sensor pair used to compute the velocity at the CG, as well as the velocity at the CG, are reported in Table A.9 for the NHTSA crash tests. Additionally, the angular velocity and angular acceleration utilized in the IIHS crash tests are also included in Table A.9. The distribution of peak raw rate used to correct for yaw motion is shown in Figure 2.22 . The average peak yaw rate was -2.6 rad/sec (-148 degrees/sec).

Across all crash tests, the longitudinal delta-v error ranged from –16.9 kph (2014 Honda Pilot CEN1405) to +11.5 kph (2013 Fiat 500 CEN1325), with the half underestimating the reference instrumentation. This underestimation is shown in Figure 2.23. On average, the EDRs in our sample underestimated the rotation corrected longitudinal delta-v by 0.77 kph (2% of the 50 kph impact speed). Lumped by manufacturer, Volvo EDRs (n=2) showed the least arithmetic error (-0.39 kph; -0.9%) and Hyundai (n=5) EDRs showed the greatest arithmetic error (4.04 kph; 8.2%), with respect to the reference instrumentation. This is shown in Table 2.14. Volvo EDRs also showed the least error in longitudinal delta-v according to average absolute error (0.39 kph; 0.9%) and RMS error (0.40 kph; 0.9%); however, Volvo had the smallest number of samples in our study. Ford showed the greatest absolute error (4.35 kph; 8.6%) and Honda showed the greatest RMS error (6.48 kph; 13.2%).

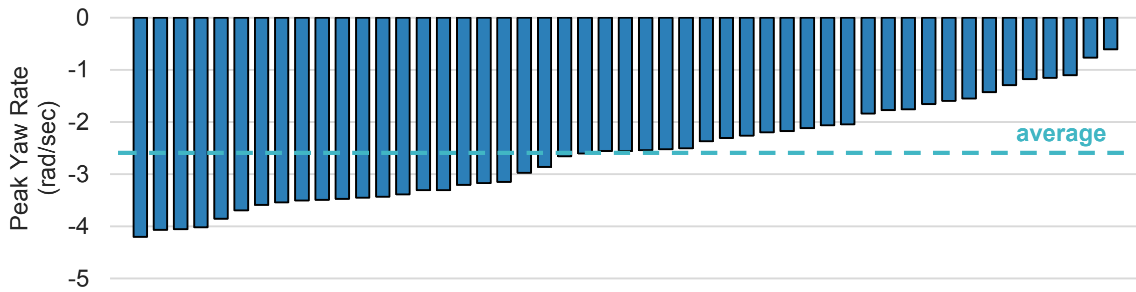

Figure 2.22 Simulated peak yaw rate for the 49 IIHS small overlap crash tests

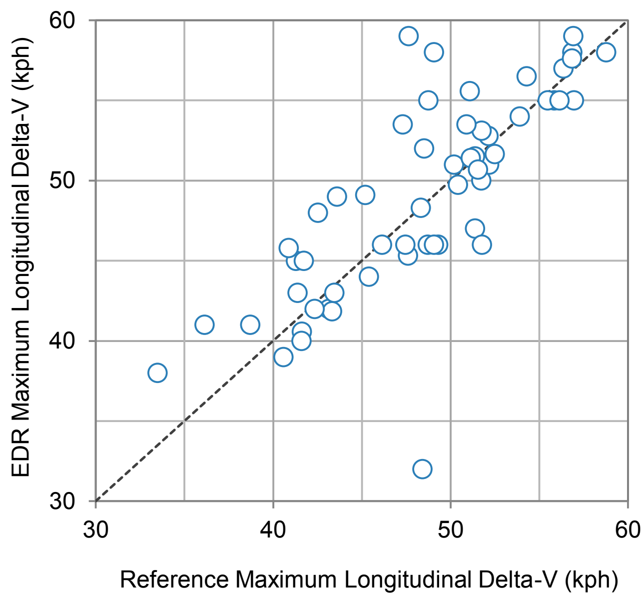

Figure 2.23 Comparison of EDR maximum longitudinal delta-v to reference instrumentation in small overlap crash tests after correction rotation

Similarly, Table 2.15 shows several error metrics by manufacturer for a comparison between the reference and maximum EDR lateral delta-v taken from the time series data. Considering the EDRs individually, the 2013 Hyundai Tucson (CEN1237) showed the greatest underestimation of lateral, arithmetic error -9.5 kph (57.7%) and the 2013 Mazda Mazda2 (CEN1324) showed the greatest overestimation of lateral, arithmetic error (3.8 kph; 24%). On average, the EDRs in our sample underestimated the rotation corrected lateral delta-v by 3.3 kph (-18%). As the magnitude of the lateral delta-v is much smaller than the longitudinal component, the percentages calculated relative to the impact delta-v are larger.

Table 2.14 EDR comparison to reference longitudinal delta-v after correction for rotation in small overlap crash tests

Vehicle Make	n	Avg. Test Delta-V (kph)	Avg. EDR Delta-V (kph)	Avg. Arithmetic Error (kph)	Avg. Absolute Error (kph)	RMS Error (kph)	Avg. Arithmetic Error (%)	Avg. Absolute Error (%)	RMS Error (%)
Chrysler	8	47.6	49.2	1.65	2.84	4.52	3.8%	6.4%	10.0%
Ford	6	49.4	52.4	2.98	4.35	5.45	5.7%	8.6%	10.7%
GM	12	47.1	45.5	-1.64	2.66	3.05	-2.9%	5.8%	6.8%
Honda	7	55.7	53.4	-2.35	3.29	6.48	-4.8%	6.5%	13.2%
Hyundai	5	50.6	54.6	4.04	4.04	4.28	8.2%	8.2%	8.8%
Mazda	7	49.7	51.1	1.49	1.97	2.69	3.7%	4.5%	6.4%
Nissan	3	43.8	45.0	1.18	2.43	3.26	2.7%	5.6%	7.5%
Toyota	10	49.8	51.6	1.80	2.14	2.91	3.9%	4.6%	6.4%
Volvo	2	42.9	42.5	-0.39	0.39	0.40	-0.9%	0.9%	0.9%
Overall	**60**	**49.1**	**49.9**	**0.77**	**2.79**	**4.10**	**1.8%**	**5.9%**	**8.7%**

Table 2.15 EDR comparison to reference lateral delta-v after correction for rotation in small overlap crash tests

Vehicle Make	n	Avg. Test Delta-V (kph)	Avg. EDR Delta-V (kph)	Avg. Arithmetic Error (kph)	Avg. Absolute Error (kph)	RMS Error (kph)	Avg. Arithmetic Error (%)	Avg. Absolute Error (%)	RMS Error (%)
Chrysler	8	17.33	13.26	-4.07	4.49	4.78	-22.4%	25.5%	26.7%
Ford	6	18.95	16.07	-2.88	3.05	3.91	-14.1%	15.1%	18.8%
GM	12	17.51	15.08	-2.42	3.33	4.01	-12.8%	19.1%	22.9%
Honda	6	17.57	11.19	-6.38	6.38	6.75	-35.4%	35.4%	36.4%
Hyundai	5	15.36	10.80	-4.56	4.59	5.58	-29.4%	29.7%	35.4%
Mazda	7	15.97	14.43	-1.54	3.03	3.64	-8.7%	18.0%	20.9%
Nissan	3	17.88	17.33	-0.55	0.55	0.55	-3.1%	3.1%	3.1%
Toyota	2	17.47	13.36	-4.11	4.67	6.22	-24.8%	27.9%	37.3%
Volvo	0	—	—	—	—	—	—	—	—
Overall	**49**	**17.24**	**13.97**	**-3.28**	**3.83**	**4.67**	**-18.3%**	**22.0%**	**26.4%**

Lumped by manufacturer, Nissan EDRs (n=3) showed the least arithmetic error (-0.55 kph; -3.1%) and Honda (n=6) EDRs showed the greatest arithmetic error (-6.38 kph; -35.4%), with respect to the reference instrumentation. Nissan EDRs also showed the least error in lateral delta-v according to average absolute error (0.55 kph; 3.1%) and RMS error (0.55 kph; 3.1%). Similarly, Honda showed the greatest absolute error (6.38 kph; 35.4%) and RMS error (6.75 kph; 36.4%). Of the 49 EDRs, 40 (67%) underestimated the rotation-corrected reference instrumentation. Note that all the EDRs are located ahead of the vehicle CG and are subject to the same rotational effects. Figure 2.24 shows the general relationship of lateral absolute error with the Bosch CDR reported EDR location. With increasing distance from the estimated vehicle CG, there was increasing lateral absolute error.

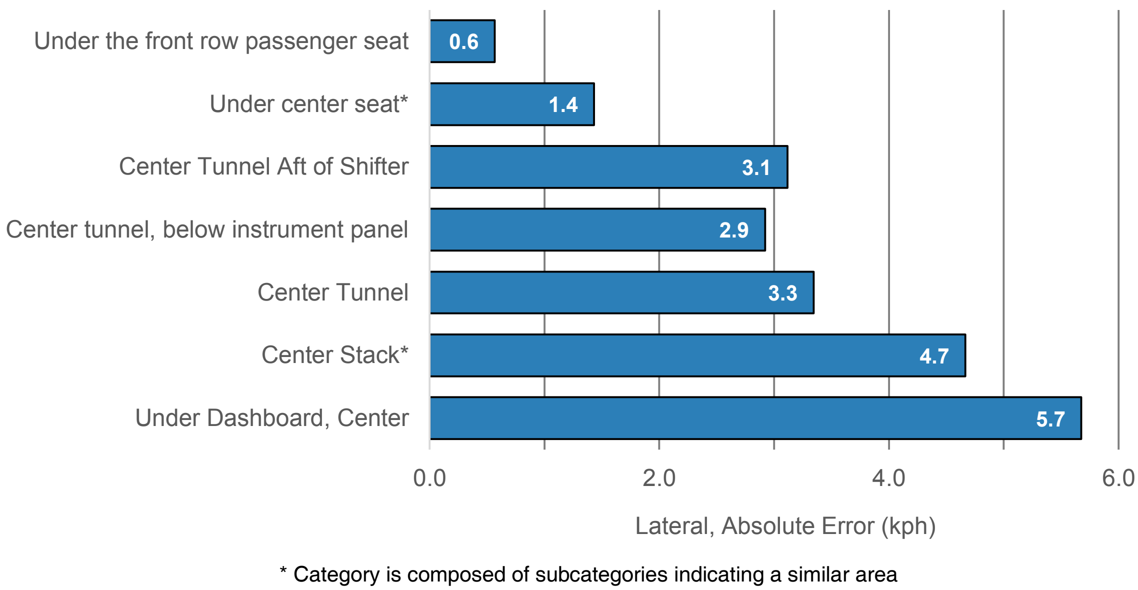

Figure 2.24 Average, absolute lateral error by Bosch CDR indicated EDR location

2.5.3.3 <u>Seatbelt Buckle Status</u>

As shown in Table A.11, in all cases, if the driver seat belt buckle status was recorded, then it was reported correctly. For the driver position, 57 out of 60 EDRs reported seat belt buckle information. Of the remaining 3 EDRs, 2 were the Acura modules which were not accompanied with a CDRx or PDF file, and the last was a 2012 Dodge Avenger (CEN1216) which was not configured for seat belt status. Of the 57 EDRs, all reports correctly recorded that seat belt buckle status for the driver was buckled.

Similarly, in all cases, if the right front passenger seat belt buckle status was recorded, then it was recorded correctly. Out of the 60 EDR reports, 55 recorded seat belt buckle information. All of the 55 EDRs that reported passenger seat belt buckle information correctly identified the right front passenger seat belt status to be unbuckled. Of the 5 remaining EDRs, 3 were the same that did not provide seat belt buckle information among the drivers: 2012 Acura TSX (CEN1202), 2012 Acura TSA (CEN1213), and 2012 Dodge Avenger (CEN1216). The 2014 Mazda CX-9 (CEN1408) did not report the seat belt buckle status data element for the right front passenger and the 2011 Dodge Ram 1500 (RB0330) was not configured to report this data element.

2.5.3.4 Airbag Deployment

For vehicles that reported frontal, side torso, or side curtain airbag deployment information, all vehicles recorded the correct status. Of the 60 vehicles analyzed in this study, all were equipped with a frontal airbag and at least one type of side airbag. There were 56 test vehicles equipped with a driver-side torso airbag, 39 of which deployed. All test vehicles equipped with a driver-side curtain airbag, 51 of which deployed. These results are shown in Table A.11.

All driver frontal airbags were deployed in all 60 side impact tests. All EDRs reported the driver frontal airbag data element and correctly reported that it had deployed. Of the 60 frontal airbag deployments, 17 also reported a time to deploy.

The side torso airbag was equipped in 56 test vehicles and deployed in 39 crash tests. Of the 39 side torso deployments, 36 EDRs which recorded the data element correctly reported the deployment. Of the remaining 3 EDRs, 2 were the Acura modules which were not accompanied with a CDRx or PDF file and the remaining module, a 2012 Toyota Camry (CEN1215), did not report this data element. The Camry, however, reported 89 for "Time to Deployment Command, B-Pillar Sensor (msec)" and reported "Not Commanded" for "Time to Deployment Command, C-Pillar Sensor (msec)", but it was not clear which airbag deployments these data elements referred to. Among the remaining 17 tests vehicles which were equipped with a side torso airbag that did not deploy, 13 EDRs correctly reported the non-deployment. The remaining 4 modules indicated that the signal was not available.

The driver-side curtain airbag was equipped in all test vehicles and deployed in 51 crash tests. Of the 51 side torso deployments, 48 EDRs which recorded the data element correctly reported the deployment. Of the remaining 3 EDRs, 2 were the Acura modules which were not accompanied with a CDRx or PDF file. The remaining module, which did not report whether the driver-side curtain airbag deployed, was the 2012 Toyota Camry (CEN1215) which was previously noted as reported unclear data elements that referred to a deployment of an unknown airbag type. Among the remaining 9 tests vehicles which were equipped with a side curtain airbag that did not deploy, 7 EDRs correctly reported the non-deployment. One of the 9 non-deployments were caused by a disabled airbag (2010 Toyota Yaris RA5135), which was indicated in the test report. The remaining 2 modules indicated that the signal was not available (2013 Toyota Yaris, CEN1331; 2012 Mazda Mazda6, CEN1220).

2.6 DISCUSSION

One potential source of the longitudinal delta-v error is that some small portion of delta-v may be lost in the interval between the time of impact and the onset time of EDR recording. The command of various algorithms, i.e. airbag deployment, requires some accumulation of delta-v or a threshold of acceleration. Comeau et al (2004) discussed the initial delta-v lost in the interval between the time of impact and the onset time of EDR recording. These findings were confirmed by Wilkinson et al (2013) in MY 2005-2008 Toyota EDRs. For a low-speed rear-end crash, Wilkinson created a model incorporating a 2 G trigger threshold and 0.4 G bias. With these adjustments, the reference qualitatively recreated the EDR recorded values for longitudinal delta-v. Evidence of a 1 G bias was additionally addressed by Chidester et al (1999). This bias could serve as a safeguard against inadvertent deployment of the airbags. Any EDRs with this bias would underreport delta-v. For example, a module with a 1 G bias would underreport delta-v at 100 ms by 3.5 kph.

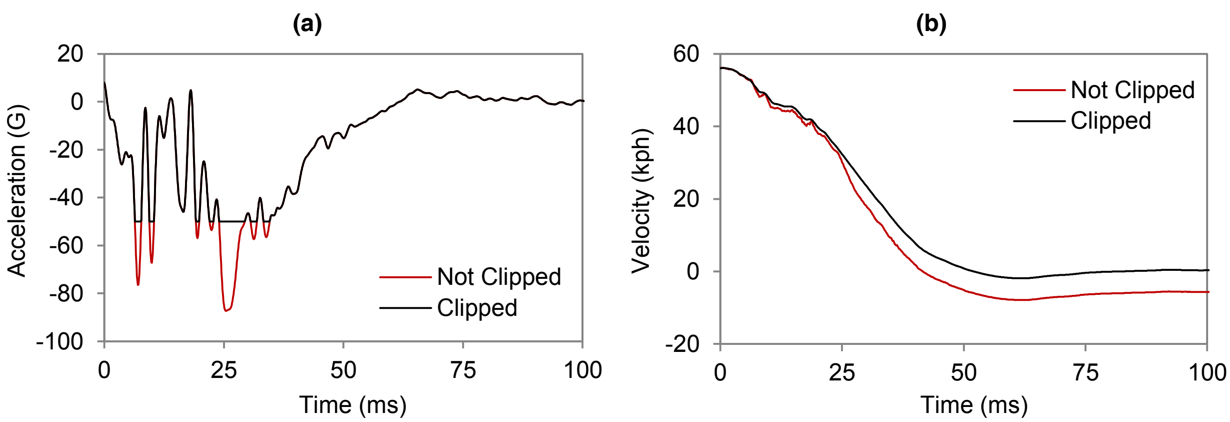

Figure 2.25 (a) Illustration of hypothetical clipping at 50 G and (b) the corresponding effect on velocity in a 56kph frontal crash test

Another possible explanation for the EDR underreporting the reference instrumentation is clipping. The Alliance of Automobile Manufacturers (Strassburger 2008) and the Association of International Automobile Manufacturers (Cammisa 2008) indicated that 50G accelerometers were commonly used in the fleet. They also noted EDR acceleration data is filtered at 400 Hz (design dependent) versus the CFC 60 Hz commonly used in NHTSA crash test analysis. The NHTSA signal processing software allows application of CFC 60, 180, 600, or 1000 Hz. In 26 of the 41 frontal tests (63%), the reference accelerometer data was greater than 50 G after the application of CFC 180. Among the 75 side MDB crash tests, 20 (27%) lateral reference accelerations exceeded 50Gs after digital filtering and rotation correction: 2 Chrysler, 3 Ford, 2 GM, 2 Honda, and 11 Toyota. Among those tests, Toyota had the greatest error in lateral delta-v due to underreporting. Five (5) out of the 11 NHTSA SOI crash tests had longitudinal accelerations that exceeded 50G and 6 out of the 11 crash tests had lateral accelerations that exceeded 50G. Figure 2.25a conceptually illustrates the effects of hypothetical clipping at 50 G in a 56 kph full-frontal crash test. Figure 2.25b shows that clipping of this magnitude would result in underreporting of delta-v by 6 kph (9.5%).

Without access to either the exact range of each manufacturer's accelerometers or the specific filtering used by each manufacturer, the exact amount of clipping cannot be ascertained for each of the NHTSA tests.

Nine (9) of the 41 EDRs (22%) from the full-frontal crash tests recorded acceleration data in addition to delta-v – five Honda, three GM, and one Mazda vehicles. In two vehicles the recorded peak was 50 G, the remainder were under 50 G, even though the reference accelerometers filtered to CFC 180 Hz exceeded 50 G in 4 of the 9 tests where EDR acceleration was reported.

In addition to clipping and the delta-v not recorded in the initial interval when some modules wake up, another potential source of error in the EDR measurements is the possibility that the EDR module mounting was damaged or the module orientation was altered during the impact. Information on the post-crash state of the EDR was not available in the publicly available test and EDR reports upon which this study was based.

Niehoff et al (2005) evaluated MY 2000-2005 primarily GM EDRs extracted from IIHS and NHTSA crash tests across several impact configurations. For lateral crash tests alone (n=3) they reported an average delta-v error of 18.56% and 15.43% for the full crash pulse and at 100ms, respectively. The Niehoff study did not correct for vehicle rotation, but did note that vehicle yaw was a source of error. Comparatively, this study reported average maximum delta-v errors of -2.7% (arithmetic) and 8.9% (absolute) for GM EDRs. These findings were more aligned with the errors Niehoff et al (2005) reported for frontal crashes: 5.82% error for the full crash pulse and 5.50% error at 100ms.

A more recent study by Gabler et al (2008) also evaluated MY 2004-2007 EDRs that were primarily extracted from GM and Toyota vehicles from an array of crash modes. For EDRs that succeeded in recording the full crash pulse, Gabler reported that the absolute maximum longitudinal delta-v error for side-impacts (n=3) was 10.8%. This value was slightly higher than the 8.9% absolute error reported in this study for GM EDRs, which each recorded more than 250ms. Although the Toyota EDR findings in this study greatly exceed (24.4%) the side-impact error results by Gabler et al (2008), more than half of their modules recorded more than 100ms. In the SINCAP results of this study, the Toyota EDRs which reported the greatest inaccuracies, recorded less than 100ms with rarely more than 70ms recorded after algorithm enable (Table A.6).

The EDR was not mounted on the true test vehicle CG and was susceptible to the same rotational effects that were corrected for in the reference, as evidenced by Figure 2.24. Although the Bosch CDR Tool provided make-, model-, and model year-specific information describing the occupant compartment region where the EDR can be found, an improved method would be to incorporate the exact EDR location into the rotational correction process. However, only 2 vehicle EDRs were not located in the center tunnel or console. Thus, this was expected to make little difference in the results. As seen in Table A.6 and Table A.9, the 2012 Chevrolet Impala (7486) and 2014 Nissan Rogue (CEN1407) EDRs were located under the right front seat.

It should be emphasized that the rotation correction indicated in this study was applied to the reference instrumentation. Relative to the vehicle reference frame in which the EDR reports its delta-v, the average maximum lateral delta-v was within 4 kph of the corrected sensor data. It is important to note that the presented accuracy results were based upon crash tests and only extend to real-world crashes similar to the SINCAP or small overlap configurations. This limitation extends to side-impacts of the far side. Although it is tempting to assume symmetry of EDR accuracy, Wilkinson et al (2013) showed discrepancies between front and rear-end crash modes in low-speed impacts. Wilkinson found EDR longitudinal delta-v to be underreported in front impacts, but overreported in rear-end impacts.

3 SURVIVABILITY OF EVENT DATA RECORDERS

3.1 BACKGROUND

As more and more EDRs were collected and read, interest in their accuracy and survivability has arisen. Many papers have been published describing the ability of an EDR to collect accurate data, but little research has been performed in the area of survivability. Among the guidelines established by the EDR regulation, Part 563.10, was a newly imposed survivability requirement on the EDR data. The regulation specifies that EDRs manufactured after September 1, 2012 must remain functional during and after compliance crash tests specified in Federal Motor Vehicle Safety Standard (FMVSS) 208, a frontal crash test, and FMVSS 214, a side crash test. The severity of these tests was representative of a major proportion of the crashes that occur on the nation's highways, and thus should insure generally available data from the EDRs in most highway crashes.

Unsurprisingly, there were passenger vehicle collisions that greatly exceed the parameters of these crash tests or experience unusual circumstances. The U.S. Motor Vehicle Safety Act of 2010 proposed EDR survivability beyond Part 563 requirements, in response to concerns over EDR operation in crashes which involved fire or immersion. This initiative was likely motivated by existing aviation standards which specify that similar devices (i.e. flight data recorders) should survive these events. Little was known, however, about whether current EDRs were capable of surviving these events or whether the data received by the EDRs can be recovered after these events. In addition, a study was needed to determine whether these events were sufficiently common to justify the expense of increasing survivability of EDRs.

The goal of this study was to determine the survivability of light vehicle EDRs in real world fire, immersion, and high delta-v cases. The specific studies identified the frequency of these extreme events and identified the EDR data download outcome when subject to damage caused by these events.

3.2 APPROACH

3.2.1 Frequency of Fire, Immersion, and High Delta-V

The first analysis sought to identify the frequency of vehicle fire, vehicle immersion, and high delta-v crashes. The variables assessed in each database to identify the three extreme events are discussed in the following section. As the cases in NASS-CDS and NMVCCS are sampled, unweighted and weighted frequencies and percentages are provided. FARS values were compared to the weighted distributions.

3.2.1.1 FARS

FARS cases were examined from case year 2009 through 2012. Vehicles were included in the analysis if the most harmful event ("m_harm") was coded to be "fire/explosion" or "immersion". Note, in addition to the most harmful event, FARS also reports fire occurrence ("fire_exp") as an alternative method to identify vehicle fires. This variable identifies all fire occurrences and is utilized in the Traffic Safety Facts (NCSA 2012) annual report. Estimates from both variables were reported.

3.2.1.2 NASS-CDS

Cases were extracted from NASS-CDS 2000-2012. Vehicle fires were identified using the variable, "Fire", which indicates the presence and severity of a fire in a particular vehicle. Coded values of "Major Fire" and "Minor Fire" were combined into a single value of "fire" for ease of comparison among datasets.

NASS-CDS also provides estimates of crash delta-v. Part 563 requires that EDR data survive frontal (FMVSS 208) and side (FMVSS 214) crash tests. For the frontal impact test, total delta-v ranges from 56-64 kph (35-40 mph) depending on the rebound velocity from the rigid wall, as determined from the previous chapter. For NHTSA side impact MDB crash tests, the previous chapter established total delta-v ranged from approximately 34-48 kph (21-30 mph). Therefore, the high delta-v threshold was set at 56 kph (35 mph) for frontal events and 34 kph (21 mph) for side impacts. Impact types were determined by "gad1" in the most harmful event. Cases coded as "F" were designated as frontal impacts and those coded as "L" or "R" were designated as side impacts. High delta-v vehicles were identified to be those with total resultant delta-v ("dvtotal") exceeding the delta-v threshold for its respective impact type.

3.2.1.3 NMVCCS

All years of NMVCCS were assessed (2005-2007). The NMVCCS variable "fire" was examined to determine fire involvement.

Immersion is not explicitly coded in NVMCCS. This database, however, is advantageous as it provides on-scene photographs at the time of the collision, often capturing the depth and extent of immersion. To isolate immersion cases, NMVCCS crash narratives were searched for terms indicative of bodies of water (*i.e.* "pond", "lake", and "ocean") and the photographs were manually scrutinized to detect immersion.

3.2.2 Download Outcomes of EDRs Subjected to Fire, Immersion, and High Delta-V Events

The second analysis sought to identify the EDR data download outcome when modules subjected to damage caused by vehicle fire, vehicle immersion, and high delta-v crashes. The results of the frequency analysis indicated that fire, immersion, and high delta-v crashes are relatively rare. To further refine these measurements, to assess EDR survivability, a case level analysis was performed using the NASS-CDS (2004-2012) and the NMVCCS datasets. An EDR was considered to have survived if the investigators were able to read the data. The dataset was limited to GM vehicles of MY 1995 and greater. GM EDRs of this model year range could be read by the publicly available Bosch CDR Tool at the time of the crash. Only NASS-CDS was used to assess vehicle fire and high delta-v. Only NMVCCS was used to assess vehicle immersion.

GM, like most automakers, installs their EDRs in the occupant compartment. Approximately 95% of Bosch CDR v.10.2 supported GM EDRs were installed underneath the driver seat, underneath the front passenger seat, or within the center tunnel. As a result, if the occupant compartment was exposed to an extreme event, the EDR was likewise assumed to be exposed to the same events. For fire and immersion, each event was also subdivided into varying levels of risk.

The online case viewer for the NASS-CDS and NMVCCS databases additionally reports whether the EDR was read and, if not read, the reasons why the EDR could not be read. For each case, the EDR download outcome was extracted. In vehicles where the EDR information was not successfully downloaded, the reason was documented. Of interest to this analysis were the download outcomes of "Vehicle damage prevents accessing EDR data" (*Damaged*) and "EDR information obtained" (*Read*). The rate of survivability was thus defined to be:

$$\text{Rate of EDR Data Survivability} = \frac{\text{Read}}{\text{Total}} = \frac{\text{Read}}{\text{Read} + \text{Damaged}} \quad \text{(Equation 13)}$$

It is important to note that "Vehicle damage prevents accessing EDR data" does not identify the specific vehicle component that was damaged. This outcome could represent several situations:

(1) Surrounding vehicle damage: vehicle crush prevented physical access to either the onboard diagnostic (OBD-II) port or the EDR itself,

(2) OBD-II Port damage: download through the OBD-II port failed, and direct connection was not attempted, or

(3) EDR damage: downloading by direct connection to the EDR was attempted, but was not successful.

For the purposes of the EDR outcome analysis, all vehicles assigned the "Vehicle damage prevents accessing EDR data" outcome were assumed to refer to EDR damage. Using this approach gives us a lower bound on the percent of EDRs which survived these events. Many of the EDRs in the damaged category may have been readable given the availability of the correct cables, use of improved download techniques, or removal of deformed components to get access to the EDR.

3.2.2.1 Risk of Fire Damage to EDR

NASS-CDS vehicles previously identified in the frequency analysis as units exposed to vehicle fire were extracted for this second analysis. Photographs of each vehicle (version 3.6, NHTSA, Washington, DC), in conjunction with the case summary, were inspected for evidence of occupant compartment damage caused by the fire. Origin of fire ("fireorig") was also assessed, but served primarily as a preliminary indicator of potential fire damage and was only used to supplement the photographed evidence. Each vehicle was then categorized into one of three groups.

- No Risk of EDR Data Loss Caused by Vehicle Fire: photograph depicted little to no fire or heat damage within the occupant compartment
- Risk of EDR Data Loss Caused by Vehicle Fire: photograph depicted fire or heat damage within the occupant compartment
- Unknown Risk of EDR Data Loss Caused by Vehicle Fire: no photographs were taken of the occupant compartment, or the photograph depicted occupant compartment damage, but the cause of damage could not be attributed to fire alone (often due to severe vehicle deformation)

Exemplar photographs of each category are shown in Table 3.1.

3.2.2.2 Risk of Immersion Damage to EDR

As previously discussed, NMVCCS does not code explicitly for immersion. Vehicles identified in the frequency analysis were classified into one of three risk categories. Photographs of each vehicle (version 3.6, NHTSA, Washington, DC), in conjunction with the case summary, were inspected for evidence of water exposure to the occupant compartment.

- No Risk of EDR Data Loss Caused by Immersion: photograph depicted no water or a shallow body of water that could not have entered the occupant compartment
- Risk of EDR Data Loss Caused by Immersion: photograph depicted a body of water of significant depth, but no apparent water in the occupant compartment.
- Submerged: photograph illustrated water in the occupant compartment

Exemplar photographs of each category are shown in the Table 3.2.

Table 3.1 Rating scheme to determine the risk of EDR damage due to vehicle fire from the NASS XML Case Viewer (version 3.6, NHTSA, Washington, DC)

No risk from vehicle fire	Risk from vehicle fire	Unknown
		
NASS Case ID: 762013627	NASS Case ID: 768011337	NASS Case ID: 613009786

Table 3.2 Rating scheme to determine the risk of EDR damage due to submersion from the NASS XML Case Viewer (version 3.6, NHTSA, Washington, DC)

No risk from submersion	Risk from submersion	Submerged
		
NMVCCS ID: 2005005289782	NMVCCS ID: 2007075584329	NMVCCS ID: 2006078598347

3.2.2.3 Risk of High Delta-V Damage to EDR

High delta-v crashes from NASS-CDS were identified by the criteria defined in the previous analysis on the frequency of these severe events in real world crashes. No risk severity assessment was conducted as most vehicles involved in these crashes contained significant intrusion into the occupant compartment. Both crash modes, however, were separated into two groups to observe whether there were changes in the rate of EDR survivability with increasing delta-v. Frontal crashes were divided into (1) 56-75 kph and (2) greater than or equal to 75 kph. Side crashes were divided into (1) 34-50 kph and (2) greater than or equal to 50 kph.

3.3 RESULTS

3.3.1 Frequency of Fire, Immersion, and High Delta-V

There were 35,667,569 weighted vehicles in NASS-CDS (2000-2012), 3,880,818 weighted vehicles in NMVCCS, and 180,249 vehicles in FARS (2009-2012). These totals exclude cases in which the exposure to the extreme event was unknown.

3.3.1.1 Fire

Table 3.3 shows the frequency and percentages of vehicle fires for all 3 datasets as unweighted and weighted values. Fires were a rare event. Weighted estimates of vehicle fire range between 0.2% (NASS-CDS) and 3.0% (FARS fire_exp). These percentages were based upon 680 and 61 unweighted case vehicle fires in NASS-CDS and NMVCCS, respectively.

Table 3.3 Vehicle fire frequency in NASS-CDS (2000-2012), NMVCCS, and FARS (2009-2012)

		No Fire	Fire[a]	Total[b]
NASS-CDS				
Unweighted	#	78,246	680	78,926
	%	(99.14)	(0.86)	(100.00)
Weighted	#	36,589,364	78,205	36,667,569
	%	(99.79)	(0.21)	(100.00)
NMVCCS				
Unweighted	#	12,670	61	12,731
	%	(99.52)	(0.48)	(100.00)
Weighted	#	3,854,533	26,285	3,880,818
	%	(99.32)	(0.68)	(100.00)
FARS				
m_harm	#	178,210	2,039	180,249
	%	(98.87)	(1.13)	(100.00)
fire_exp	#	175,005	5,476	180,481
	%	(96.97)	(3.03)	(100.00)

[a] "Major fire" and "minor fire" were combined to create "fire" for NASS-CDS
[b] Total populations do not include vehicles if "fire" involvement unknown

3.3.1.2 Risk of Immersion Damage to EDR

NMVCCS vehicles exposed to water were organized by severity by evaluating on-scene photographs and classified into one of three categories. "No risk of submersion" characterizes a shallow body of water. "Risk for submersion" identifies a significant body of water with no apparent water in the occupant compartment. Lastly, "submerged" designates water in the occupant compartment. Examples of each category were shown in Table 3.2. EDR download outcomes were recorded for each case and compared to these categories in order to determine if the severity of submersion plays a role in whether the EDR data was obtained.

3.3.1.3 Immersion

Vehicle immersion was also a rare event, as shown in Table 3.4. In NMVCCS, only 0.1% of vehicles were exposed to some extent of immersion. In terms of unweighted vehicles. NMVCCS contained only 16 out of 13,304 vehicle immersions. FARS (2009-2012) had an even lower percentage, 0.4%.

Table 3.4 Immersion frequency in NMVCCS and FARS (2009-2012)

		No Immersion	Immersion[a]	Total
NMVCCS				
Unweighted	#	13,288	16	13,304
	%	(99.88)	(0.12)	(100.00)
Weighted	#	4,027,207	3,868	4,031,075
	%	(99.91)	(0.09)	(100.00)
FARS				
-	#	179,498	751	180,249
	%	(99.58)	(0.42)	(100.00)

[a] Risk of immersion" and "submerged" were combined to create "immersion" for NMVCCS

3.3.1.4 High Delta-V

Analysis of the NASS-CDS database (2000-2012) showed that a total of 11,988,059 vehicles suffered frontal damage in the most harmful event. Recall that the delta-v in FMVSS 208 frontal crash tests fall within 56-64 kph (35-40 mph). As shown in Figure 3.1, only 0.86% of vehicles (110,016 out of 11,987,513) exceeded the lower delta-v threshold of 56 kph (35 mph).

There were 5,191,892 vehicles where the general area of damage was the left or right side in the most harmful event. Delta-v from FMVSS side MDB crash tests varies from 34-48 kph (21-30 mph). By using a delta-v threshold of 34 kph (21 mph), the number of side-impact vehicles experiencing high delta-v was 4.3% (247,098 out of 5,191,892 vehicles). This is illustrated in Figure 3.2.

3.3.2 Download Outcome of EDRs Subjected to Fire, Immersion, and High Delta-V Events

As shown in Table 3.5, the NASS-CDS (2004-2012) database contains, 17,123 unweighted GM vehicles of MY 1995 and later. In 35% of these vehicles, investigators successfully downloaded the EDR data. However, 43% of EDRs were not read. In addition, there were 3,799 vehicles (22%), indicated as "data not available", that did not have an EDR download outcome.

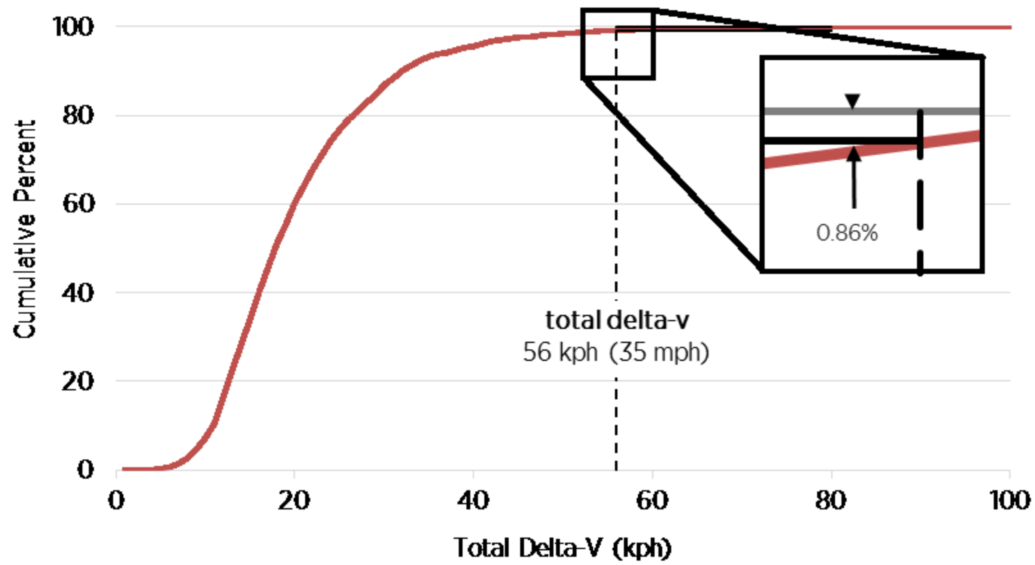

Figure 3.1 Distribution of vehicles in a frontal crash by total delta-v (NASS-CDS 2000-2012)

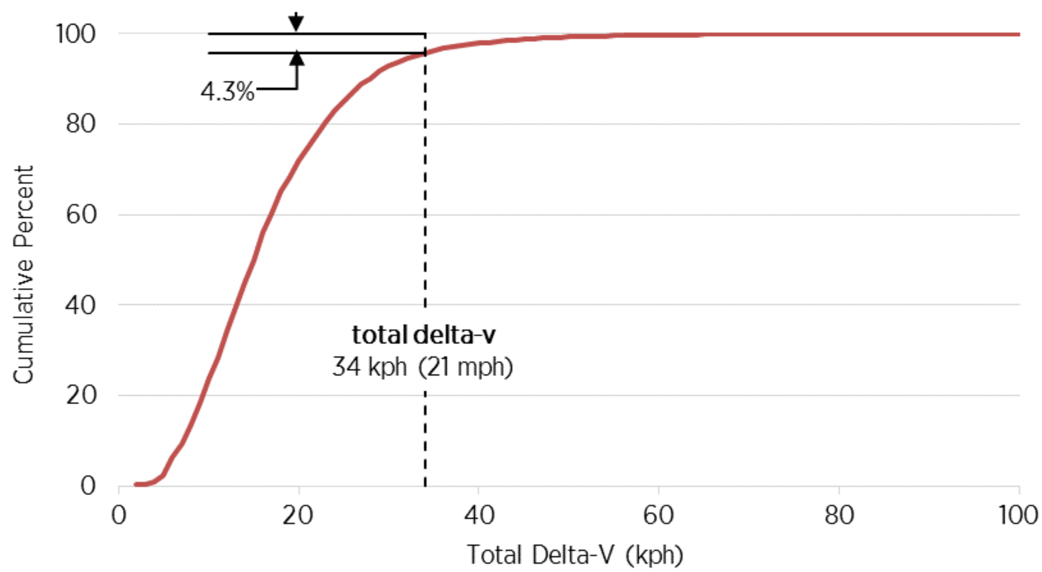

Figure 3.2 Distribution of vehicles in a side crash by total delta-v (NASS-CDS 2000-2012)

The most common reason cited for not downloading the EDR data was "permission not received [from vehicle owner]". This lack of permission constituted 2,674 of the 7,388 EDRs not read (36%). All GM vehicles in the dataset contained an EDR supported by the Bosch CDR tool. However, over 800 vehicles NASS investigators stated the "vehicle was not equipped with EDR" or "vehicle not supported by software".

Table 3.5 EDR download outcomes in GM vehicles of model year 1995 and greater (NASS-CDS 2004-2012)

	2004	2005	2006	2007	2008	2009	2010	2011	2012	Sum	
EDR information obtained	827	653	712	598	527	565	515	894	645	5,936	(34.67)
EDR information not obtained	710	658	805	1,008	1,193	1,195	1,124	485	210	7,388	(43.15)
Vehicle not equipped with EDR	211	206	185	0	0	0	0	0	0	602	(3.52)
Vehicle not supported by software	86	61	93	0	0	0	0	0	0	240	(1.40)
Vehicle make/model not supported by software or hardware	0	0	0	269	320	229	151	84	30	1,083	(6.32)
Vehicle damage prevents accessing EDR data	129	146	205	158	158	174	151	69	30	1,220	(7.12)
Permission not received	281	237	315	317	387	425	450	202	60	2,674	(15.62)
Other reasons	0	0	0	219	251	317	327	104	73	1,291	(7.54)
Unknown	0	0	0	0	0	1	1	2	1	5	(0.03)
Software issue	0	0	0	28	42	37	33	19	6	165	(0.96)
Hardware issue	0	0	0	17	35	12	10	5	9	88	(0.51)
EDR submitted to manufacturer	0	0	0	0	0	0	1	0	1	2	(0.01)
Unknown if vehicle equipped with EDR	3	8	7	0	0	0	0	0	0	18	(0.11)
Data not available	371	278	377	462	411	421	442	399	638	3,799	(22.19)
Total	**1,908**	**1,589**	**1,894**	**2,068**	**2,131**	**2,181**	**2,081**	**1,778**	**1,493**	**17,123**	**(100.00)**

Only 1,220 of the 7,388 unread EDRs (17%) cited vehicle damage as the reason for unsuccessful download. Note that this category simple indicates whether an EDR could be downloaded, regardless of whether the vehicle was involved in a fire, immersion, or a high delta-v crash. Based upon the 1,220 EDRs not downloaded due to vehicle damage and the 5,936 EDRs successfully downloaded, the rate of EDR data survivability can be calculated:

$$\text{Rate of EDR Data Survivability} = \frac{\text{Read}}{\text{Read} + \text{Damaged}}$$
$$= \frac{5{,}936}{5{,}936 + 1{,}220} = 83\%$$

(Equation 14)

Thus, the overall rate of survivability for all GM vehicles from NASS-CDS (2004-2012) was 83%. Note again, that this is a lower bound on survivability as some of the EDRs in the "Damaged" category could potentially have been read by using improved techniques.

3.3.2.1 GM EDRs Subjected to Vehicle Fire

Of the 17,123 GM vehicles of MY 1995 and later in NASS-CDS, vehicle fire exposure was unknown for 3,514 vehicles, leaving 13,238 cases with an identified fire exposure. Only 0.7% of vehicles (95 of 13,238) were subjected to a vehicle fire. Weighted, this population is equivalent to 8,014 out of 5,439,461 vehicles (0.2%). As shown in Table 3.6, the percentage of weighted GM vehicle fires was the same order of magnitude to the overall fleet. These exposures to fire were further categorized as 32 minor fires and 63 major fires.

Table 3.6. Distribution of vehicle fire vehicles among GM vehicles after model year 1995 in NASS-CDS (2004-2012)

		No Fire	Fire[a]	Total[b]
Unweighted	#	13,143	95	13,238
	%	(99.28)	(0.72)	(100.00)
Weighted	#	5,430,566	8,895	5,439,461
	%	(99.84)	(0.16)	(100.00)

[a] "Major fire" and "minor fire" were combined to create "fire"
[b] Total population does not include vehicles if "fire" involvement unknown

Of the 95 vehicles exposed to fire, the majority (61) of the vehicle fires originated in the engine compartment. As shown in Table 3.7, regardless of fire origin, 52 vehicles (55%) showed visible signs of damage in the occupant compartment, 28 vehicles (29%) had no risk of EDR data loss (e.g. minor engine fire). Sixteen (16) EDRs were successfully read and 53 not read due to vehicle damage. Exemplar photographs are shown in the Appendix. Overall, the rate of EDR data survivability for the 69 vehicles without considering risk of fire damage was 23%. However, if only EDRs at risk of vehicle fire damage are considered, the rate of EDR data survivability was 14%. Note that these are lower bounds on survivability. The actual percentage may be higher.

Table 3.7. Distribution of heat exposure severity for GM Vehicles (NASS-CDS 2004-2012)

	EDRs read	EDR not read due to		Sum
		Vehicle Damage[a]	Non-Damage Reason	
No Risk of EDR Data Loss Caused by Vehicle Fire	8 + 0[b]	11 + 2[b]	7 + 0[b]	28
Risk of EDR Data Loss Caused by Vehicle Fire	4 + 1[b]	27 + 5[b]	14 + 1[b]	52
Unknown risk of EDR Data Loss Caused by Vehicle Fire	0 + 3[b]	6 + 2[b]	4 + 0[b]	15
Total	**16**	**53**	**26**	**95**

[a] Download outcome "Vehicle damage prevents accessing EDR data"
[b] Vehicles exposed to both fire and high delta-v

3.3.2.2 GM EDRs Subjected to Vehicle Immersion

The percentage of GM vehicle immersions (0.1%) was similar to the overall population of cars. This is shown in Table 3.8. As shown in the frequency analysis, vehicle immersion was relatively rare in NMVCCS. Of the 2,759 GM vehicles of MY 1995 and later in NMVCCS, 0.4% of vehicles (10 of 2,759) were involved in some degree of vehicle immersion. Weighted, this population is equivalent to 4,871 out of 868,818 vehicles (0.6%).

Table 3.8. Distribution of NMVCCS vehicle immersion for GM Vehicles

		No Water Exposure	Water Exposure	Total
Unweighted	#	2,749	10	2,759
	%	(99.64)	(0.36)	(100.00)
Weighted	#	863,944	4,874	868,818
	%	(99.44)	(0.56)	(100.00)

As shown in Table 3.9, 5 of the 10 vehicles exposed to water were submerged (50%), only 1 vehicle (10%) was at risk for EDR damage from immersion, and 4 vehicle EDRs (40%) were not at risk. There were 2 EDRs successfully read and 3 not read due to vehicle damage. The remaining 5 were not read due to non-damage reasons. Exemplar photographs are shown in the Appendix. Overall, the rate of EDR data survivability for the 5 vehicles without considering risk of damage caused by immersion was 40%. When only considering vehicles in the "submerged" and "risk of immersion" categories, the rate of EDR data survivability was 50%. This calculation was based upon only 1 EDR not downloaded due to vehicle damage and 1 EDR successfully downloaded. Note that these are lower bounds on survivability and are based on a very small sample size.

Table 3.9. Distribution of water exposure severity for GM Vehicles (NMVCCS)

	EDRs read	EDR not read due to		Sum
		Vehicle Damage[a]	Non-Damage Reason	
No Risk of EDR Data Loss Caused by immersion	1 + 0[b]	2 + 0[b]	1 + 0[b]	4
Risk of EDR Data Loss Caused by immersion	0 + 0[b]	0 + 0[b]	1 + 0[b]	1
Submerged	1 + 0[b]	1 + 0[b]	3 + 0[b]	5
Total	**2**	**3**	**5**	**10**

[a] Download outcome "Vehicle damage prevents accessing EDR data"
[b] Vehicles exposed to both immersion and high delta-v

3.3.2.3 GM EDRs Subjected to High Delta-V Crashes

The percentage of GM EDRs subjected to high delta-v was similar to the overall fleet. Of the 17,123 GM vehicles of MY 1995 and later in NASS-CDS, 53% of vehicles (7,021 of 17,123) were involved in frontal crashes and 3% (186 of 7,021) experienced a delta-v of 56 kph (35 mph) or greater. Weighted, this population of frontal crashes with high delta-v is equivalent to 12,891 out of 2,857,435 vehicles (0.5%). The percentage of high delta-v frontal crashes determined from the NASS-CDS (2000-2012) frequency analysis (0.86%) was slightly higher. Additionally, 27% of vehicles (3,573 of 17,123) were involved in side crashes and 9% (316 of 3,573) experienced a delta-v of 34 kph (21 mph) or greater. This population of side crashes with high delta-v constituted a weighted population of 33,641 vehicles out of 1,325,895 or 3%. The percentage of high delta-v side crashes determined from frequency analysis (4.3%) was slightly higher. This is shown in Table 3.10.

As shown in Table 3.11, 60 EDRs in frontal high delta-v crashes were read, 61 were not read due to vehicle damage, and 65 vehicle EDRs could not be read for non-damage reasons, *e.g.* lack of owner permission. When segmented, the EDR survivability rate decreased with increasing delta-v. Overall, the rate of EDR data survivability for these frontal crashes was 50%. For high delta-v side crashes, 112 EDRs were read, 91 were not read due to vehicle damage, and in another 113 vehicles the download was not completed for non-damage reasons. When segmented, the EDR survivability rate decreased with increasing delta-v. Overall, the rate of EDR data survivability for these side crashes was 55%. Note that this is a lower limit on survivability. The actual survivability may be higher.

Table 3.10. Distribution of GM vehicles in high delta-v crashes (NASS-CDS 2004-2012)

		Not High Delta-V	High Delta-V	Total
Frontal				
Unweighted	#	6,835	186	7,021
	%	(97.35)	(2.65)	(100.00)
Weighted	#	2,844,544	12,891	2,857,435
	%	(99.55)	(0.45)	(100.00)
Side				
Unweighted	#	3,257	316	3,573
	%	(91.16)	(8.84)	(100.00)
Weighted	#	1,292,254	33,641	1,325,895
	%	(97.46)	(2.54)	(100.00)

Table 3.11. Distribution of high delta-v severity for GM vehicles (NASS-CDS 2004-2012)

High Delta-V (kph)	EDRs read	EDR not read due to		Sum	EDR Survivability Rate
		Vehicle Damage[a]	Non-Damage Reason		
Frontal					
56-75 kph	44 + 2[b]	39 + 6[b]	52 + 1[b]	144	51%
$\geq$ 75 kph	13 + 1[b]	14 + 2[b]	12 + 0[b]	42	47%
Total	**60**	**61**	**65**	**186**	**50%**
Side					
34-50 kph	93 + 1[b]	64 + 0[b]	93 + 0[b]	251	59%
$\geq$ 50 kph	18 + 0[b]	26 + 1[b]	20 + 0[b]	65	40%
Total	**112**	**91**	**113**	**316**	**55%**

[a] Download outcome “Vehicle damage prevents accessing EDR data”
[b] Vehicles exposed to both fire and high delta-v

3.3.3 Overlapping Damage Modes

In NASS-CDS, there were 14 GM EDRs that were involved with both vehicle fire and high delta-v crashes, as shown in Table 3.12.

Table 3.12. Overlapping damage in GM vehicles (NASS-CDS 2004-2012)

Case Year	PSU	Case No.	Vehicle No.	EDR Download Outcome	Exposure Severity	
					Fire	Delta-V
2004	47	62	1	EDR information obtained	Unknown	F (< 75)
2005	12	160	1	Vehicle damage prevents accessing EDR data	Risk from vehicle fire	F (≥ 75)
2006	9	191	1	Vehicle damage prevents accessing EDR data	Risk from vehicle fire	F (< 75)
2006	12	189	1	Vehicle damage prevents accessing EDR data	No risk from vehicle fire	F (< 75)
2006	75	175	1	Vehicle not equipped with EDR	Risk from vehicle fire	F (< 75)
2006	76	73	1	Vehicle damage prevents accessing EDR data	Unknown	R (≥ 50)
2006	76	73	2	Vehicle damage prevents accessing EDR data	Risk from vehicle fire	F (< 75)
2008	12	88	1	Vehicle damage prevents accessing EDR data	No risk from vehicle fire	F (< 75)
2008	76	89	1	Vehicle damage prevents accessing EDR data	Risk from vehicle fire	F (< 75)
2011	8	142	2	Vehicle damage prevents accessing EDR data	Risk from vehicle fire	F (< 75)
2011	73	42	1	Vehicle damage prevents accessing EDR data	Unknown	F (≥ 75)
2011	74	70	1	EDR information obtained	Unknown	F (≥ 75)
2012	49	139	1	EDR information obtained	Unknown	F (< 75)
2012	49	156	5	EDR information obtained	Risk from vehicle fire	L (< 50)

Table 3.13. Exemplar cases of vehicle EDRs at risk where the EDR was successfully read or not read due to damage from the NASS XML Case Viewer (version 3.6, NHTSA, Washington, DC)

	EDR Successfully Read	EDR Not Read Due to Vehicle Damage
Risk of EDR Data Loss Caused by Vehicle Fire	 NASS-CDS Case ID: 520016113	 NASS-CDS Case ID: 162009244
Submerged	 NMVCCS Case ID: 2005073623201	 NMVCCS Case ID: 2006078598647

3.4 DISCUSSION

Although the rates of EDR data survivability were lower when exposed to vehicle fire (14%), vehicle immersion (50%), and high delta-v (frontal: 50%, side: 55%) compared to all GM vehicles (83%). We emphasize that these are lower bounds on survivability rate. With improved download techniques, better access to cables, and additional training, many of these EDRs may have been downloaded. Dissertations to increase EDR survivability requirements must be balanced against the rarity of these extreme events. Even if EDR enclosures were modified to become more survivable during these events, vehicle damage is only the third most common reason why NASS did not download the data. What this analysis has shown is that the current EDR survivability requirements to survive FMVSS 208 and 214 may be adequate to survive the vast majority of crashes. For crashes beyond these limits, including fire and immersion, this analysis has shown in many cases the EDR is still capability of being downloaded (e.g. Table 3.13).

The download outcome analysis was limited to vehicles with EDRs which could have been downloaded between 2004 and 2012 NASS-CDS or the 2005 to 2007 NMVCCS period from MY 1995 and greater GM vehicles. The analysis was restricted to GM vehicles to ensure that the vehicles assessed were equipped with EDRs and investigators at the time of the crash could download those EDRs. The findings on EDR survivability may or may not generalize to the EDRs of other automakers.

Some of the EDRs discussed in this paper were developed many years ago, potentially before any EDR research or rulemaking activity by NHTSA. The performance of the EDRs and preservation of their data in crashes was the result of then-current industry practices. The findings of this analysis may or may not be relevant to EDRs that are currently being designed and installed in MY 2013 and later vehicles.

Further, few of the vehicles in the study were required to meet Part 563. NMVCCS only encompassed motor vehicle collisions through case year 2007 and NASS-CDS would have only captured a few MY 2013 in the last quarter of 2012. Hence, the results of this analysis do not measure the impact of the survivability requirements associated with Part 563.

This analysis was also limited by the 12 download outcomes given by investigators. The lack of detail for the reason "Vehicle damage prevents accessing EDR data" cannot be interpreted that the EDR is damaged. Instead other damage may have blocked access to the EDR. Thus, the rates of EDR survivability presented are lower bounds on survivability. This presents the most compelling story for those seeking to improve the EDR module. However, in conjunction with the frequencies, perhaps even this lower bound is not significant enough to justify such changes. Potential refinements to crash investigation that may assist future studies include: (1) whether the Bosch CDR reader was actively connected to the EDR, (2) if so, whether the EDR could be downloaded either through the OBD-II port or by direct connection.

4 Evaluation of NASS-CDS Seat Belt Use Estimates

4.1 BACKGROUND

Seat belt use is a critical factor in occupant injury outcome in motor vehicle crashes. Retrospective studies often gather usage information from the NASS-CDS, a collection of real world crashes. To determine seat belt use, this database primarily relies upon post-crash vehicle inspection by trained investigators. The resulting estimates are believed to be much more accurate than police-reported belt use (Viano and Parenteau 2009) and are used as the gold standard when evaluating the effectiveness of seat belts. However, no study has quantified the accuracy of NASS-CDS seat belt use estimates. The objective of this study was to determine the agreement of NASS-CDS investigator-determined seat belt usage observations to EDRs and the factors which control the agreement of this measurement.

4.1.1 Forensic Techniques for Determining Seat Belt Usage

Crash investigators have traditionally examined the post-crash vehicle and utilize forensic techniques to determine seat belt use. These techniques principally involve the scrutiny of the seat belt webbing, latch plate, and D-ring covering for marks caused by occupant loading. Primarily this includes examination of the degree of wear on plastic components (Heydinger et al 2008, Raymond et al 2006, Tanner et al 2006) and plastic transfer onto the webbing (Heydinger et al 2008, Jakstis et al 2009, Raymond et al 2006, Tanner et al 2006). However, the inspection is often subjective as the evidence varies with vehicle history, crash severity, correctness of seat belt wear, location of compliant (*i.e.* plastic) material, and seat belt system geometry.

For instance, investigators must distinguish normal wear marks from occupant loading marks. Heydinger et al (2008) compared crash tested vehicles to used vehicles without crash history, i.e. those with wear and tear from everyday use. They found deep grooves in the compliant D-ring covering and latch plate components of crash tested vehicles, compared to the “polishing/smoothing” observed in vehicles without crash history. Other studies have described low severity (10G) markings as “polishing” (Raymond et al 2006). Fraying, snags, and grime on the webbing, were characteristics of normal webbing wear unless accompanied by other evidence. Heydinger et al stressed the importance of knowing the vehicle’s particular restraint system, as the characteristics are vehicle dependent.

A particular challenge is determining seat belt use in crashes of low severity. These crashes display less evident markings than the deep grooves and high amount of plastic transfer exhibited in severe collisions, e.g. crash tests. Tanner et al (2006) simulated collisions with varying speed, impact type, airbag deployment, and seat belt use. At the lowest tested speed (10 mph) they observed marks on the webbing, D-ring cover, and plastic latch plate all belted tests, except during a center pole-impact. The plastic D-ring and plastic latch plate evidence was described as “slight wiping or scuffing”, however, the tests were conducted on new components. Unaddressed was whether these markings could be distinguished from normal wear. A similar study by Raymond et al (2006) also identified the intended and controlled failure of load limiting stitches on the webbing, where higher severity corresponded to an increasing number of stitch failures. In unbelted tests, Tanner et al (2006) additionally observed steering wheel and knee bolster deformation.

Newer technologies, e.g. pretensioners, can also add to the seat belt usage evidence available to investigators. Pretensioners are responsible for retracting the seat belt webbing to eliminate slack and better couple the occupant to the seat. Pretensioners are placed in two locations, within the seat buckle or the retractor. Vehicles equipped with buckle pretensioners eliminate slack by reducing the length of the buckle, and may appear sunken when fired. Vehicles equipped with retractor pretensioners eliminate slack by reeling in excess webbing when fired. If the occupant was belted, the webbing would freeze at an extracted length after the crash. If the occupant was unbelted, the webbing would be locked in a fully retracted position after the crash. Jakstis et al (2009) observed markings on field vehicles and on crash tested vehicles equipped with retractor pyrotechnic pretensioners and torsion-type load limiters. When occupants were unbelted, however, the webbing would fully retract, often accompanied by the stay button (the plastic convenience stop found on the webbing) dislodging. Additionally, when the occupant was belted and the pretensioner activated, unique angular striations appeared on the flat surface of the inboard side of the plastic latch plate.

Improper belt use can also affect the forensic evidence of belt use. Brown et al (2009) investigated forensic evidence to determine whether children properly wore their seat belts or routed the webbing behind their back. Improper belt use was observed in case studies of severe (>40kph) frontal crashes. The effect of improper belt use was investigated in four 32kph sled tests, of varying tongue types, equipped with coupled dummies donning proper and improper (behind-the-back) 3-point belt routing. In proper belt use the authors observed uniform and perpendicular abrasion on the plastic latch plate, angled D-ring abrasion, and angled D-ring bolt impression. During improper belt use, the buckle rotated 90° and the tongue abrasion were angled and found on the rear web slot. As a result, the angle of D-ring abrasion and bolt impression were reduced.

4.1.2 Previous Belt Use Reporting Accuracy

Several studies have compared NASS-CDS investigator-determined seat belt usage and police reported usage. Schiff and Cummings (2004) found police usage agreed with investigator usage for 88% of occupants. Overall, agreement increased with injury severity. Sensitivity was 96% and decreased with injury severity. Specificity was 69% and increased with injury severity. Sensitivity measures the ability of the police to correctly identify belted occupants as belted. Specificity measures the ability of the police to correctly identify unbelted occupants. Schiff and Cummings speculated that occupants with lower severity injuries were less likely to be confined to the vehicle, which prevented the police from directly observing seat belt use. Thus overall agreement generally increased with increasing injury severity because the police could directly observe seat belt use for the fatally injured. Schiff and Cummings also discussed that NASS-CDS estimations are vulnerable to error, and suggested the use of EDRs.

Moore et al (2009) found that police overreported belt use across almost all crash types, case years, injury severities, and vehicle types. Overall, sensitivity was reported to be 97% and specificity 64%. Police agreed with NASS-CDS most in rear-end crashes (93.5%), but crash types overall were not found to be a major factor in agreement. Seat belt usage agreement was greatest among uninjured occupants (92.9%), but was followed closely by fatally injured occupants (92.7%). Occupants sustaining a maximum abbreviated injury severity (MAIS) score of 1 (89%), MAIS 2 (86%), or MAIS 3+ (85%) showed decreasing agreement with increasing severity. Moore et al emphasized the lack of direct observation of true restraint status and the lack of objective evidence as reasons for police disagreement.

Viano and Parenteau (2009) compared police reported belt use to NASS-CDS belt use. They reported that the police overestimated seat belt use by 8%. Occupants sustaining MAIS 3 injuries showed the greatest police disagreement compared to grouped injuries of lower (MAIS 1-2) and higher (MAIS4+F and fatal) severity. They found that the police typically overreported belt use most often in accidents without occupant injury. The police also had a much higher percentage of unknown seat belt use cases (27.6%) compared to NASS-CDS (0.52%), particularly among the fatally injured. NASS-CDS contained 8 unweighted cases in which the restraint type was misidentified as a child safety seat, however, the restraint type was incorrect and the occupants were not children. This prompted Viano and Parenteau to suggest misinformation or misentered data as reasons for disagreement.

4.1.3 Event Data Recorders

EDRs are devices typically integrated into the airbag control module that store precrash and crash parameters in the event of a collision. EDRs can provide objective insight into the moments prior to and during a motor vehicle collision, making them ideal for seat belt use determination. An early study of real-world seat belt buckle status on nine model year 1995-1998 GM EDRs showed that one was inaccurate (Chidester et al 1998). However, more recent studies evaluating EDR seat belt buckle status in crash tests indicated 100% accuracy when reported [Correia et al 2001 (n=5), Gabler et al 2008 (n=48), Niehoff et al

2005 (n=25), Tsoi et al 2013 (n=41), 2014 (n=75)]. EDRs are collected and downloaded in conjunction with the NASS-CDS investigation using the publicly available Bosch CDR tool. The data is available online. However, vehicle inspection, medical records, and interviews are typically the only sources used in NASS-CDS to determine seat belt use and the data EDRs provide are not currently utilized.

4.2 METHODS

The dataset analyzed in this study was limited to vehicles with deployment events from NASS-CDS case years 2000-2013. Investigator determined belt use was recorded in the “MANUSE” variable. “MANUSE” values of “None used not available/removed or destroyed” and “Inoperative” were considered unbuckled. "Shoulder belt", "Lap belt", "Lap and shoulder belt", "Belt used — type unknown", "Other belt used", "Shoulder belt with child safety seat", "Lap belt with child safety seat", "Lap and shoulder belt with child safety seat", "Belt with child safety seat — type unknown", and "Other belt with child safety seat" were considered buckled. Occupants were excluded if the NASS-CDS seat belt status was unknown.

The EDR reports were obtained from the NHTSA NASS-CDS website. Each EDR report provided a complete file recorded status flag that indicated whether the event was successfully recorded. If the complete file recorded status flag indicated that it was interrupted, then the report contents could be unreliable. Thus, if the vehicle EDR report was not available, or if the complete file recorded flag indicated interrupted data, then the case was excluded from the analysis. The NHTSA EDR dataset only encompasses case years 2000-2013 and only includes model years 1994 and later. Additionally, the EDR dataset only contained vehicles manufactured by Chrysler, Ford, GM, or Toyota as these were the only OEMs supported by the Bosch CDR tool at the time of download. Each report provided a seat belt buckle status of “Buckled” or “Unbuckled” for the driver. Only vehicles for which the EDR data had been previously validated with respect to crash tests in studies by Gabler et al (2008), Niehoff et al (2005), and Tsoi et al (2013, 2014) were included. Validation signifies that an EDR of the same module type correctly reported seat belt status when compared to crash test photographs and the test report. Additionally, this dataset was restricted to deployment events, excluding non-deployment and deployment-level events. EDRs capture and “lock” the crash data if the vehicle was involved in a deployment event. Restricting the dataset to deployment events ensured that the event captured was the same event indicated in NASS-CDS.

Table A.13 presents the dataset composition by occupant weight, occupant age, vehicle body type, number of events, delta-v, general area of damage, and rollover. For this study, high speed crashes were defined to be vehicles with a NASS-CDS calculated total delta-v of 20 mph or greater. Low speed crashes were defined to be those with total delta-v under 20 mph. The NHTSA SaferCar database, in conjunction with the Rescuer’s Guide to Vehicle Safety Systems (Holmatro 2007), were utilized to identify vehicles equipped with pretensioners. Vehicles from the same make, model, and generation were assumed to be equipped with identical safety features. The investigator-determined seat belt use was compared to the corresponding seat belt status reported by the vehicle EDR for drivers. The vehicles identified as having pretensioners were merged with the NASS-CDS database by the “makmod” code. The disagreement rate (DR) is a ratio of the cases where the investigator disagreed with the EDR such that a belted occupant was identified as unbelted or an unbelted occupant was identified as belted, relative to the total number of cases. The inverse of the DR is the agreement rate (AR). Unweighted estimates are referred to as investigator estimates and weighted estimates are referred to as NASS-CDS estimates.

As the EDR dataset is a subset of the NASS-CDS database, we first compared the EDR cases with the NASS-CDS cases to determine how representative the EDR subsample was of the database under identical exclusion criteria. Similar to the dataset analyzed in this study, the NASS-CDS database was gathered from case years 2000-2013 and required to report a driver seat belt use estimate. The NASS-CDS database was also restricted to model year 1994 and later vehicles that experienced an airbag deployment. The unweighted and weighted cumulative distribution of resultant delta-v, “DVTOTAL”, was compared between the EDR subset and NASS-CDS database. Additionally, unweighted and weighted comparisons were conducted for each of the factors accessed in this study: rollover involvement, level of serious injury, and pretensioner presence.

When the EDR and the NASS-CDS investigator did not agree, additional checks were conducted for vehicles equipped with pretensioners. Then, using the NASS-CDS XML Case Viewer (version 3.6, NHTSA, Washington, DC), investigator photographs of the seat belt system were manually examined for evidence of pretensioner deployment. In many cases, photographs of the buckle were not taken or were taken at an unaccommodating angle, making it difficult to determine if the buckle pretensioner had fired. Thus, the visual checks could only be conducted with vehicles equipped with retractor pretensioners. Vehicle owner’s manuals for the specific make, model, and model year were sought to identify if the vehicle was equipped with a retractor pretensioner. If the photograph showed webbing that was permanently extended, then the driver was assumed to have been belted at the time of the crash. If the photograph showed webbing that was fully retracted and taut against the B-pillar, then the driver was assumed to have been unbelted. If no clear evidence showed that the webbing was fully retracted, then it was excluded from the results of the visual check analysis.

Comparisons were also made between the EDR and police-determined seat belt use. The variable “PARUSE” indicates police reported seat belt use. “None used” was considered unbuckled. "Shoulder belt", "Lap belt", "Lap and shoulder belt", "Belt used - type unknown", " Child safety seat", and " Other type belt (specify)" were considered buckled.

Among the unweighted population, the belt use estimates were compared using the chi square test in SAS 9.3 (SAS, Cary, NC) using PROC FREQ and the table option "chisq". Similarly, among the weighted population, the belt use estimates were compared using the modified Rao-Scott chi square test using PROC SURVEYFREQ and the table option "chisq1". This test was conducted on weighted contingency tables for the overall population. This test requires that each cell of the contingency table contains a non-zero frequency, so there must be at least one case for each possible estimate combination:

- EDR reports the driver as belted and NASS-CDS estimates the driver is belted
- EDR reports the driver as belted and NASS-CDS estimates the driver is unbelted
- EDR reports the driver as unbelted and NASS-CDS estimates the driver is belted
- EDR reports the driver as unbelted and NASS-CDS estimates the driver is unbelted

PROC SURVEYFREQ accounts for the complex sampling scheme used in NASS-CDS. For both populations, the null hypothesis was that there was no association between the belt estimates. An alpha of 0.05 was used.

4.3 RESULTS

Our weighted dataset contained belt use on 404,904 drivers, based upon 1,086 unweighted drivers. The EDR dataset is a subset of the entire NASS-CDS database. The NASS-CDS database under identical exclusion criteria contained 45,368 unweighted and 17,287,197 weighted drivers. Figure 4.1 shows that the study EDR dataset contains a qualitatively comparable cumulative distribution of delta-v crashes to the NASS-CDS dataset. Figure 4.2 compares the frequency of rollover involvement, level of serious injury, and pretensioner presence within the EDR dataset compared to the NASS-CDS dataset over the same time period (2000-2013) for unweighted and weighted frequencies. Compared to NASS-CDS, the study dataset contained slightly fewer rollovers for both unweighted and weighted drivers. For injury severity, the unweighted datasets showed the EDR subset had fewer serious injuries (11%) compared to the NASS-CDS dataset (17%). However, the weighted dataset showed identical distribution for injury severity. Presence of pretensioners between the two datasets showed the greatest difference. The EDR subset showed the majority of vehicles to be equipped with pretensioners, whereas the NASS-CDS dataset showed the majority of vehicles were not equipped. There was a 33% difference between the weighted datasets. Despite the difference in pretensioner frequency, these figures largely indicate that the EDR subset was comparable to the NASS-CDS sample.

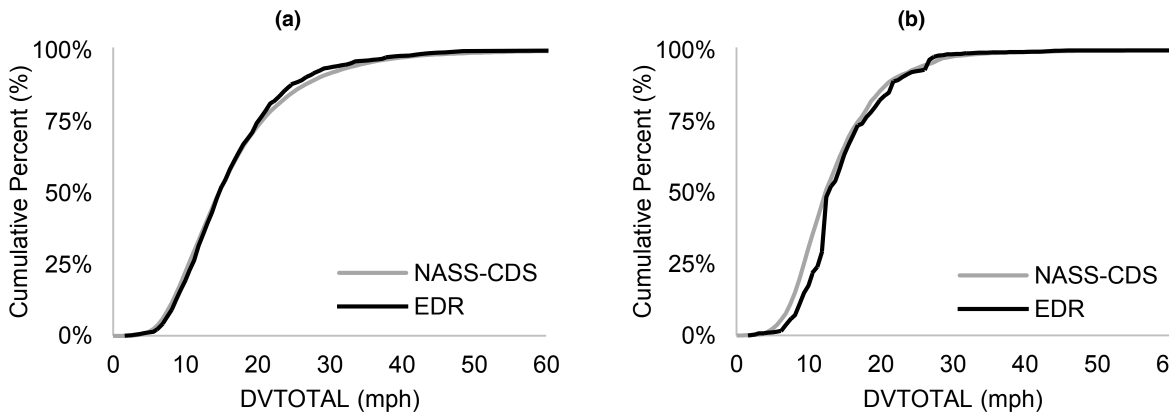

Figure 4.1. (a) Unweighted and (b) weighted cumulative delta-v for study EDR subset and all NASS-CDS cases

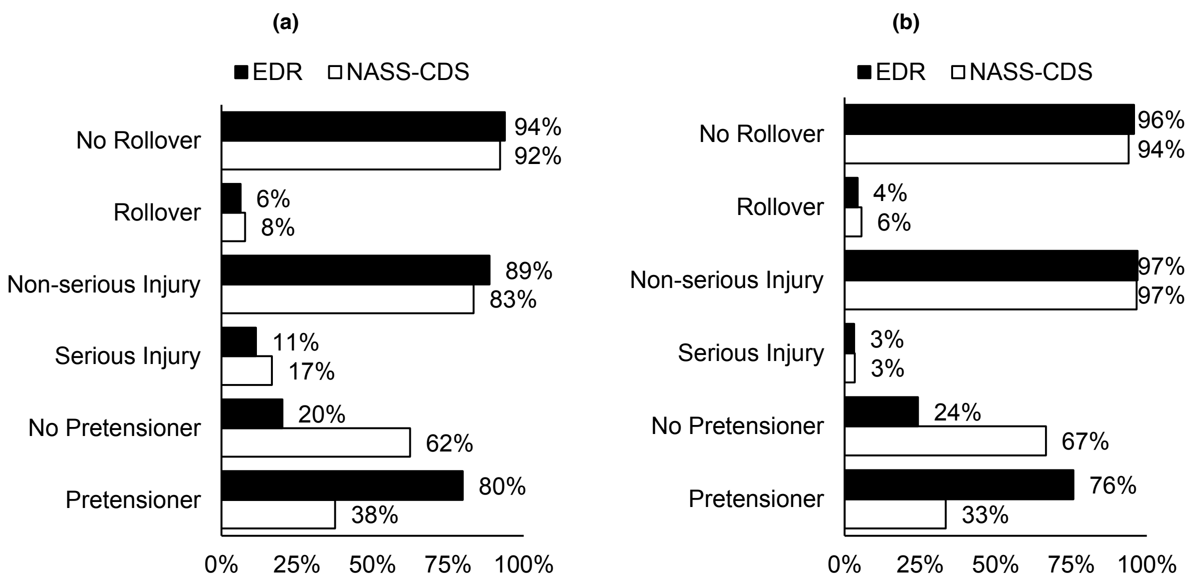

Figure 4.2. Comparison of EDR and investigator (a) unweighted and (b) weighted distribution of factors affecting agreement

The unweighted and weighted estimates of seat belt use are shown in Table 4.1 and Table 4.2, respectively. As shown Table 4.2, out of the 404,904 drivers the EDR reported 267,908 (66%) drivers as belted. NASS-CDS reported 318,017 (79%) drivers as belted. The police reported 392,677 (97%) as belted. The modified Rao-Scott chi square test showed statistically significant differences between the EDR and NASS-CDS (x^2=20.4; p<0.0001), and the EDR and police (x^2=7.0; p=0.0080). Investigators agreed with the EDR in 96% of unweighted driver seat belt use estimates. The unweighted and weighted rates of agreement are shown in Figure 4.3. As seen in Figure 4.3(a), among drivers identified as belted by the EDR, 4.1 % of the investigators disagreed with the EDR: 3.5% were unbelted drivers identified as belted and 0.6% were belted drivers identified as unbelted.

Table 4.1 EDR and investigator unweighted belt use estimates with chi square test results

	EDR Belt Use		NASS Belt Use		x^2
	n	(%)	n	(%)	
Overall					
	784	(72%)	815	(75%)	p < 0.0001
Pretensioner					
Unequipped	144	(66%)	164	(75%)	p < 0.0001
Equipped	640	(74%)	651	(75%)	p < 0.0001
Rollover					
No	737	(73%)	770	(76%)	p < 0.0001
Yes	42	(68%)	40	(65%)	p < 0.0001
Speed					
Low	445	(73%)	471	(77%)	p < 0.0001
High	158	(76%)	159	(76%)	p < 0.0001
Injury Severity					
MAIS2-	669	(74%)	703	(78%)	p < 0.0001
MAIS3+	69	(59%)	65	(56%)	p < 0.0001
Source					
Not Equip/Avail	1	(50%)	1	(50%)	p = 0.1573
Vehicle Inspect	777	(72%)	808	(75%)	p < 0.0001
Off Injury Data	1	(50%)	1	(50%)	p = 0.1573
Interview	5	(63%)	5	(63%)	p = 0.0047
Other	0	(00%)	0	(00%)	*

* Not computed because one contingency table row has 0 frequency

Investigators agreed more with the EDR when estimating seat belt use for vehicles equipped with pretensioners. In vehicles without pretensioners, EDRs reported 39% to be belted and NASS-CDS estimated 88% to be belted, but there was no significant association between the estimates given by the EDR and NASS-CDS (x^2=1.1; p=0.2998). Investigators disagreed with the EDR among 12.8% of drivers in vehicles not equipped with pretensioners: 11.0% were unbelted drivers identified as belted and 1.8% were belted drivers identified as unbelted. In vehicles equipped with pretensioners, EDRs reported 75.0% to be belted and the NASS-CDS estimated 75.6% to be belted (x^2=48.3; p<0.0001). Investigators disagreed with the EDR in only 2.0% of drivers in vehicles equipped with pretensioners: 1.6% were unbelted drivers identified as belted and 0.3% were belted drivers identified as unbelted.

Investigators agreed more with the EDR when estimating seat belt use for vehicles that experienced rollover. The majority of vehicles did not experience a rollover, and for these 387,528 drivers (96%), EDRs reported 66% to be belted and NASS-CDS estimated 79% to be belted (x^2=18.5; p<0.0001). The investigator agreement rate (95.8%) was nearly identical to the overall dataset. Of the remaining 4.2% of drivers where the investigator belt use did not match the EDR, 3.7% were unbelted drivers identified as belted and 0.5% were belted drivers identified as unbelted. For the 4% of drivers (16,242 out of 404,966) that did experience a rollover, the EDRs reported 60.4% to be belted and NASS-CDS estimated 59.7% to be belted. The modified Rao-Scott chi-square tests could not be applied as NASS-CDS did not mismatch any unbelted occupants as belted. In these rollover crashes, the investigator agreement rate increased (96.8%), where the remainder was composed only of belted drivers identified as unbelted (3.2%).

Table 4.2 EDR and NASS-CDS weighted belt use estimates with Rao-Scott chi square test results

	EDR Belt Use		NASS Belt Use		x^2
	n	(%)	n	(%)	
Overall					
	267,908	(66%)	318,017	(79%)	p < 0.0001
Pretensioner					
Unequipped	38,119	(39%)	86,397	(88%)	p = 0.2998
Equipped	229,789	(75%)	231,620	(76%)	p < 0.0001
Rollover					
No	257,619	(66%)	307,845	(79%)	p < 0.0001
Yes	9,806	(60%)	9,690	(60%)	*
Speed					
Low	137,297	(59%)	186,123	(81%)	p = 0.0043
High	41,216	(85%)	41,683	(86%)	p = 0.0006
Injury Severity					
MAIS2-	247,523	(67%)	298,637	(81%)	p < 0.0001
MAIS3+	7,337	(61%)	5,972	(50%)	*
Source					
Not Equip/Avail	906	(88%)	906	(88%)	*
Vehicle Inspect	262,197	(66%)	312,307	(79%)	p < 0.0001
Off Injury Data	898	(91%)	898	(91%)	*
Interview	3,908	(88%)	3,908	(88%)	*
Other	0	(00%)	0	(00%)	*

* Not computed because one contingency table cell has 0 frequency

Investigators agreed more with the EDR when estimating seat belt use for high speed crashes ($\geq$ 20 mph) than low speed crashes (< 20 mph). In low speed crashes, EDRs reported 59% to be belted and NASS-CDS estimated 81% to be belted (x^2=8.1; p=0.0043), with an agreement rate of 77.7%. The investigator agreement rate was 94.8%, where a total of 4.7% unbelted drivers were identified as belted and 0.5% of belted drivers identified as unbelted. In high speed crashes, EDRs estimated belt use to be 84.6% and NASS-CDS estimated belt use to be 85.6% (x^2=11.8; p=0.0006), with an agreement rate of 99.0%. The investigator agreement rate was 98.6%. There were only slightly more belted drivers identified as unbelted (1.0%) compared to unbelted drivers identified as belted (0.5%).

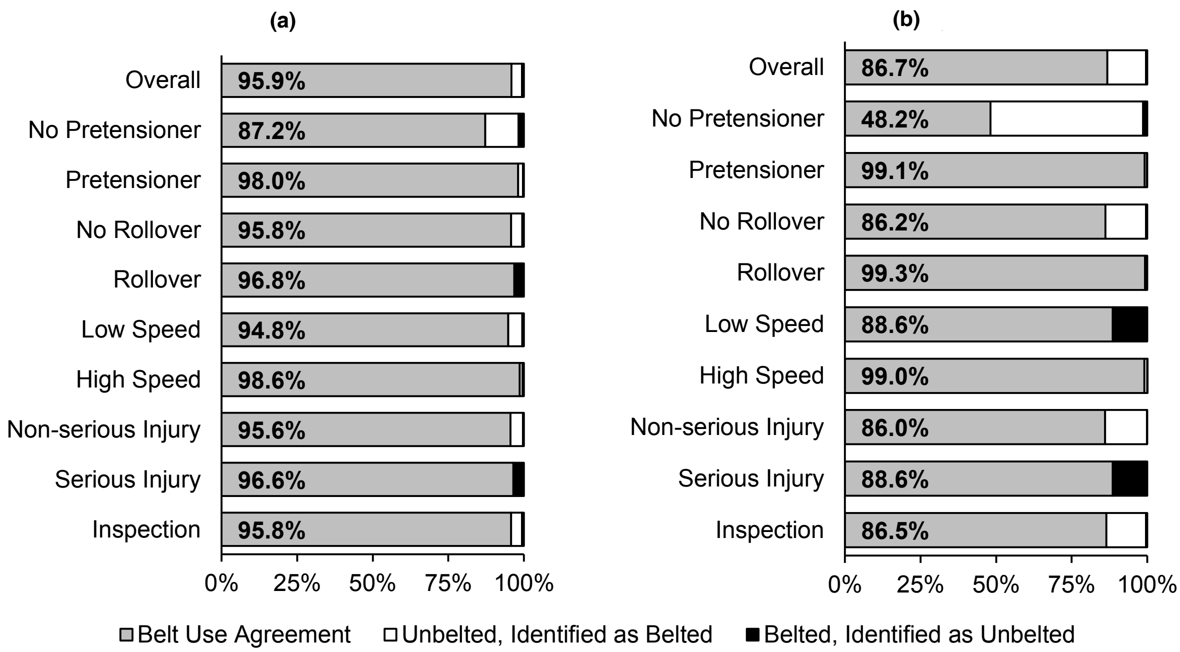

Figure 4.3 Misclassification rates of investigator-determined belt use, relative to the EDR

Among drivers sustaining no injury, a minor injury, or a moderate injury (MAIS2-) the EDR reported 67% as belted, compared to NASS-CDS which reported 81% (x^2=17.1; p<<0.0001). Investigators agreed with the EDR in 95.6% of these unweighted cases. Investigators did not agree with the EDR in 4.4% of drivers sustaining a non-serious injury: 4.1% were unbelted drivers identified as belted and 0.3% were belted drivers identified as unbelted. Among the 11,970 weighted drivers sustaining a serious, severe, critical, or maximum injury (MAIS3+), the EDR reported 61% belt use compared to NASS-CDS which reported 50% belt use, but no statistical tests could be conducted because NASS-CDS agreed with the EDR among all unbelted drivers. The agreement rate between the investigators and EDR was 96.6%. In the remaining 3.4% of drivers where investigators disagreed with the EDR, all were belted drivers identified as unbelted.

Investigators used vehicle inspection in 1,072 of the 1,086 cases, corresponding to 396,940 of the 404,904 weighted cases. When the vehicle inspection was the source for determining seat belt use, the EDR reported 66% belt use when NASS-CDS estimated 79% (x^2=19.5; p<0.0001). The investigator agreement rate was 95.8%, where a total of 3.5% unbelted drivers were identified as belted and 0.7% of belted drivers identified as unbelted. In less than 2% of the cases, the investigator did not use vehicle inspection to determine the seat belt use. Due to the low frequencies, the modified Rao-Scott chi square test could not be applied to these other categories of belt use estimate source as there were no mismatched cases. For two vehicles, the belt source indicated that the vehicle was unequipped with a seat belt or that it was unavailable (NASS-CDS ID: 828017424 vehicle 1, 932017023 vehicle 1), but photographs from the NASS-CDS XML

Case Viewer (version 3.6, NHTSA, Washington, DC) showed that the vehicle was equipped with the restraints.

Table 4.3 EDR and police belt use estimates with Rao-Scott chi square test results.

	EDR Belt Use		Police Belt Use		x^2
	n	(%)	n	(%)	
Overall					
	267,908	(66%)	392,677	(97%)	p = 0.008
Pretensioner					
Unequipped	38,119	(39%)	94,452	(96%)	p = 0.2793
Equipped	229,790	(75%)	298,226	(97%)	p = 0.0055
Rollover					
No	257,620	(66%)	376,827	(97%)	p = 0.0171
Yes	9,806	(60%)	14,729	(91%)	p = 0.0403
Speed					
Low	137,297	(59%)	226,152	(98%)	p = 0.0341
High	41,216	(85%)	47,592	(98%)	p = 0.0294
Injury Severity					
MAIS2-	247,524	(67%)	362,095	(98%)	p = 0.0468
MAIS3+	7,337	(61%)	9,028	(75%)	p < 0.0001
Source					
Not Equip/Avail	906	(88%)	906	(88%)	*
Vehicle Inspect	262,197	(66%)	385,341	(97%)	p = 0.0109
Off Injury Data	898	(91%)	984	(100%)	*
Interview	3,908	(88%)	3,934	(89%)	*
Other	0	(00%)	1,513	(100%)	*

* Not computed because at least one table cell has 0 frequency

Out of the 45 unweighted, investigator-mismatched cases, only 11 vehicles with deployed retractor pretensioners could be identified. We examined the investigator photographs in these cases to check the belt use recorded by the EDR. Our inspection showed that the EDR belt use was correct in 9 cases. However, in two cases, our inspection showed that the EDR was incorrect (NASS-CDS ID: 748014970 vehicle 2, a 2008 Toyota Tundra; 837016654 vehicle 1, a 2007 Chevrolet Cobalt). The photographs for these two cases showed the seat belt webbing was recoiled and taut against the B-pillar. This would indicate that the driver was unbelted. However, in these cases, the EDR recorded buckled when the investigator indicated unbelted. For both modules, however, there were signs of incorrectly recorded data. The Toyota Tundra indicated in its Bosch CDR report that the right front passenger airbag had deployed, but NASS-CDS and the investigator photographs showed that it had not deployed. The Chevrolet Cobalt indicated that the supplemental inflatable restraint (SIR) warning light was on and that the right front passenger airbag was suppressed, despite that it was occupied during the crash. These additional errors may suggest that there were other problems with the specific module. Alternatively, it could be that the case ID given to the EDR was not correct and the report contains data for another crash altogether.

Table 4.3 summarizes the comparison of seat belt usage between the EDR and the police. Overall, the EDRs estimated 66% of drivers to be belted, much lower than the 97% reported by the police (x^2=7.0; p=0.0080). Overall, the police belt use estimates only agreed with the EDR in 67.8% crashes. Among the remaining 32.2% of cases estimated by police, 31.5% of unbelted drivers were identified as belted and 0.7% of belted drivers were identified as unbelted. The mismatched drivers also were less frequently uninjured (23% compared to 37% overall) and more frequently sustained minor injuries (62% compared to 49%).

4.4 DISCUSSION

This study found that, in our sample, belt use was 66% as reported by EDRs, 79% when estimated by NASS-CDS, and 97% when estimated by police. NASS-CDS disagreed with the EDR the seat belt use in 15% of estimates, primarily by identifying an occupant as belted when they were unbelted. This study found that the agreement of investigators determined seat belt use with EDRs reported seat belt use status improved in vehicles equipped with pretensioners, vehicles involved in rollover, and vehicles which experienced higher delta-v crashes. Pretensioners are responsible for retracting the webbing to eliminate slack and couple the occupant to the vehicle. As described by Jakstis et al (2009), pretensioners offer distinct webbing marks and characteristics separate from those caused by occupant loading, which are distinctly different when the occupant is belted or unbelted. These well-defined features allow investigators to unmistakably determine belt use. The investigators (98%) and NASS-CDS (99.1%) showed very high agreement to the EDR among the population of vehicles equipped with pretensioners. As pretensioners increasingly infiltrate the U.S. fleet, the agreement of the investigators seat belt use estimates to the EDR will likely increase for overall cases. In rollovers, occupant ejections offer greater evidence to investigators to help determine seat belt use. Vehicles experiencing high delta-v crashes were subject to lower disagreement rates likely because they display more distinguished occupant loading marks, as suggested by Raymond et al (2006) and Tanner et al (2006).

The results of the police and investigator belt estimates fall reasonably close to the estimates reported by previous studies. Viano and Parenteau (2009) reported police estimates of 93% and NASS-CDS estimates of 88%. Moore et al reported police estimates of 85% and NASS-CDS estimates of 80%. The minor differences observed are likely due to the difference in the case years analyzed, as well as the restrictions required to properly align the EDR data to the NASS-CDS case (i.e. airbag deployment). Schiff and Cummings (2004), Moore et al, and Viano and Parenteau did not exclude cases based upon airbag deployment. This study examined NASS-CDS case years 2000-2013, restricted to the years of NASS-CDS

EDR data available. However, Viano and Parenteau (2009) focused on a subset of 1993-2007 case years and Moore et al (2006) studied 1988-2006. Seat belt usage has increased among drivers from 58% in 1994 (Glassbrenner and Ye 2006) to 87% in 2013 (Pickrell and Liu 2014) according to NHTSA's Traffic Safety Facts. This trend was also observed in other studies evaluating seat belt use (Moore et al 2009).

4.4.1 Limitations

Our study only examined events which deployed the airbag. We did not examine lower severity cases. However, as determining belt use from forensic evidence becomes increasingly difficult as crash severity declines, we expect that our findings will extend to lower severities, i.e. the seat belt usage estimates of NASS-CDS and EDRs would further diverge. The dataset in this study was also limited as it only assessed the driver seat because there are fewer EDR validation studies which have checked the accuracy of right front passenger seat belt buckle status. This study was limited to those modules which had been validated in previous studies.

As Chidester et al (1998) reported, and as observed from this study, EDRs may occasionally record incorrect seat belt status. Although the accuracy studies evaluating EDR seat belt status have been conducted on many modules (Gabler et al 2008; Niehoff et al 2005; Tsoi et al 2013, 2014), the studies have largely evaluated crash tests in which the driver crash test dummies were belted. Thus, these tests would not identify a module that erroneously always recorded that the driver was belted. In our validation, there were only two cases where the EDR was incorrect; however, we only checked those cases with retractor pretensioners. We cannot make any statement about accuracy in vehicles equipped with buckle pretensioners or unequipped with any pretensioner. Both cases were identified by the EDR to be belted, but our examination of the photographs confirmed the investigators assessment that the drivers were unbelted. However, the erroneous cases also contained other flaws in the EDR report could indicate that either there were other problems with the specific module, or that the assigned case ID given to the EDR was not correct and the report contains data for another crash altogether. This highlights the need to use EDR data in conjunction with investigations, as opposed to relying solely on the reports.

Also, there is a distinction between what EDRs and investigators are reporting: EDRs record seat belt buckle status and investigators record seat belt use. Typically these are the same. However, EDRs cannot distinguish proper use from misuse, e.g. using only the lap belt and routing the torso webbing behind-the-back (Brown et al 2009). Studies evaluating automatic seat belt systems have estimated misuse in only 6% of drivers (Reinfurt et al 1991). EDRs cannot determine if the seat belt was misused.

Additionally Part 563 requires EDRs to record seat belt use information for only the two front outboard occupants. There is no requirement to record belt status for rear occupants. Investigators are capable of not only determining seat belt use for all occupants, but they can provide details including the type of seat belt restraint, whether a child seat was integrated, and whether the seat belt was inoperative. All vehicles in the current fleet are not equipped with EDRs. EDRs may occasionally not survive collisions involving vehicle fire, vehicle immersion, or very high delta-v (Tsoi et al 2015). Thus EDR data cannot be obtained from all motor vehicle crashes. Although EDRs offer a direct measure of seat belt buckle status, investigators will still need to estimate belt use.

5 EVALUATION OF VEHICLE-BASED CRASH SEVERITY METRICS

5.1 INTRODUCTION

Delta-v is a widely used crash severity metric used to estimate occupant injury risk in real world crashes (Kononen et al 2006; Gabauer and Gabler 2008). Despite its widespread use and ease of calculation, delta-v has several limitations. Delta-v is a vehicle-based metric which is computed entirely from vehicle kinematics. Additionally, it does not consider the acceleration crash pulse shape, even though two dissimilar crash pulses can produce identical delta-v. If injury severity was solely a function of delta-v, we would expect every car tested under the U.S. NCAP to have the same rating, as the frontal crash tests all have a delta-v of approximately 56 kph (35 mph). However, because each of the NCAP vehicles have different crash pulses and restraint systems, their vehicle safety ratings can vary widely. Arguably the most important factor not accounted for by delta-v is the performance of occupant restraints, e.g. seatbelts and airbags, which have been shown to greatly reduce occupant injury (Evans 1986; Glassbrenner and Starnes 2009). These criticisms have prompted the search for alternative impact severity metrics based upon vehicle kinematics.

Vehicle-based crash severity metrics are one basis for the evaluation of occupant injury risk in collision with roadside hardware, e.g. crash cushions and guardrails, because these tests are conducted without instrumented ATDs. In the US, the flail space model (FSM) is used. Developed by Mitchie (1981a), the FSM was first incorporated into the National Cooperative Highway Research Program (NCHRP) Report 230 (Mitchie 1981b) testing procedure as the primary measure of risk and has been included in the subsequent updates: NCHRP Report 350 (Ross et al 1993) and the American Association of State Highway and Transportation Officials' Manual for Assessing Safety Hardware (MASH) standard (AASHTO 2009). The model relies upon the assumption that occupant injury is related to the impact velocity between the occupant and vehicle interior (occupant impact velocity; OIV), and subsequent deceleration of the vehicle and occupant (occupant ridedown acceleration; ORA). The FSM simulates an unbelted occupant, modeled as a point mass, that "flails" forward until inelastic collision within the passenger compartment. The occupant is limited to 0.6 m (2 ft) of movement longitudinally and 0.3 m (1 ft) laterally, and the movement components are assumed to be independent of one another. FSM does not consider the effects of yaw, pitch, and roll. Acceptable OIV values are less than 12 m/s (26 mph) and represent serious injury, but 9 m/s (20 mph) is the preferred value. For ORA, less than 20 G (196 m/s^2) is acceptable, but 15 G (147 m/s^2) is preferred (Mitchie 1981a).

In Europe, three other vehicle-based crash severity metrics are calculated to determine occupant injury risk in collisions with roadside hardware. The theoretical head impact velocity (THIV) and post-impact head deceleration (PHD) are analogous to OIV and ORA, respectively, but also incorporate the effect of yaw motion and relies upon resultant, rather than component, velocities (CEN 1998). Additionally, the European Committee for Standardization (CEN) recommends the calculation of the acceleration severity index (ASI). ASI assumes the occupant is in constant contact with the vehicle due to belt use. Thus, unlike delta-v, ASI considers restraints in the computation. As shown in Eq. (1), ASI is a ratio relating peak averaged acceleration, over a duration of 50 ms, to predetermined thresholds for each directional component. The protocol specifies that these thresholds are 12 G for longitudinal acceleration, 9 G for lateral acceleration, and 10 G for vertical acceleration. ASI is dimensionless. ASI values less than 1.4 are deemed acceptable and represent light injury, but a value of 1.0 is recommended (CEN 1998).

$$ASI(t) = \sqrt{\left(\frac{\bar{a}_{50ms,x}}{12}\right)^2 + \left(\frac{\bar{a}_{50ms,y}}{9}\right)^2 + \left(\frac{\bar{a}_{50ms,z}}{10}\right)^2} \qquad \text{(Equation 15)}$$

As a note, the European testing procedures additionally evaluate roadside hardware with metrics not determined from vehicle kinematics. These include the energy absorbed by the vehicle structure: equivalent energy speed (EES), equivalent test speed (ETS), and equivalent barrier speed (EBS). These measures are scalar quantities based upon deformation energy determined through vehicle crush (ISO 2002; Ross et al 1998).

More recently, a new injury metric, vehicle pulse index (VPI), was proposed by the International Organization for Standardization (ISO 2013). Illustrated by Figure 5.1 and Equations 16-18, VPI models the occupant as a single degree of freedom (SDOF) lumped mass-spring system that incorporates restraint use in its estimates of occupant motion. The mass, M, represents the occupant and $y(t)$ represents the occupant motion. The vehicle motion is shown as $x(t)$. The vehicle and occupant motion are connected by the restraint systems, summarized as the function $P(t)$, which is defined by a spring of stiffness, k, and slack, s. The standard ISO model is based upon a single set of parameters which are applied to all vehicles. The recommended values are 1kg for the mass, 2,500 N/m for the stiffness, and 0.03 m for the slack, leaving only vehicle motion as an unknown. The ISO standard only describes the computation procedure, but does not relate VPI to occupant injury.

Figure 5.1 Schematic of the impact severity metric, vehicle pulse index (VPI), as a mass-spring system.

$$\mathrm{VPI} = \max(\ddot{y}) \quad \text{(Equation 16)}$$

$$M\ddot{y} + ky = P(t) \quad \text{(Equation 17)}$$

$$P(t) = \begin{cases} 0 & , x < s \\ k(x-s) & , x \geq s \end{cases} \quad \text{(Equation 18)}$$

Each of these vehicle-based crash severity metrics requires a source of vehicle kinematics data. One promising source of vehicle kinematics information is EDR data. The NHTSA estimated 96% of the model year 2013 light vehicle fleet were equipped (NHTSA 2013). Several studies have evaluated the accuracy of EDRs (Chidester et al 1999; Niehoff et al 2005; Gabler et al 2008; Tsoi et al 2013 and 2014) with a primary focus on longitudinal maximum delta-v. EDRs from vehicles in full-frontal crash tests typically underreport the reference instrumentation delta-v with an absolute error reported between 3% (Gabler et al 2008) and 7% (Tsoi et al 2013). As EDRs directly measure delta-v in a crash and have reasonable accuracy, EDRs are an ideal source for obtaining real world crash kinematics.

Since 2000, NHTSA has downloaded EDR data as part of the NASS-CDS. NASS-CDS is a public database containing a probability sample of motor vehicle crashes where at least one vehicle was towed due to damage (Zhang and Chen 2013). The sampling scheme and case weighting allow for nationally representative estimates of towaway crashes and crash injuries. NASS-CDS data is collected by trained investigators that obtain information including accident, vehicle, and occupant data from approximately 5,000 motor vehicle crashes annually. Therefore, in addition to the real world crash kinematics obtained from the EDR, NASS-CDS provides corresponding occupant injury outcome.

Gabauer and Gabler (2008) previously conducted a study that utilized EDRs to evaluate longitudinal ASI, delta-v, and OIV. They concluded that these alternative crash severity metrics offered no significant predictive advantage over the simpler, traditional delta-v in a sample of 180 real world crashes involving belted and unbelted occupants. Though previous studies have shown the ability of VPI to predict head and chest injuries in crash tests (Prasad and Weston 2011), no study has evaluated VPI in real world collisions or with respect to traditional delta-v. Thus, the purpose of this study was to assess the ability of the ASI, delta-v, OIV, and VPI to predict serious injury in real world crashes.

5.2 METHODS

The study dataset was drawn from NASS-CDS crashes from case years 2000-2013 using EDRs that were downloaded as part of these investigations. Crashes were restricted to frontal collisions (“F”) as determined by the general area of damage, GAD1. Crashes involving rollover were excluded. No exclusion criteria was placed upon the type of collision partner, i.e. fixed object or another vehicle. Cases were included only if the principal direction of force (PDOF) was ± 20° from the vehicle's longitudinal axis to focus the study on crashes with predominant loading in the frontal direction. Lateral and vertical delta-v were assumed to be negligible. These restrictions are consistent with MASH and NCHRP 350 crash test protocols, which specify impact angles varying between 0° and 25° (AASHTO 2009). Cases were excluded if the NASS-CDS case weighting exceeded 5,000. For this calculation, the only EDR data needed was longitudinal delta-v, the only direction of recording in many older modules (Chidester et al 1999; Gabler et al 2008). Vehicles were included only if the crash caused an airbag deployment. In an airbag deployment, the EDR locks the crash data and prevents the data from being overwritten.

Only single event crashes were included to ensure that any injuries which occurred were the result of the recorded event. Vehicles were also restricted to those manufactured by GM, which encompassed 83% of EDRs downloaded by NASS-CDS investigators. Only EDR data which met two quality control criteria were included. First, the EDR was required to have a completed recording status flag that indicated that the recording was successfully completed. Second, the longitudinal delta-v data was inspected to ensure a full crash pulse, defined for our study as a final derived acceleration of 2 G or less. Any EDR data downloads not meeting these two criteria were excluded.

Drivers were the only occupant assessed in this study. Only drivers with known belt use and injury severity were included. Belt use was determined from the EDR report, as opposed to NASS-CDS. Several studies have shown EDR belt use to be accurate (Chidester et al 1999; Niehoff et al 2005; Gabler et al 2008; Tsoi et al 2013 and 2014). The maximum abbreviated injury scale (MAIS) was used to describe occupant injury outcome. In this study, only regions of thorax, abdomen, and spine were included in the determination of MAIS, as the point mass assumptions of each vehicle-specific crash severity metric are less likely to be good predictors of lower extremity, upper extremity, head, and face injuries. MAIS is reported on a scale from 1 to 6, where 1 indicates minor injury and 6 represents a maximum injury, often fatal (AAAM 2001). Uninjured drivers were indicated with MAIS=0. If the driver MAIS was "injured, unknown severity" but fatally injured, then the case was included as an MAIS=6. Otherwise, drivers were excluded if the MAIS was unknown, i.e. "unknown if injured" and "injured, unknown severity" (without known fatality). Drivers were categorized into either a non-serious (MAIS2-) or serious (MAIS3+) injury group.

5.2.1 Longitudinal Maximum Delta-V

Maximum longitudinal delta-v was directly taken from the delta-v versus time series data recorded in the EDR report.

5.2.2 Longitudinal Occupant Impact Velocity

Calculation of OIV first required trapezoidal integration of the EDR vehicle velocity to obtain displacement. As the dataset was restricted to frontal crashes with small deviation from a 0° PDOF, the lateral displacement component of the FSM was ignored. The data was linearly interpolated to obtain the time corresponding to 0.6 m (2 ft) of longitudinal displacement. The change in velocity at this time was the OIV. If the displacement did not exceed 0.6 m, however, the OIV was equivalent to the maximum longitudinal delta-v.

5.2.3 Longitudinal Acceleration Severity Index

ASI, as defined by CEN (1998), includes components that incorporate the effect of lateral and vertical movement; however, as this study focused only on frontal crashes, the ASI equation was simplified as shown in Equation 19. As the EDR longitudinal velocity was recorded at 100 Hz for our dataset, the maximum 50 ms average vehicle longitudinal acceleration, $\overline{a}_x$, was calculated according to Equation 20, where v_i represents the *i*-th EDR longitudinal velocity. Additionally, $\hat{a}_x$ was specified to be 12 G, corresponding to light injury as recommended by the protocol (CEN 1998).

$$ASI = \frac{\overline{a}_x}{\hat{a}_x} \qquad \text{(Equation 19)}$$

$$\overline{a}_x = \frac{v_i - v_{i-5}}{0.05s} \qquad \text{(Equation 20)}$$

5.2.4 Vehicle Pulse Index

As occupant restraints vary from vehicle to vehicle, the stiffness and slack parameters utilized in the calculation were first computed for specific makes and models of VPI. Data from NCAP full-frontal crash tests were used. In our dataset there were 65 GM model year 1995 and newer vehicles that could be cross-referenced to a NASS-CDS "makmod" vehicle code. Each crash test was instrumented with several accelerometers in the occupant compartment. Two such accelerometers measuring along the longitudinal axis of the vehicle were averaged and used as the vehicle motion, x(t). As there was only one channel measuring the pelvis longitudinal acceleration in each ATD, the occupant motion, y(t), was computed by averaging the driver and right front passenger pelvis sensor along the longitudinal axis. All accelerations were filtered at channel frequency class (CFC) 180 Hz following SAE J211-1 guidelines (SAE 2007) for vehicle structural accelerations for use in integration for velocity or displacement.

The SDOF mass-spring system was modeled using the Structural Impact Simulation and Model Extraction (SISAME; Washington, D.C.) program developed by NHTSA (Mentzer 2006). SISAME models uniaxial mass-spring systems and allows for parameter extraction from crash tests. Our model used a segmented inelastic spring and extracted a single stiffness and slack. Example code for test 8316, which evaluated a 2014 Chevrolet Silverado 1500 in a full-frontal crash test, is shown as follows:

```
SISAME Input File

Run Information

   RunID=8316
      Title=2014 Chevrolet Silverado 1500
      DelTOut=0.0001  FinTOut=0.129

Model Information

   MdlID=vpi
      DimSys=Metric
      IniVel=56.55
      Cutoff=180

   MassID=Veh  Descr=FLOORPAN – LEFT REAR
      Class=D
      File=v08316_veh.uds

   SprID=Restraints
      NegMass=Occ.Pelvis  PosMass=Veh
      StaType=SI  SU=?  ST=?  XSlk=?
         X=0  #
         F=0  ?

   VehID=Occ

      MassID=Pelvis  Decr=PELVIS - CENTER
         Wt=1
         File=v08316_pel.uds

Output Information

   OutClass=MassTS  Qty=AVD
   OutClass=SprPar  Spr=*
   OutClass=Model
```

The value given for “XSlk” was the slack and the ratio of force, “F”, to displacement, “X”, was the stiffness. VPI was calculated with both the ISO recommended and vehicle-specific values. Both VPI values and longitudinal delta-v were compared to the injury surrogates measured during the crash tests to evaluate which parameters better predicted occupant injury. R-square was used to determine the best relationship. The extracted vehicle-specific parameters from the crash tests were related to the NASS-CDS vehicles by “makmod” code and generation model years. VPI was then calculated according to Equations 16-18.

5.2.5 Statistics

All statistical analyses were conducted in SAS (9.3, Cary, NC) using PROC SURVEYLOGISTIC. ASI, delta-v, OIV, and VPI were assessed individually as predictors of occupant injury outcome in binary logistic regression. For each crash severity metric, two separate models were created for belted and unbelted drivers. Non-serious injuries (MAIS2-) were assigned a "0" and serious injuries (MAIS3+) were assigned a "1". The observed injury outcome and 95% Wald confidence limits were overlaid on the injury risk curves. The Wald x^2 test was applied to assess whether the regression coefficient of each vehicle-based crash severity metric was statistically different from zero in the model.

The goodness-of-fit, or how well the model's predicted outcome matches the observed outcome, was determined for each vehicle-based crash severity metric using the Akaike Information Criterion (AIC). AIC is presented as an assessment of the intercept, and of the intercept and covariates. Lower AIC values indicate better fit. Thus, if the AIC of the intercept and covariates is lower than the AIC of only the intercept (null model), the evaluated model offers an improved relationship to the response compared to the null model. In addition, receiver operator characteristic (ROC) curves were generated for each model using PROC LOGISTIC (Agnelli 2014). The ROC represents the sensitivity and specificity at varying discrimination levels. Sensitivity measures the ability of the vehicle-based severity metric to correctly identify seriously injured drivers. Specificity measures the ability of the metric to correctly identify non-seriously injured drivers. Two thresholds were reported from these ROC curves: 50% threshold and best threshold. The 50% threshold indicates a value of the severity metric such that the probability of serious injury is 50%. The best threshold indicates a value of the severity metric that provides the best separation between the seriously and non-seriously injured. Pairwise comparisons were also made for the ROC values to determine whether there were statistically significant differences between the candidate metrics using the ROCCONTRAST statement. The area under the curve of the ROC (AUC) can be compared among models, such that larger AUC values indicate better predictive capabilities.

5.3 RESULTS

As shown in Table 5.1, the real-world dataset used in this study was composed of 334 GM vehicles for which all 4 vehicle-based crash severity metrics were computed. The 334 vehicles corresponds to 102,744 vehicles when weighted. Among the 102,744 drivers, 72% (74,080) wore their seat belts. The majority of drivers were involved in a crash with a PDOF of 0° (55%). Among the 102,744 drivers, only 1,863 (2%) sustained a serious injury (MAIS3+). Of the remaining 100,881 drivers, 96,010 sustained no injury (MAIS=0) or a minor injury (MAIS=1).

5.3.1 VPI Restraint Model

The SISAME extraction of restraint parameters from crash tests computed vehicle-specific slack (5.88 ± 9.31 mm) and stiffness (1,964 ± 787 N/m). These average values were lower than the ISO recommended values of 30 mm for slack and 2,500 N/m for stiffness. A table of the vehicle-specific stiffness and slack values is presented in the Appendix (Table A.14). If the channel failed, then the test was excluded from the analysis. One case (test 2376 Geo Tracker) was excluded as an outlier in the chest deflection analysis (437 mm). In general, VPI better predicted occupant injury criteria than longitudinal delta-v. For longitudinal (x) pelvis acceleration, vehicle-specific VPI showed the best relationship (R^2=0.291), followed by ISO VPI (R^2=0.156) and delta-v (R^2=0.020). The order of best-fit metrics was identical for two chest injury metrics: 3 ms clip (R^2=0.354; R^2=0.173; R^2=0.009) and chest G (R^2=0.333; R^2=0.184; R^2=0.004). For chest compression, vehicle-specific VPI showed the best fit (R^2=0.080), followed by ISO VPI (R^2=0.037) and delta-v (R^2=0.004). For head injury criterion (HIC_{15}), each metric showed poor predictive power; vehicle-specific VPI showed the best relationship (R^2=0.019), followed by ISO VPI (R^2=0.0006) and delta-v (R^2=0.0002). The poor head injury prediction of each metric supports the criteria to exclude the lower extremity, upper extremity, head, and face regions in the real world crash analysis. A figure of ISO VPI and vehicle-specific VPI with respect to the injury metrics is available in the Appendix (Figure A.10).

5.3.2 Logistic Regression

Injury risk curves assessing the cumulative probability of serious injury as a function of ASI, delta-v, OIV, and VPI for generated for both belted (Figure A.11aceg) and unbelted (Figure A.11bdfh) drivers. The model parameters are presented in Table 5.2. The Wald χ^2 test showed each vehicle-based crash severity metric estimate to be significant in the model ($p<0.05$), regardless of belt use. In addition, the model estimates for each vehicle-based crash severity metric were positive, indicating that increases in each metric led to higher probabilities of MAIS3+ injury.

For each model, the AIC of the intercept and covariate values were lower than the AIC of the intercept (belted: 11,029; unbelted: 7,395). Among the belted drivers, the AIC of the intercept and covariate values showed the following trend of decreasing predictive ability: ASI (6,703), VPI (6,844), OIV (7,526), and delta-v (7,882). This indicates that ASI showed the greatest predictive ability and delta-v showed the least predictive ability among the belted dataset relative to the other metrics. Among the unbelted models, the metrics' predictive ability decreased in the following order: delta-v (2,238), OIV (2,572), VPI (3,141), and ASI (3,310). This indicates that delta-v showed the greatest predictive ability and OIV showed the least predictive ability among the unbelted dataset relative to the other metrics.

Table 5.1 Distribution of dataset characteristics for vehicle-based crash severity metric analysis

	Unweighted			Weighted		
Characteristic	Belted	Unbelted	Total	Belted	Unbelted	Total
Injury Severity						
MAIS2-	219	91	310	73,030	27,851	100,881
MAIS3+	17	7	24	1,050	813	1,863
PDOF						
0°	103	44	147	41,407	14,837	56,244
±10°	89	37	126	21,271	8,789	30,061
±20°	44	17	61	11,402	5,037	16,439
ASI Recommended Threshold						
< 1.0	182	75	257	66,984	25,860	92,844
> 1.0	54	23	77	7,096	2,804	9,900
ASI Acceptable Threshold						
< 1.4	221	86	297	72,100	27,449	99,548
> 1.4	25	12	37	1,981	1,214	3,195
OIV Recommended Threshold						
< 9.0 m/s	174	74	248	65,557	25,774	91,332
> 9.0 m/s	62	24	86	8,523	2,889	11,412
OIV Acceptable Threshold						
< 12.0 m/s	211	86	297	71,924	27,449	99,374
> 12.0 m/s	25	12	37	2,156	1,214	3,370
Delta-V						
< 56 kph	224	88	312	73,702	27,583	101,286
> 56 kph	12	12	22	378	1,080	1,458
Total	236	98	334	74,080	28,663	102,744

Table 5.2 Summary of logistic regression model parameters

Belt Status	Crash Severity Metric	Intercept Estimate (95% CL)	Metric Estimate (95% CL)	Standard Error	Wald χ^2
Belted	ASI (G/G)	-8.38 (-10.74, -6.69)	4.69 (3.10, 6.27)	0.537	30.62 (p<0.0001)
	Delta-v (m/s)	-8.38 (-10.53, -6.22)	0.48 (0.30, 0.66)	0.041	27.25 (p<0.0001)
	OIV (m/s)	-9.12 (-11.74, -6.50)	0.58 (0.34, 0.81)	0.106	25.28 (p<0.0001)
	VPI (m/s^2)	-8.14 (-10.00, -6.27)	0.02 (0.01, 0.02)	0.003	31.03 (p<0.0001)
Unbelted	ASI (G/G)	-7.51 (-9.89, -5.13)	3.64 (1.62, 5.66)	0.624	12.23 (p<0.0001)
	Delta-v (m/s)	-9.27 (-12.56, -5.98)	0.50 (0.24, 0.75)	0.050	14.34 (p<0.0001)
	OIV (m/s)	-9.98 (-13.66, -6.29)	0.65 (0.33, 0.96)	0.134	11.32 (p<0.0001)
	VPI (m/s^2)	-8.04 (-11.10, -4.99)	0.02 (0.01, 0.03)	0.003	12.77 (p<0.0001)

Table 5.3 Summary of goodness-of-fit test results

Belt Status	Crash Severity Metric	AIC		AUC
		Intercept	Intercept & Covariates	
Belted	ASI (G/G)	11,029	6,703	0.9158
	Delta-v (m/s)	11,029	7,882	0.8617
	OIV (m/s)	11,029	7,526	0.8711
	VPI (m/s^2)	11,029	6,844	0.9068
Unbelted	ASI (G/G)	7,395	3,310	0.9053
	Delta-v (m/s)	7,395	2,238	0.9238
	OIV (m/s)	7,395	2,572	0.9252
	VPI (m/s^2)	7,395	3,141	0.9046

Table 5.4 Summary of model prediction accuracy at a 50% threshold and the best threshold.

Belt Status	Crash Severity Metric	Threshold Value	Sensitivity (%)	Specificity (%)	Accuracy (%)
			50% Threshold		
Belted	ASI (G/G)	1.79	23.5	99.9	98.8
	Delta-v (m/s)	17.3	7.1	99.9	98.6
	OIV (m/s)	15.7	10.7	99.9	99.8
	VPI (m/s^2)	452	28.0	99.9	98.9
Unbelted	ASI (G/G)	2.06	43.8	99.3	97.7
	Delta-v (m/s)	18.7	76.7	99.5	98.9
	OIV (m/s)	15.4	76.7	99.5	98.9
	VPI (m/s^2)	447	43.8	99.7	98.1
			Best Threshold		
Belted	ASI (G/G)	1.18	76.8	95.9	95.6
	Delta-v (m/s)	9.7	61.3	94.3	93.8
	OIV (m/s)	9.7	61.3	96.2	95.7
	VPI (m/s^2)	309	57.4	97.6	97.0
Unbelted	ASI (G/G)	1.57	96.7	98.5	98.4
	Delta-v (m/s)	16.8	96.1	99.1	99.0
	OIV (m/s)	13.2	96.7	98.5	98.5
	VPI (m/s^2)	334	96.1	98.5	98.4

The ROC curves for all vehicle-based crash severity metrics are shown in Figure A.12. The 50% threshold sensitivity, specificity, and accuracy are shown in Table 5.4. The AUC for all models exceeded 0.86. For the belted models, AUC was the highest for ASI (0.92) and lowest for delta-v (0.86). The pairwise comparisons indicated significant difference, at the 0.05 level, only between VPI and delta-v. Additionally, the delta-v and ASI comparison were close to significance (p=0.07; Table 5.5). No statistically significant differences were seen between the two metrics modeling belted drivers, ASI and VPI (p=0.45). The ROC curves showed that the threshold to achieve the highest sensitivity and specificity for serious injury were 1.18 for ASI, 9.7 m/s (34.9 kph) for delta-v, 9.7 m/s (34.9 kph) for OIV, and 309 m/s^2 (31.5 G) for VPI.

For the unbelted drivers, OIV had the highest AUC (0.93), followed by delta-v (0.92), ASI (0.91), and VPI (0.90). However, for unbelted drivers, the pairwise comparisons showed that there was no statistically significant difference between the crash severity metrics (Table 5.5). The best thresholds were determined to be 1.57 for ASI, 16.8 m/s (60.5 kph) for delta-v, 13.2 m/s (47.5 kph) for OIV, and 334 m/s² (31.4 G) for VPI.

Using the best threshold, the unweighted and weighted serious injury prediction of each metric is shown in Table 5.5, relative to the known injury severity. All of the vehicle-based crash severity metrics overpredicted the number of MAIS3+ injuries among belted drivers. VPI showed the least amount of overprediction (+1,322) and delta-v showed the greatest overprediction (+4,824). Similarly, all metrics overpredicted the number of unbelted drivers sustaining MAIS3+ injuries: delta-v showed the least amount of overprediction (+220) and ASI showed the greatest amount of overprediction (+402). Thus, if used in applications such as advanced automatic crash notification (AACN), each of these metrics would over triage MAIS3+ drivers.

Table 5.5 Statistical significance tests of ROC pairwise comparisons

Pairwise Comparison	Belted	Unbelted
ASI : MDV	p=0.0730	p=0.1827
ASI : OIV	p=0.1453	p=0.1638
ASI : VPI	p=0.4470	p=0.5939
MDV : OIV	p=0.0134	p=0.8726
MDV : VPI	p=0.0420	p=0.1860
OIV : VPI	p=0.1121	p=0.1880

Table 5.6 Unweighted and weighted frequency of predicted injury severity using best threshold values.

	Unbelted				Belted			
	MAIS2-		MAIS3+		MAIS2-		MAIS3+	
	Unweighted	Weighted	Unweighted	Weighted	Unweighted	Weighted	Unweighted	Weighted
Observed	91	27,851	7	813	219	73,030	17	1,050
Predicted: ASI	86	27,449	12	1,214	199	70,290	37	3,790
Predicted: Delta-v	90	27,631	8	1,032	189	69,256	47	4,824
Predicted: OIV	87	27,472	11	1,192	197	70,643	39	3,437
Predicted: VPI	87	27,454	11	1,210	209	71,709	27	2,372

5.4 DISCUSSION

The broad findings of this study suggest it is feasible to improve injury prediction if we consider adding restraint performance to classic measures, e.g. delta-v. Applications, such as AACN, should consider using a different crash severity metric for belted drivers than for unbelted drivers. The findings of this study have also established serious injury (MAIS3+) thresholds for belted and unbelted drivers for longitudinal delta-v and particularly, VPI, which had not been established previously in the standard (ISO 2013).

ASI, OIV, and VPI were better predictors than delta-v for seriously injured, belted drivers. However, the best threshold contingency table for the sample analyzed in this study, showed VPI was a better predictor of belted MAIS3+ injuries. Note that VPI and ASI are both metrics designed for belted drivers and overall the results of the goodness-of-fit tests showed each metric performed similarly. Although OIV models an unrestrained occupant, recall that OIV restricts occupant movement to 0.6 m (2 ft) of movement longitudinally and 0.3 m (1 ft) of movement laterally. This feature serves as a crude restraint, which may explain why OIV outperformed delta-v ($p=0.013$). Additionally, OIV considers the crash pulse more than delta-v as OIV determines the occupant motion by integration of the velocity. Gabauer and Gabler (2008) conducted an unweighted analysis on a sample size of only 145 belted occupants and concluded that ASI and OIV offered no greater predictive ability than delta-v. Unlike Gabauer and Gabler (2008), this study has shown that ASI and OIV (as well as VPI) are better predictors than delta-v for belted drivers. All body regions were considered in the Gabauer and Gabler (2008) study.

For unbelted drivers, no significant differences were found among the crash severity metrics according to the ROC pairwise comparison. This was reflected in the inconsistent rankings given by the goodness-of-fit tests, which suggested the metrics had relatively similar predictive ability. The AIC indicated that delta-v was a modestly better predictor than the other metrics. This was supported by the best threshold contingency table for the sample analyzed in this study, where delta-v showed the closest prediction of unbelted MAIS3+ injuries. Perhaps not surprising, delta-v and OIV, which model unbelted drivers, marginally outperformed VPI and ASI which model belted occupant kinematics. Delta-v may have outperformed OIV among unbelted drivers because the occupant movement restriction may not be representative of all vehicle interiors, particularly among this study dataset of airbag deployments. On the other hand, AUC indicated OIV provided the most predictive ability to discern serious injury. These AUC findings are consistent with the Gabauer and Gabler (2008) study, which conducted an unweighted analysis on a sample size of only 35 unbelted occupants.

5.4.1 Limitations

This study only assessed vehicles involved in a frontal collision and did not consider other crash modes, e.g. side impact. Moreover, this study only assessed longitudinal delta-v and assumed that other components of delta-v were negligible. Among the 334 vehicles, 181 were accompanied by lateral delta-v data averaging a maximum lateral delta-v of 1.70 ± 1.67 m/s (3.8 ± 3.7 mph). Lastly, this study only assessed GM vehicles. It is not known how these results generalize to other vehicle makes in the U.S. fleet.

EDRs are reasonably accurate, but are not perfect. EDRs have been shown to underreport the delta-v measured by onboard reference accelerometers by 3-7% in full-frontal crash tests (Gabler et al 2008; Tsoi et al 2013). The errors associated with EDR delta-v were not accounted for in this study, which may affect the goodness-of-fit of these models. However, this error equally affects the vehicle-based crash severity metrics and allows the relative comparison conclusions to be meaningful.

The reliance upon EDRs also limits this study in other ways, as the distribution of MAIS in this subsample of vehicles with EDRs may not be representative of all model year 1995 and later vehicles in NASS-CDS. Our dataset contained a slightly smaller proportion of uninjured and minor injured drivers (93%) than in NASS-CDS 2000-2013 (95%). Moreover, not all vehicles are equipped with EDRs and not all crashes involved airbag deployments, limiting the available vehicles we could study.

The methodology for determining vehicle-specific parameters is not limited to the 65 GM crash tests vehicles. Future studies should expand the vehicle-specific parameter calculation to other OEMs and other crash modes besides full-frontal tests. The subset was merely chosen as a proof-of-concept and selected according to the most common vehicles equipped with EDRs in the NASS-CDS database. NASS-CDS investigators use the publically available Bosch Crash Data Retrieval (CDR) Tool to download EDR data, which only supported GM vehicles when it was first established. NASS-CDS also contains EDRs extracted from BMW, Chrysler, Ford, Honda, Hyundai, Mazda, Nissan, Toyota, and Volvo vehicles. However, the number of EDRs extracted from these vehicles is much less frequent and the accuracy of the EDR reported delta-v has not been evaluated in many of these modules.

This study only considers injury prediction to the occupant trunk, i.e. the chest, abdomen, and spine. Our rationale was that these body regions are most consistent with the assumption of ASI, delta-v, OIV, and VPI that the occupant can be modeled as a point mass. Our results do not necessarily apply to other body regions.

6 IMPLICATIONS AND FINAL THOUGHTS

EDRs are an invaluable data source that have begun to, and will increasingly, provide novel insight into motor vehicle crash characteristics. This data has the potential to eclipse the many traditional surrogate measures used in vehicle safety that often rely upon assumptions and simplifications of real world crashes (Gabler et al 2003, 2004ab; Hampton and Gabler 2009ab; Johnson and Gabler 2014). Ultimately the completion of this dissertation will make users of EDR data more confident in their data and will greatly simplify the approach utilized to obtain data, such as delta-v. The specific aims were to (1) validate EDR accuracy in full-frontal, side-impact moving deformable barrier, and small overlap crash tests; (2) evaluate EDR survivability beyond regulatory crash test requirements, (3) determine the seat belt accuracy in current crash databases, and (4) assess the merits of other vehicle-based crash severity metrics relative to delta-v. A list of publications anticipated from this work is shown in Table 6.1.

Table 6.1 Published and submitted works derived from this dissertation

Chapter	Citation	Status
2	Tsoi AH, Hinch J, Ruth R, Gabler HC. Validation of Event Data Recorders in High Severity Full-Frontal Crash Tests. *SAE Int J Trans Safety*. 2013; 1: 76-99.	Published
2	Tsoi AH, Johnson N, Gabler HC. Validation of Event Data Recorders in Side-Impact Crash Tests. *SAE Int J Trans Safety*. 2014; 1: 130-164.	Published
2	Tsoi AH, Mueller B, Gabler HC. Validation of Event Data Recorders in Small Overlap Crash Tests.	To Be Submitted: Accident Analysis & Prevention
3	Tsoi AH, Hinch J, Gabler HC. Analysis of Event Data Recorder Survivability in Crashes with Fire, Immersion, and High Delta-V. Paper presented at: Society of Automotive Engineers (SAE) World Congress. April 21-23, 2015; Detroit, MI. doi:10.4271/2015-01-1444.	Published
4	Tsoi AH, Gabler HC. Evaluation of NASS-CDS Seat Belt Use Estimates. Traffic Injury Prevention	To Be Submitted: Traffic Injury Prevention
5	Tsoi AH, Gabler HC. Evaluation of Vehicle-Based Crash Severity Metrics.	Submitted: Traffic Injury Prevention (Special AAAM Issue)

The first specific aim (Chapter 2) of this dissertation established the accuracy of EDR measurements recorded during full-frontal, side-impact, and small overlap crash tests. A total of 176 crash tests were analyzed, corresponding to 29 EDR module types, 5 model years, 9 manufacturers, and 4 testing configurations. This study assessed the accuracy of precrash speed, longitudinal delta-v, lateral delta-v recorded, driver seat belt use status, right front passenger seat belt use status, driver-side front airbag deployment status, driver-side torso airbag deployment status, and driver-side curtain airbag deployment status. The work provided in this chapter bridged the growing gap between pre-regulatory EDRs and those currently equipped in new model year vehicles. Additionally, this study has established methodologies for computing rotation-corrected velocity for EDR modules with multiple accelerometers (i.e. Toyota modules). For vehicles without multiple sensors, this chapter has also provided reference values for rotational velocity and rotational acceleration, and the corresponding equations to correct for rotation in modes similar to the IIHS small overlap crash test.

The second specific aim (Chapter 3) of this dissertation showed the survivability of EDRs in crashes beyond the scope of FMVSS 208 and 214. This work, in conjunction with experimental studies (Tsoi et al 2015b), has important implications on future survivability regulations, as it established that extreme events of vehicle fire, vehicle immersion, and high delta-v are rare and that anecdotal evidence shows modules are surviving these events. Beyond these implications, the study established weaknesses of the existing NASS-CDS database, as it does not clearly define reasons for which an EDR cannot be read.

The third specific aim (Chapter 4) showed that EDRs were a plausible source for the determination of seat belt use. The short-term implications were revised restraint effectiveness measures and improved injury risk curves that rely upon seat belt use. A long-term goal of this work was to establish a methodology that will expand to assess the accuracy of other NASS-CDS investigator-determined elements. Moreover, expanded validation studies to evaluate other data elements will ultimately provide researchers with data unobtainable, or very difficult to obtain, by conventional inspection methods, *e.g.* steering wheel angle, roll rate, and occupant seat position.

The fourth specific aim (Chapter 5) of this dissertation assessed the ability of the ASI, delta-v, OIV, and VPI to predict serious injury in real world crashes. This chapter showed that for belted occupants, the ASI, OIV, and VPI vehicle-based crash severity metrics were better predictors of serious injury outcome than delta-v. For unbelted occupants, none of the alternative crash severity metrics showed statistical difference to the traditional and simplistic delta-v metric. As other studies have begun to show, the vehicle crash kinematics downloaded from EDRs offer immense potential in evaluating vehicle-based crash severity metrics (Gabauer and Gabler 2004, 2005). This study additionally established a methodology to refine VPI parameters, which may allow us to better model occupant kinematics and perhaps better understand serious injuries that occur even when occupants are restrained (Chen and Gabler 2014). The broad findings of this study suggest it is feasible to improve injury prediction if we consider adding restraint performance to classic measures, e.g. delta-v. This may have implications in applications, such as AACN, which may rely on using a vehicle-based crash severity metric to predict occupant injury risk for the purpose of improving emergency medical service (EMS) response and triage (Gabler et al 2001; Ayoung-Chee et al 2013). By using different metrics among belted and unbelted occupants, AACN algorithms could potentially better predict serious injury. This is emphasized by a study conducted by Funk et al (2008), which showed how errors in metrics, i.e. delta-v, can affect injury risk curves. Additionally, regulatory agencies, e.g. the NHTSA, should perhaps consider crash severity metrics other than just delta-v in their in-depth crash databases, e.g. NASS-CDS.

Furthermore, EDR data discloses other details important to crash reconstruction that were not assessed in this dissertation. Other studies have utilized this data to evaluate airbag deployment algorithms in real world crashes (Gabler and Hinch 2008c). Additionally, Kusano and Gabler (2011) used EDR data to estimate time to collision at braking in real world rear-end crashes. Although some EDRs additionally record vehicle roll angle, anti-lock braking system status, and stability control information (SAE 1698-1) which have clear potential to further explain vehicle dynamics, there is untapped occupant information (i.e. seat track position, occupant position) that may aid the understanding of thoracic injuries seen in motor vehicle crashes (Gayzik et al 2009).

Additionally, the implications of this work extend beyond the immediate conclusions of the performed studies, which have established a groundwork for analyses within light vehicle crash reconstruction. For instance, the precrash information that EDRs record has potential to enlighten the active safety community regarding driver behavior in the moments leading up to a crash. Some studies have relied on data sources several decades old, i.e. Hutchinson and Kennedy (1966) and Cooper (1980), for driver behavior characteristics (Daniello et al 2013; Johnson et al 2015a). Kusano and Gabler (2013a, 2013b, 2013c) utilized EDR precrash data, e.g. of steering wheel angle, speed, and brake application, to elucidate driver crash avoidance maneuvers. Although similar information could be gained from naturalistic driving studies, the number of crashes recorded is very low (Guo et al 2010) and EDR data is a greater resource for automotive crashes. The improvement of these active safety systems, i.e. lane departure warning, may reduce road departure (Gorman et al 2013; Kusano and Gabler 2012a, 2014a, 2014b; Scanlon et al 2015a, 2015b) and the subsequent roadside barrier impacts that are often studied (Gabauer and Gabler 2010; Kusano and Gabler 2012b; Hampton and Gabler 2013; Johnson and Gabler 2013, 2015b).

As the potential of EDR data is realized, the importance of measuring real time data could spread to other types of vehicles. For instance, similar devices to EDRs are already found in heavy trucks (Steiner et al 2009; Bowman et al 2013), aircrafts (EUROCAE 2003, 2009), trains (German et al 2001), and boats (Braasch 1989). As these devices have provided unique insight into various transportation modes, their implementation may reach vulnerable road users, i.e. motorcyclists and pedestrians, which have posed data collection challenges in terms of instrumentation. In particular, many studies have attempted to better understand motorcyclist injuries with respect to impact object (Daniello et al 2010, 2011a, 2011b, 2012;

Gabler 2007a, 2007b) and trajectory (Daniello et al 2014), especially as there is contention over the effectiveness of motorcycle training (Daniello et al 2009). Condro et al (2012) have suggested the use of smartphone sensors to detect high-risk motorcycle maneuvers to alert the rider.

Ultimately, this work has strong implications for EDR users, regulatory agencies, and future technologies.

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A Appendix

Table A.1 Description of the full-frontal crash tests accuracy study dataset

Test No.	NHTSA No.	Module Type	Make & Model	Location	Channels Averaged		Impact Speed (kph)	Deployment
7460	MC0300	CHRY0305	Chrysler Town & Country	Rear Floorpan	93	100	56.4	Deployed
7464	MC0310	CHRY0305	Dodge Avenger	Rear Floorpan	93	94	56.6	Deployed
7471	MC0319	CHRY4101	Dodge Journey	Rear Floorpan	93	100	56.5	Deployed
7475	MC0210	FordRC6_2011	Ford Mustang	Rear Sill	93	99	56.4	Deployed
7478	MC0200	FordAB10	Ford Focus	Rear Sill	94	99	56.3	Deployed
7482	MC0307	CHRY0305	Chrysler 200	Rear Seat	93	94	56.6	Deployed
7488	MC0100	SDM11_AUTOLIVNEW	Chevrolet Impala	Rear Seat	93	100	56.2	Deployed
7494	MC0106	SDM10	Chevrolet Camaro	Rear Floorpan	93	100	56.2	Deployed
7495	MC0204	FordRC62011CGEAD	Ford Explorer	Rear Floorpan	93	100	56.4	Deployed
7502	MC5105	Toyota001	Toyota Tacoma	Rear Sill	93	100	56.6	Deployed
7505	MC0325	CHRY0000	Fiat 500	Rear Sill	94	100	56.0	Deployed
7509	MC0103	SDM10	Chevrolet Suburban 1500	Rear Floorpan	93	94	56.3	Deployed
7520	YC5100	Toyota001	Toyota Camry	Rear Floorpan	94	100	56.3	Deployed
7521	MC0121	SDM10	Cadillac CTS	Rear Sill	93	99	56.1	Deployed
7525	MC0322	CHRY0305	Dodge Durango	Rear Seat	93	99	56.3	Deployed
7527	MC0303	CHRY0403	Ram 1500 Quad Cab	Rear Floorpan	93	99	56.2	Deployed
7531	MC0115	SDM10P	Cadillac SRX	Rear Sill	93	94	56.3	Deployed
7564	MC0109	SDM10	Chevrolet Sonic	Rear Floorpan	94	99	56.2	Deployed
7566	MC5400	MAZDA002	Mazda Mazda6	Rear Seat	93	99	56.4	Deployed
7567	MC0334	CHRY0305	Jeep Liberty	Rear Seat	94	99	56.6	Deployed
7577	MC0900	Volvo001	Volvo S60	Rear Sill	93	94	56.5	Deployed
7579	MC5316	Honda001	Honda Fit	Rear Floorpan	94	100	56.5	Deployed
7582	MC0112	SDM10	Chevrolet Silverado 2500	Rear Floorpan	93	100	56.2	Deployed
7585	MC5109	Toyota001	Toyota Tundra	Rear Sill	94	99	56.2	Deployed
7587	MC0331	CHRY4005	Chrysler 300	Rear Floorpan	93	99	56.2	Deployed
7592	MC0306	CHRY0403	Ram 1500 Crew Cab	Rear Floorpan	94	99	56.5	Deployed
7605	MC5106	Toyota001	Toyota Yaris Liftback	Rear Sill	93	94	56.1	Deployed
7606	MC0316	CHRY4005	Dodge Charger	Rear Floorpan	93	100	56.3	Deployed
7615	QC5100	Toyota001	Toyota Sienna	Rear Seat	94	99	56.2	Deployed
7618	MC5115	Toyota001	Lexus ES350	Rear Sill	94	100	55.9	Deployed
7619	MC5300	Honda001	Honda Civic IMA	Rear Floorpan	94	99	56.3	Deployed
7622	MC5319	Honda001	Honda CR-Z	Rear Seat	93	99	56.3	Deployed
7623	MC0207	FordRC62011CGEAD	Ford F250 Super Crew	Rear Sill	93	94	56.3	Deployed
7624	MC0213	FordRC6_2011	Ford Expedition	Rear Sill	93	94	56.4	Deployed
7625	MC0203	FordRC62011CGEAD	Ford F150 Supercab	Rear Sill	93	100	56.6	Deployed
7627	MC5310	Honda001	Honda Civic	Rear Sill	93	99	56.6	Deployed
7729	MC5119	Toyota001	Scion iQ	Rear Sill	99	100	56.4	Deployed
7732	MC5303	Honda001	Honda CR-V	Rear Floorpan	93	94	56.3	Deployed
7744	MC5102	Toyota001	Toyota RAV4	Rear Sill	94	99	56.7	Deployed
7747	MC0313	CHRY0403	Ram 2500 Crew Cab	Rear Sill	93	94	55.8	Deployed
7755	MC5112	Toyota001	Toyota 4Runner	Rear Sill	93	94	56.3	Deployed

Table A.2 EDR and crash test characteristics of the full-frontal crash tests accuracy study dataset

Test No.	Make & Model	EDR Recording Complete	ΔV Freq. (Hz)	EDR Time Shift (ms): Time Between t0 & AE	EDR Time Shift (ms): First EDR Time	EDR Time Shift (ms): Incr. ΔV Alignment Time	EDR Time Shift (ms): Total Alignment Time	ΔV Shift (kph)	>50G Peak Reference Acceleration (180 Hz Filter)
7460	Chrysler Town & Country	☑	500		---	---	---	---	☑
7464	Dodge Avenger	☑	500		0	4.3	4.3	0.81	☐
7471	Dodge Journey	☐	100		0	4.8	10.7	0.50	☑
7475	Ford Mustang	☑	100		1.5	1.6	3.1	0.95	☐
7478	Ford Focus	☑	500		0	4.5	4.5	0.98	☐
7482	Chrysler 200	☑	100		0	6.0	6.0	0.74	☐
7488	Chevrolet Impala	☑	100	9	-70	26.4	17.4	0.00†	☐
7494	Chevrolet Camaro	☑	100	6	-70	15.2	9.2	0.00†	☑
7495	Ford Explorer	☑	100		0.5	8.7	9.2	1.68	☑
7502	Toyota Tacoma	☑	500		10	-4.7	5.3	0.00‡	☑
7505	Fiat 500	☑	100		0	3.2	3.2	0.76	☑
7509	Chevrolet Suburban 1500	☑	100	6	-70	9.3	3.3	0.00†	☐
7520	Toyota Camry	☑	100		10	1.2	11.2	0.00	☐
7521	Cadillac CTS	☑	500	9	-70	12.7	3.7	0.00†	☑
7525	Dodge Durango	☑	500		0	8.0	8.0	2.12	☑
7527	Ram 1500 Quad Cab	☑	100		0	8.7	8.7	0.85	☐
7531	Cadillac SRX	☑	100		10	4.5	14.5	0.20	☑
7564	Chevrolet Sonic	☑	500	3	-70	16.6	13.6	0.00†	☑
7566	Mazda Mazda6	☑	100		0	26.8	26.8	10.07	☐
7567	Jeep Liberty	☑	100		0	8.0	8.0	1.58	☑
7577	Volvo S60	☑	100		0	9.5	9.5	1.08	☑
7579	Honda Fit	☑	100		0	9.2	9.2	2.60	☐
7582	Chevrolet Silverado 2500	☑	100	3	-70	18.3	15.3	0.00†	☐
7585	Toyota Tundra	☑	500		10	-4.7	5.3	0.00‡	☑
7587	Chrysler 300	☑	500		0	8.1	8.1	1.31	☑
7592	Ram 1500 Crew Cab	☑	100		0	8.1	8.1	0.89	☐
7605	Toyota Yaris Liftback	☑	500		10	2.1	12.1	0.00	☑
7606	Dodge Charger	☑	100		0	11.2	11.2	2.26	☑
7615	Toyota Sienna	☑	100		10	11.6	21.6	1.61	☐
7618	Lexus ES350	☑	100		10	4.2	14.2	0.48	☑
7619	Honda Civic IMA	☑	100		0	4.7	4.7	0.83	☐
7622	Honda CR-Z	☑	100		0	8.1	8.1	1.40	☑
7623	Ford F250 Super Crew	☑	100		9	3.2	12.2	0.04	☐
7624	Ford Expedition	☑	100		6	6.2	12.2	0.12	☐
7625	Ford F150 Supercab	☑	100		8.5	9.1	17.6	0.65	☐
7627	Honda Civic	☑	100		0	1.5	1.5	0.00	☐
7729	Scion iQ	☑	100		10	-3.0	7.0	0.00‡	☑
7732	Honda CR-V	☑	100		0	24.3	24.3	10.31	☑
7744	Toyota RAV4	☑	500		10	4.0	14.0	0.06	☑
7747	Ram 2500 Crew Cab	☑	100		0	8.4	8.4	0.94	☐
7755	Toyota 4Runner	☑	500		10	5.2	15.2	0.07	☑

† EDR provided time points before t = 0, showing no accumulation of ΔV
‡ Algorithm optimized a time shift before t = 0

Table A.3 Comparison of EDR and crash test data elements (full-frontal crash test study)

Test No.	Make & Model	Airbag Deployed				Seatbelt Buckled			
		Driver		RFP		Driver		RFP	
		Test	EDR (ms)	Test	EDR (ms)	Test	EDR	Test	EDR
7460	Chrysler Town & Country	☑	†	☑	†	☑	a	☑	☑
7464	Dodge Avenger	☑	†	☑	†	☑	a	☑	a
7471	Dodge Journey	☑	9	☑	9	☑	☑	☑	☑
7475	Ford Mustang	☑	8.5	☑	8.5	☑	☑	☑	☑
7478	Ford Focus	☑	8	☑	8	☑	☑	☑	☑
7482	Chrysler 200	☑	†	☑	†	☑	a	☑	a
7488	Chevrolet Impala	☑	9	☑	9	☑	☑	☑	☑
7494	Chevrolet Camaro	☑	6	☑	6	☑	☑	☑	☑
7495	Ford Explorer	☑	4.5	☑	4.5	☑	☑	☑	☑
7502	Toyota Tacoma	☑	6	☑	6	☑	☑	☑	☑
7505	Fiat 500	☑	5	☑	5	☑	☑	☑	☑
7509	Chevrolet Suburban 1500	☑	6	☑	6	☑	☑	☑	☑
7520	Toyota Camry	☑	8	☑	8	☑	☑	☑	☑
7521	Cadillac CTS	☑	9	☑	9	☑	☑	☑	☑
7525	Dodge Durango	☑	†	☑	†	☑	☑	☑	☑
7527	Ram 1500 Quad Cab	☑	4	☑	4	☑	☑	☑	a
7531	Cadillac SRX	☑	6	☑	6	☑	☑	☑	☑
7564	Chevrolet Sonic	☑	3	☑	3	☑	☑	☑	☑
7566	Mazda Mazda6	☑	6	☑	6	☑	☑	☑	☑
7567	Jeep Liberty	☑	†	☑	†	☑	a	☑	☑
7577	Volvo S60	☑	5	☑	5	☑	☑	☑	☑
7579	Honda Fit	☑	9	☑	9	☑	☑	☑	☑
7582	Chevrolet Silverado 2500	☑	3	☑	3	☑	☑	☑	b
7585	Toyota Tundra	☑	4	☑	4	☑	☑	☑	☑
7587	Chrysler 300	☑	9	☑	9	☑	☑	☑	☑
7592	Ram 1500 Crew Cab	☑	3	☑	3	☑	☑	☑	a
7605	Toyota Yaris Liftback	☑	1	☑	1	☑	☑	☑	☑
7606	Dodge Charger	☑	7	☑	7	☑	☑	☑	☑
7615	Toyota Sienna	☑	9	☑	9	☑	☑	☑	☑
7618	Lexus ES350	☑	5	☑	5	☑	☑	☑	☑
7619	Honda Civic IMA	☑	8	☑	8	☑	☑	☑	☑
7622	Honda CR-Z	☑	7	☑	7	☑	☑	☑	☑
7623	Ford F250 Super Crew	☑	12	☑	12	☑	☑	☑	c
7624	Ford Expedition	☑	5.5	☑	5.5	☑	☑	☑	☑
7625	Ford F150 Supercab	☑	4.5	☑	4.5	☑	☑	☑	☑
7627	Honda Civic	☑	9	☑	9	☑	☑	☑	☑
7729	Scion iQ	☑	4	☑	4	☑	☑	☑	☑
7732	Honda CR-V	☑	3	☑	3	☑	☑	☑	☑
7744	Toyota RAV4	☑	2	☑	2	☑	☑	☑	☑
7747	Ram 2500 Crew Cab	☑	10	☑	10	☑	☑	☑	a
7755	Toyota 4Runner	☑	4	☑	4	☑	☑	☑	☑

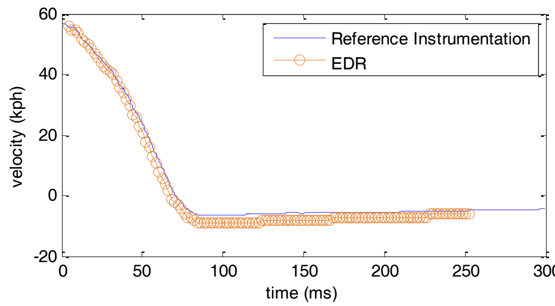
† Module indicated deployment, but did not provide time to deployment
a Driver or right front passenger seat belt switch was not configured
b EDR contained the recording status data element, but reported only “N/A”
c Data element not in report

Table A.4 Comparison of EDR and crash test precrash speed (full-frontal crash test study)

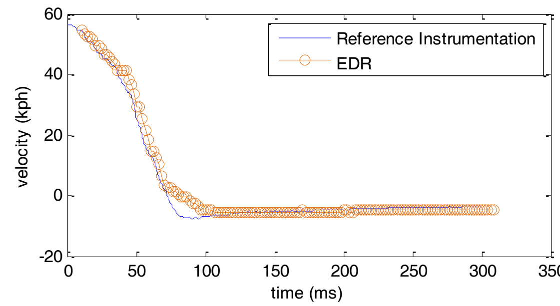
Test No.	Make & Model	Precrash Speed (kph)			
		Test	EDR	Error	% Error
7460	Chrysler Town & Country	56.4	56	-0.40	-0.7%
7464	Dodge Avenger	56.6	56	-0.60	-1.1%
7471	Dodge Journey	56.5	57	0.50	0.9%
7475	Ford Mustang	56.4	56	-0.40	-0.7%
7478	Ford Focus	56.3	56.1	-0.16	-0.3%
7482	Chrysler 200	56.6	56	-0.62	-1.1%
7488	Chevrolet Impala	56.2	56	-0.15	-0.3%
7494	Chevrolet Camaro	56.2	57	0.80	1.4%
7495	Ford Explorer	56.4	56	-0.40	-0.7%
7502	Toyota Tacoma	56.6	56	-0.61	-1.1%
7505	Fiat 500	56.0	56	-0.03	-0.1%
7509	Chevrolet Suburban 1500	56.3	56	-0.30	-0.5%
7520	Toyota Camry	56.3	54	-2.30	-4.1%
7521	Cadillac CTS	56.1	56	-0.12	-0.2%
7525	Dodge Durango	56.3	57	0.69	1.2%
7527	Ram 1500 Quad Cab	56.2	56	-0.20	-0.4%
7531	Cadillac SRX	56.3	57	0.73	1.3%
7564	Chevrolet Sonic	56.2	57	0.80	1.4%
7566	Mazda Mazda6	56.4	55	-1.44	-2.6%
7567	Jeep Liberty	56.6	56	-0.62	-1.1%
7577	Volvo S60	56.5	56	-0.53	-0.9%
7579	Honda Fit	56.5	56	-0.50	-0.9%
7582	Chevrolet Silverado 2500	56.2	56	-0.20	-0.4%
7585	Toyota Tundra	56.2	56	-0.18	-0.3%
7587	Chrysler 300	56.2	56	-0.20	-0.4%
7592	Ram 1500 Crew Cab	56.5	56	-0.50	-0.9%
7605	Toyota Yaris Liftback	56.1	56	-0.09	-0.2%
7606	Dodge Charger	56.3	56	-0.30	-0.5%
7615	Toyota Sienna	56.2	56	-0.18	-0.3%
7618	Lexus ES350	55.9	54	-1.92	-3.4%
7619	Honda Civic IMA	56.3	56	-0.30	-0.5%
7622	Honda CR-Z	56.3	56	-0.28	-0.5%
7623	Ford F250 Super Crew	56.3	56	-0.34	-0.6%
7624	Ford Expedition	56.4	55	-1.41	-2.5%
7625	Ford F150 Supercab	56.6	56	-0.62	-1.1%
7627	Honda Civic	56.6	57	0.42	0.7%
7729	Scion iQ	56.4	56	-0.42	-0.7%
7732	Honda CR-V	56.3	56	-0.30	-0.5%
7744	Toyota RAV4	56.7	54	-2.67	-4.7%
7747	Ram 2500 Crew Cab	55.8	56	0.24	0.4%
7755	Toyota 4Runner	56.3	56	-0.28	-0.5%

Table A.5 Comparison of EDR and crash test ΔV (full-frontal crash test study)

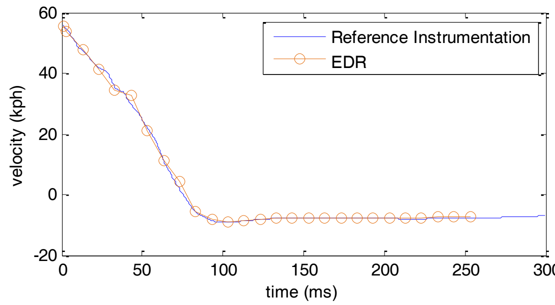
Test No	Make & Model	Final ΔV (kph)				Maximum ΔV (kph)				Report Single Max ΔV (kph)				Max. EDR ΔV Comparison	
		Test	EDR	Error	Error (%)	Test	EDR	Error	Error (%)	Test	EDR	Error	Error (%)	Error (mph)	Error (%)
7460	Chrysler Town & Country	61.43	---	---	---	62.26	---	---	---	62.26	---	---	---	---	---
7464	Dodge Avenger	61.09	62	0.91	1.49%	63.22	65	1.78	2.82%	63.22	---	---	---	---	---
7471	Dodge Journey	60.08	59	-1.08	-1.79%	64.15	60	-4.15	-6.47%	64.15	60	-4.15	-6.47%	0	0.00%
7475	Ford Mustang	63.43	62.73	-0.70	-1.10%	65.63	64.5	-1.13	-1.72%	65.63	64.6	-1.04	-1.58%	-0.1	-0.14%
7478	Ford Focus	63.32	64	0.68	1.07%	65.36	65	-0.36	-0.55%	65.36	65	-0.36	-0.55%	0	0.00%
7482	Chrysler 200	64.24	63	-1.24	-1.93%	66.80	66	-0.80	-1.20%	66.80	---	---	---	---	---
7488	Chevrolet Impala	64.12	57	-7.12	-11.10%	66.36	63	-3.36	-5.06%	66.36	63	-3.36	-5.06%	0	0.00%
7494	Chevrolet Camaro	60.85	54	-6.85	-11.26%	61.96	54	-7.96	-12.84%	61.96	54	-7.96	-12.84%	0	0.00%
7495	Ford Explorer	63.21	59.45	-3.76	-5.95%	64.97	60.98	-3.99	-6.13%	64.97	61	-3.98	-6.12%	-0	-0.02%
7502	Toyota Tacoma	64.02	57.3	-6.72	-10.50%	66.76	61.2	-5.56	-8.33%	66.76	61.2	-5.56	-8.33%	0	0.00%
7505	Fiat 500	62.72	55	-7.72	-12.31%	64.06	58	-6.06	-9.46%	64.06	58	-6.06	-9.46%	0	0.00%
7509	Chevrolet Suburban 1500	60.75	64	3.25	5.35%	62.24	65	2.76	4.44%	62.24	65	2.76	4.44%	0	0.00%
7520	Toyota Camry	61.15	56	-5.15	-8.42%	63.37	56.3	-7.07	-11.16%	63.37	56.3	-7.07	-11.16%	0	0.00%
7521	Cadillac CTS	63.89	62	-1.89	-2.95%	65.25	63	-2.25	-3.45%	65.25	63	-2.25	-3.45%	0	0.00%
7525	Dodge Durango	64.16	65	0.84	1.32%	68.09	66	-2.09	-3.07%	68.09	---	---	---	---	---
7527	Ram 1500 Quad Cab	59.97	59	-0.97	-1.62%	62.26	63	0.74	1.19%	62.26	63	0.74	1.19%	0	0.00%
7531	Cadillac SRX	64.54	59	-5.54	-8.59%	65.01	59	-6.01	-9.25%	65.01	59	-6.01	-9.25%	0	0.00%
7564	Chevrolet Sonic	61.44	56	-5.44	-8.86%	63.26	57	-6.26	-9.90%	63.26	57	-6.26	-9.90%	0	0.00%
7566	Mazda Mazda6	64.98	50	-14.98	-23.05%	66.19	51	-15.19	-22.95%	66.19	51	-15.19	-22.95%	0	0.00%
7567	Jeep Liberty	62.51	62	-0.51	-0.81%	63.74	64	0.26	0.40%	63.74	---	---	---	---	---
7577	Volvo S60	62.97	61	-1.97	-3.13%	64.58	62	-2.58	-3.99%	64.58	63	-1.58	-2.45%	-1	-1.59%
7579	Honda Fit	62.28	64	1.72	2.77%	64.38	64	-0.38	-0.59%	64.38	65	0.62	0.96%	-1	-1.54%
7582	Chevrolet Silverado 2500	61.22	62	0.78	1.27%	63.99	64	0.01	0.02%	63.99	64	0.01	0.02%	0	0.00%
7585	Toyota Tundra	62.93	61.5	-1.43	-2.28%	67.49	65.9	-1.59	-2.35%	67.49	65.9	-1.59	-2.35%	0	0.00%
7587	Chrysler 300	64.00	66	2.00	3.13%	66.06	68	1.94	2.94%	66.06	68	1.94	2.94%	0	0.00%
7592	Ram 1500 Crew Cab	60.66	59	-1.66	-2.73%	62.80	64	1.20	1.91%	62.80	64	1.20	1.91%	0	0.00%
7605	Toyota Yaris Liftback	65.42	58.5	-6.92	-10.58%	66.75	58.6	-8.15	-12.20%	66.75	58.6	-8.15	-12.20%	0	0.00%
7606	Dodge Charger	64.07	65	0.93	1.46%	66.39	67	0.61	0.92%	66.39	67	0.61	0.92%	0	0.00%
7615	Toyota Sienna	63.84	45.1	-18.74	-29.35%	65.11	46.3	-18.81	-28.89%	65.11	46.3	-18.81	-28.89%	0	0.00%
7618	Lexus ES350	63.30	58.2	-5.10	-8.05%	64.52	58.6	-5.92	-9.18%	64.52	58.6	-5.92	-9.18%	0	0.00%
7619	Honda Civic IMA	61.57	64	2.43	3.95%	64.99	65	0.01	0.02%	64.99	66	1.01	1.55%	-1	-1.52%
7622	Honda CR-Z	63.73	48	-15.73	-24.68%	67.16	48	-19.16	-28.52%	67.16	48	-19.16	-28.52%	0	0.00%
7623	Ford F250 Super Crew	63.99	65.05	1.06	1.66%	66.27	66.33	0.06	0.09%	66.27	66.4	0.15	0.22%	-0.1	-0.14%
7624	Ford Expedition	62.71	61.98	-0.73	-1.17%	67.16	65.73	-1.43	-2.13%	67.16	65.9	-1.27	-1.89%	-0.2	-0.24%
7625	Ford F150 Supercab	62.71	63.23	0.52	0.83%	64.97	65.41	0.44	0.68%	64.97	65.4	0.45	0.70%	-0	-0.02%
7627	Honda Civic	64.95	63	-1.95	-3.01%	68.08	66	-2.08	-3.06%	68.08	66	-2.08	-3.06%	0	0.00%
7729	Scion iQ	65.11	59	-6.11	-9.38%	65.50	59.3	-6.20	-9.47%	65.50	59.3	-6.20	-9.47%	0	0.00%
7732	Honda CR-V	63.86	53	-10.86	-17.01%	66.38	53	-13.38	-20.16%	66.38	53	-13.38	-20.16%	0	0.00%
7744	Toyota RAV4	62.33	52.7	-9.63	-15.45%	63.99	54.2	-9.79	-15.29%	63.99	54.2	-9.79	-15.29%	0	0.00%
7747	Ram 2500 Crew Cab	60.87	59	-1.87	-3.08%	64.19	63	-1.19	-1.85%	64.19	63	-1.19	-1.85%	0	0.00%
7755	Toyota 4Runner	61.21	61.8	0.59	0.97%	64.47	64.3	-0.17	-0.26%	64.47	64.3	-0.17	-0.26%	0	0.00%



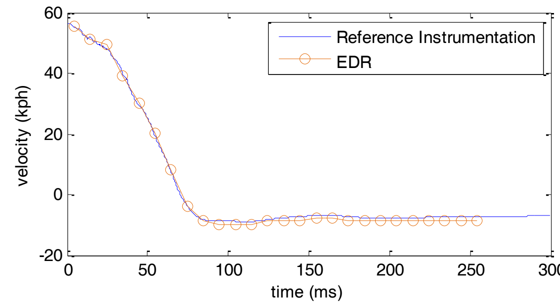
2012 Dodge Avenger (NHTSA test no. 7464): Crash Test (channel 93 & 94) vs. EDR (shifted 4.3ms to align to reference) longitudinal ΔV



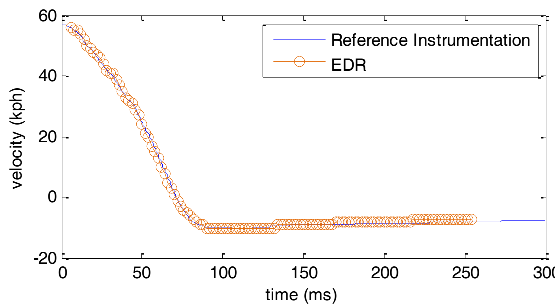
2012 Dodge Journey (NHTSA test no. 7471): Crash Test (channel 93 & 100) vs. EDR (shifted 4.8ms to align to reference) longitudinal ΔV



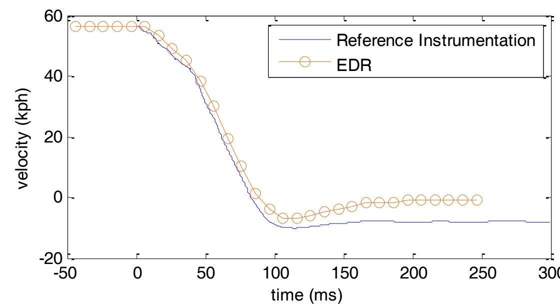
2012 Ford Mustang (NHTSA test no. 7475): Crash Test (channel 93 & 99) vs. EDR (shifted 1.6ms to align to reference) longitudinal ΔV



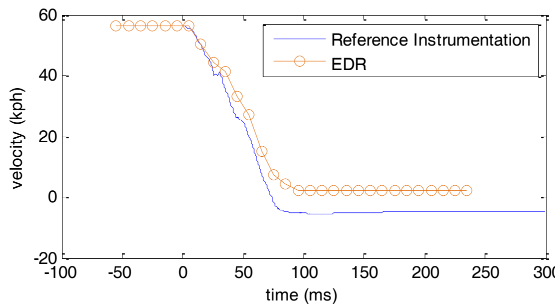
2012 Ford Focus (NHTSA test no. 7478): Crash Test (channel 94 & 99) vs. EDR (shifted 4.5ms to align to reference) longitudinal ΔV



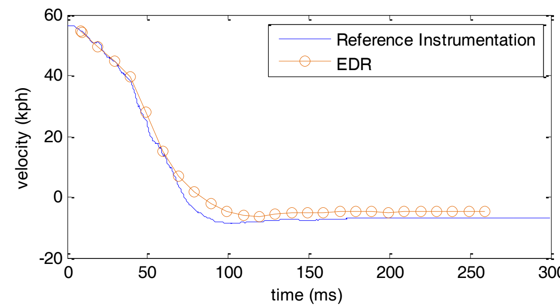
2012 Chrysler 200 (NHTSA test no. 7482): Crash Test (channel 93 & 94) vs. EDR (shifted 6ms to align to reference) longitudinal ΔV



2012 Chevrolet Impala (NHTSA test no. 7488): Crash Test (channel 93 & 100) vs. EDR (shifted -9ms to align from deployment to AE and26.4ms to align to reference) longitudinal ΔV

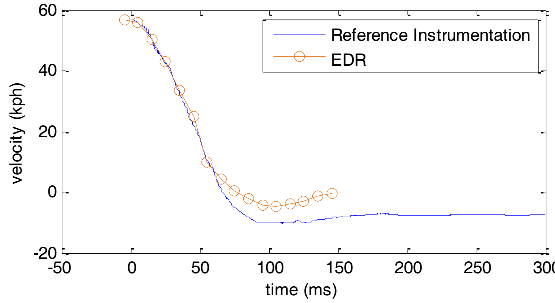


2012 Chevrolet Camaro (NHTSA test no. 7494): Crash Test (channel 93 & 100) vs. EDR (shifted -6ms to align from deployment to AE and 15.2 to align to reference) longitudinal ΔV

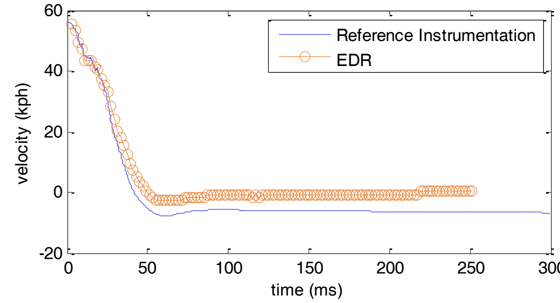


2012 Ford Explorer (NHTSA test no. 7495): Crash Test (channel 93 & 100) vs. EDR (shifted 8.7ms to align to reference) longitudinal ΔV

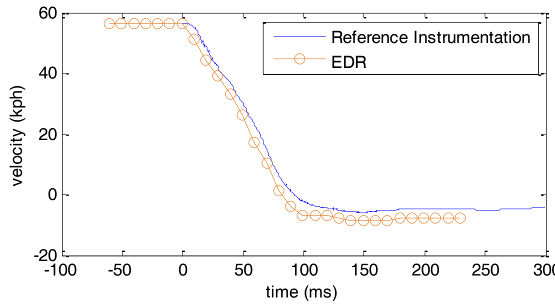
Figure A.1 Overlay of EDR and crash test ΔV versus time after velocity and time shift (full-frontal crash test study)



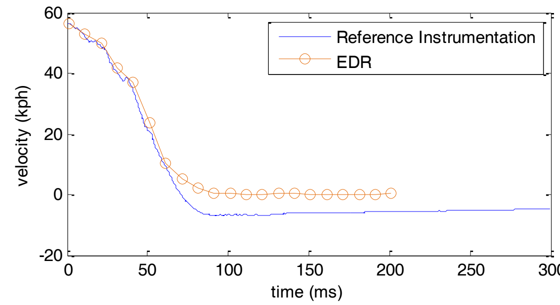
2012 Toyota Tacoma (NHTSA test no. 7502): Crash Test (channel 93 & 100) vs. EDR (shifted -4.7ms to align to reference) longitudinal ΔV



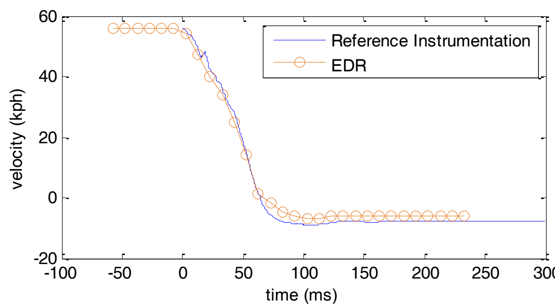
2012 Fiat 500 (NHTSA test no. 7505): Crash Test (channel 94 & 100) vs. EDR (shifted 3.2ms to align to reference) longitudinal ΔV



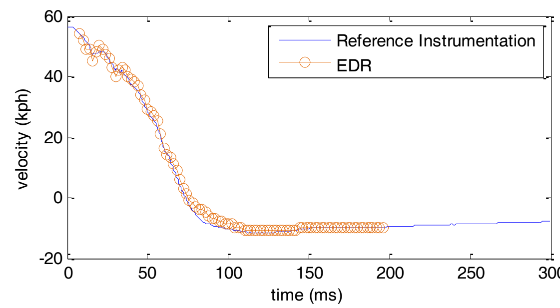
2012 Chevrolet Suburban 1500 (NHTSA test no. 7509): Crash Test (channel 93 & 94) vs. EDR (shifted -6ms to align from deployment to AE and 9.3ms to align to reference) longitudinal ΔV



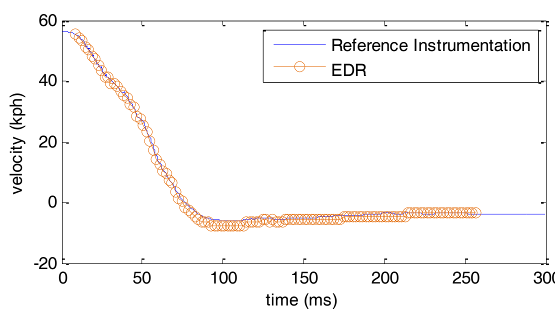
2012 Toyota Camry (NHTSA test no. 7520): Crash Test (channel 94 & 100) vs. EDR (shifted 1.2ms to align to reference) longitudinal ΔV



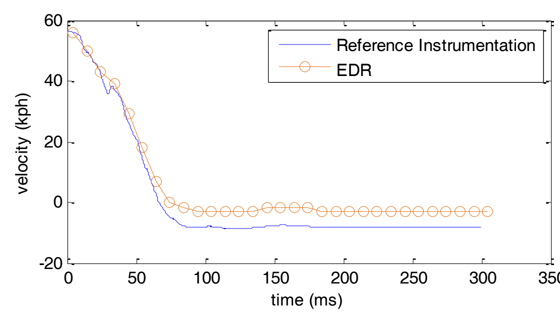
2012 Cadillac CTS (NHTSA test no. 7521): Crash Test (channel 93 & 99) vs. EDR (shifted -9ms to align from deployment to AE and 12.7ms to align to reference) longitudinal ΔV



2012 Dodge Durango (NHTSA test no. 7525): Crash Test (channel 93 & 99) vs. EDR (shifted 8ms to align to reference) longitudinal ΔV

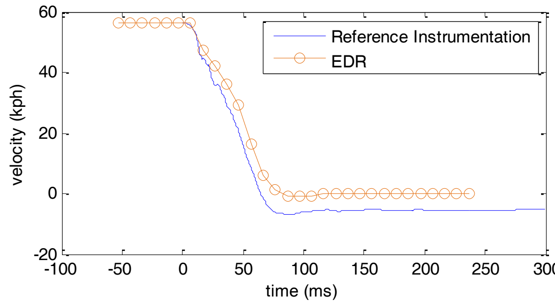


2012 Ram 1500 Quad Cab (NHTSA test no. 7527): Crash Test (channel 93 & 99) vs. EDR (shifted 8.7ms to align to reference) longitudinal ΔV

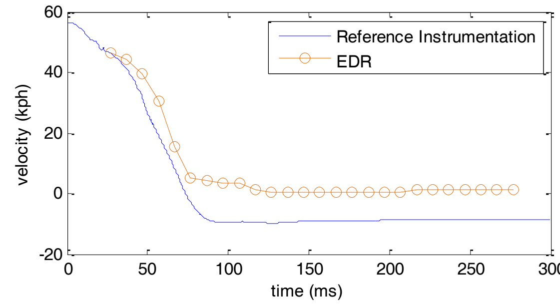


2012 Cadillac SRX (NHTSA test no. 7531): Crash Test (channel 93 & 94) vs. EDR (shifted 4.5ms to align to reference) longitudinal ΔV

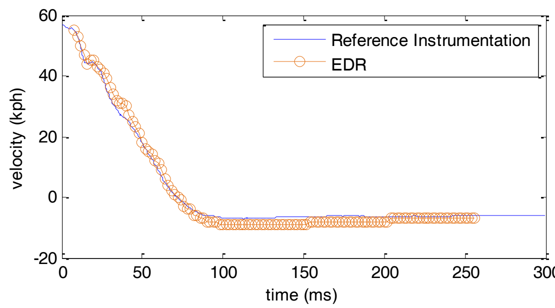
Figure A.1 (Cont'd) Overlay of EDR and crash test ΔV versus time after velocity and time shift (full-frontal crash test study)



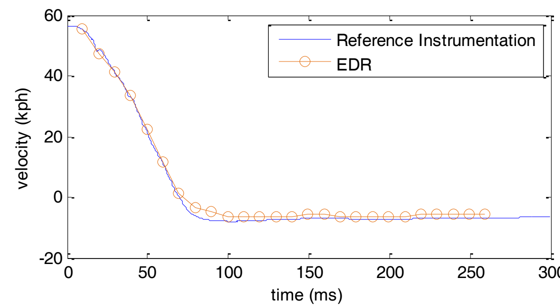
2012 Chevrolet Sonic (NHTSA test no. 7564): Crash Test (channel 94 & 99) vs. EDR (shifted -3ms to align from deployment to AE and 16.6ms to align to reference) longitudinal ΔV



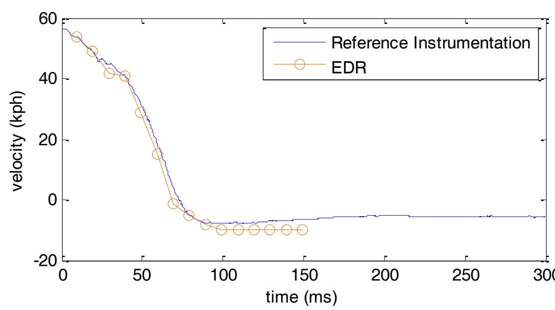
2012 Mazda Mazda6 (NHTSA test no. 7566): Crash Test (channel 93 & 99) vs. EDR (shifted 26.8ms to align to reference) longitudinal ΔV



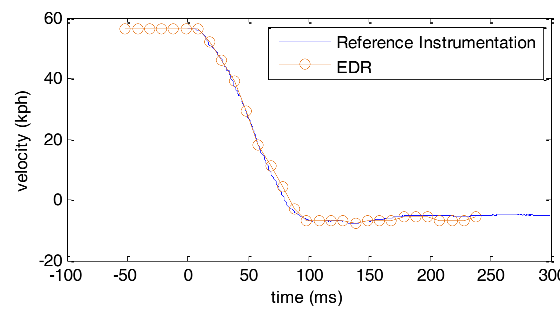
2012 Jeep Liberty (NHTSA test no. 7567): Crash Test (channel 94 & 99) vs. EDR (shifted 8ms to align to reference) longitudinal ΔV



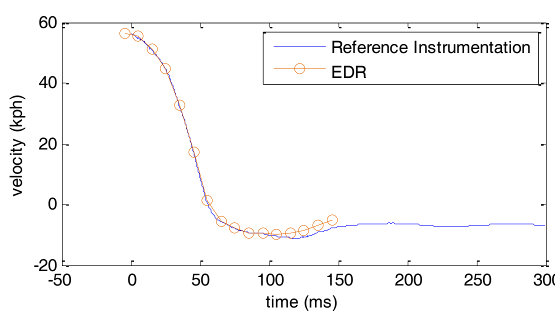
2012 Volvo S60 (NHTSA test no. 7577): Crash Test (channel 93 & 94) vs. EDR (shifted 9.5ms to align to reference) longitudinal ΔV



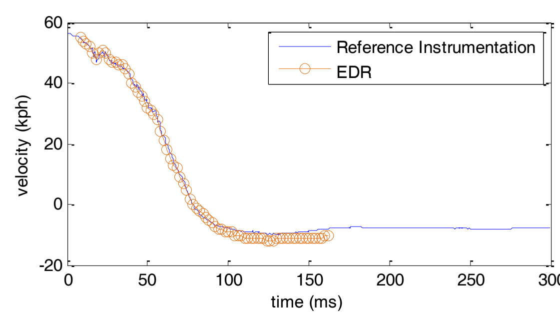
2012 Honda Fit (NHTSA test no. 7579): Crash Test (channel 94 & 100) vs. EDR (shifted 9.2ms to align to reference) longitudinal ΔV



2012 Chevrolet Silverado 2500 (NHTSA test no. 7582): Crash Test (channel 93 & 100) vs. EDR (shifted -3ms to align from deployment to AE and 18.3ms to align to reference) longitudinal ΔV

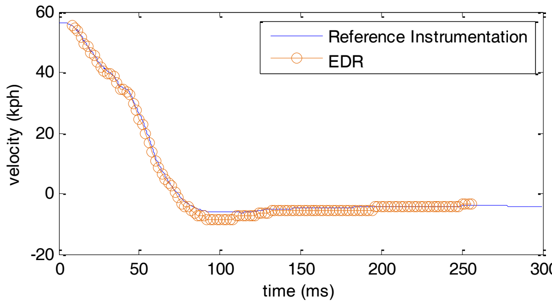


2012 Toyota Tundra (NHTSA test no. 7585): Crash Test (channel 94 & 99) vs. EDR (shifted -4.7ms to align to reference) longitudinal ΔV

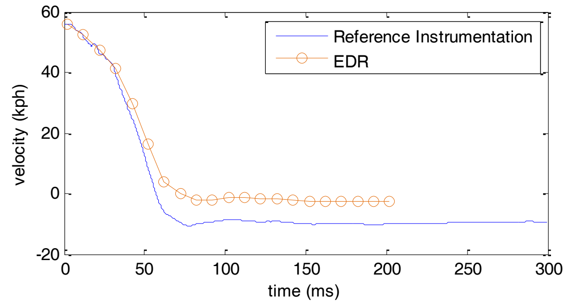


2012 Chrysler 300 (NHTSA test no. 7587): Crash Test (channel 93 & 99) vs. EDR (shifted 8.1ms to align to reference) longitudinal ΔV

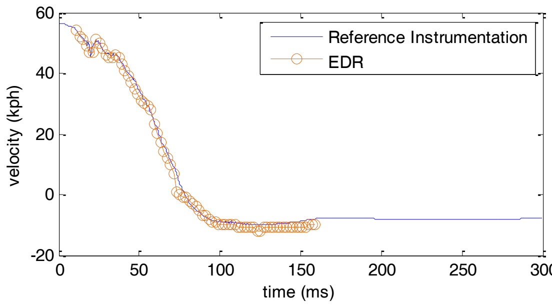
Figure A.1 (Cont'd) Overlay of EDR and crash test ΔV versus time after velocity and time shift (full-frontal crash test study)



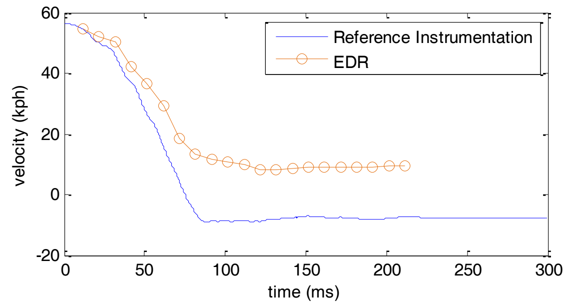
2012 Ram 1500 Crew Cab (NHTSA test no. 7592): Crash Test (channel 94 & 99) vs. EDR (shifted 8.1ms to align to reference) longitudinal ΔV



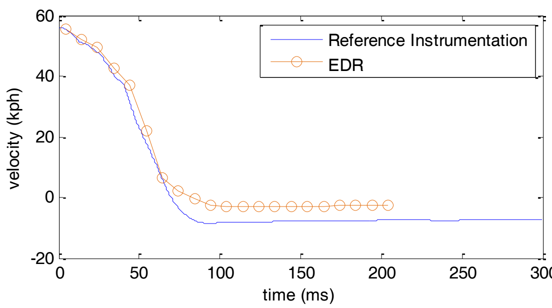
2012 Toyota Yaris Liftback (NHTSA test no. 7605): Crash Test (channel 93 & 94) vs. EDR (shifted 2.1ms to align to reference) longitudinal ΔV



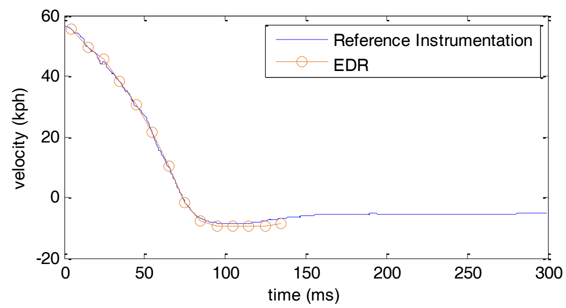
2012 Dodge Charger (NHTSA test no. 7606): Crash Test (channel 93 & 100) vs. EDR (shifted 11.2ms to align to reference) longitudinal ΔV



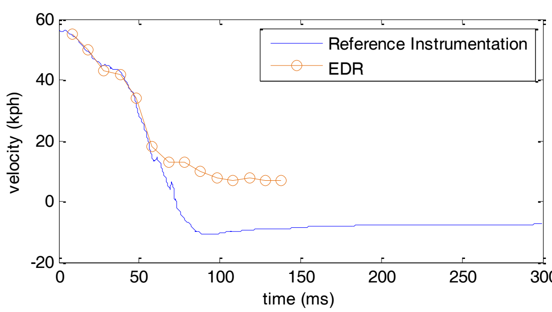
2012 Toyota Sienna (NHTSA test no. 7615): Crash Test (channel 94 & 99) vs. EDR (shifted 11.6ms to align to reference) longitudinal ΔV



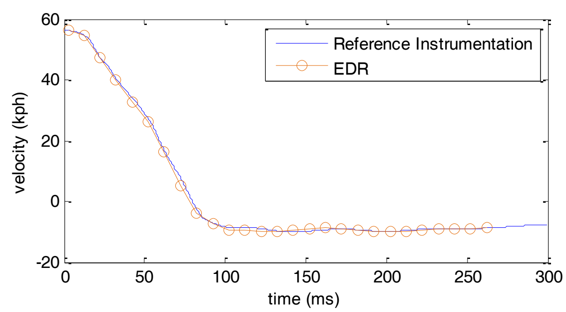
2012 Lexus ES350 (NHTSA test no. 7618): Crash Test (channel 94 & 100) vs. EDR (shifted 4.2ms to align to reference) longitudinal ΔV



2012 Honda Civic IMA (NHTSA test no. 7619): Crash Test (channel 94 & 99) vs. EDR (shifted 4.7ms to align to reference) longitudinal ΔV

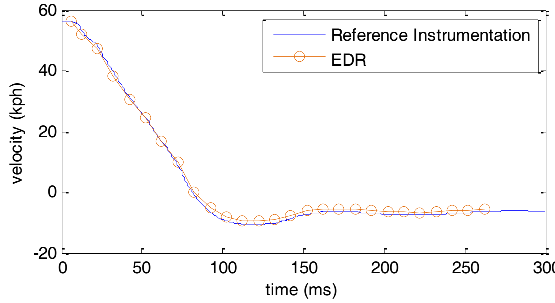


2012 Honda CR-Z (NHTSA test no. 7622): Crash Test (channel 93 & 99) vs. EDR (shifted 8.1ms to align to reference) longitudinal ΔV

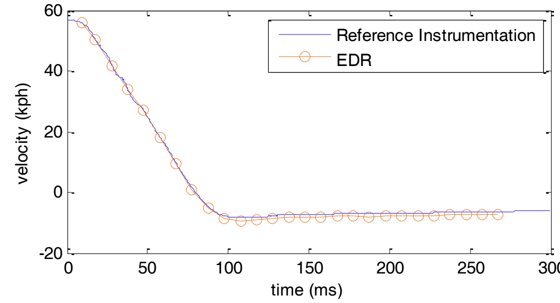


2012 Ford F250 Super Crew (NHTSA test no. 7623): Crash Test (channel 93 & 94) vs. EDR (shifted 3.2ms to align to reference) longitudinal ΔV

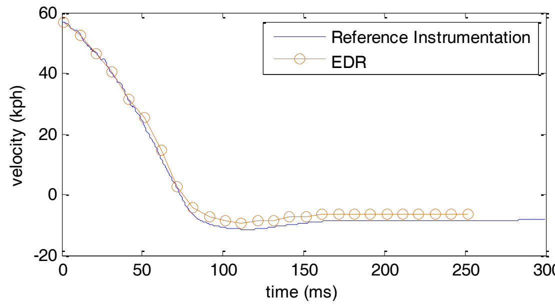
Figure A.1 (Cont'd) Overlay of EDR and crash test ΔV versus time after velocity and time shift (full-frontal crash test study)



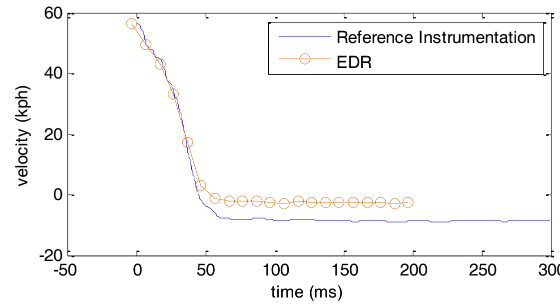
2012 Ford Expedition (NHTSA test no. 7624): Crash Test (channel 93 & 94) vs. EDR (shifted 6.2ms to align to reference) longitudinal ΔV



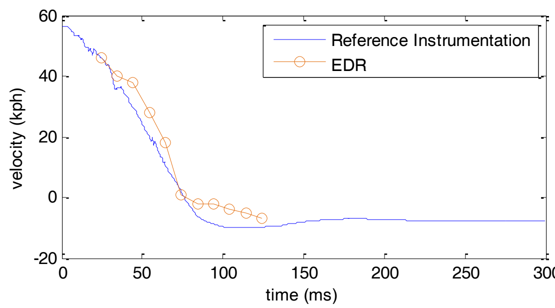
2012 Ford F150 Supercab (NHTSA test no. 7625): Crash Test (channel 93 & 100) vs. EDR (shifted 9.1ms to align to reference) longitudinal ΔV



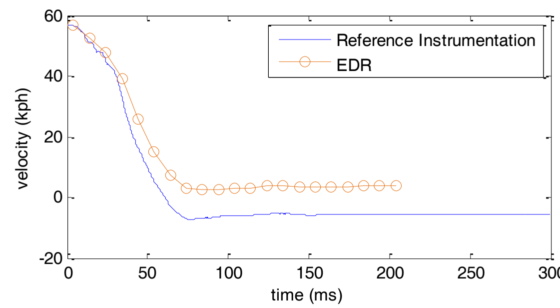
2012 Honda Civic (NHTSA test no. 7627): Crash Test (channel 93 & 99) vs. EDR (shifted 1.5ms to align to reference) longitudinal ΔV



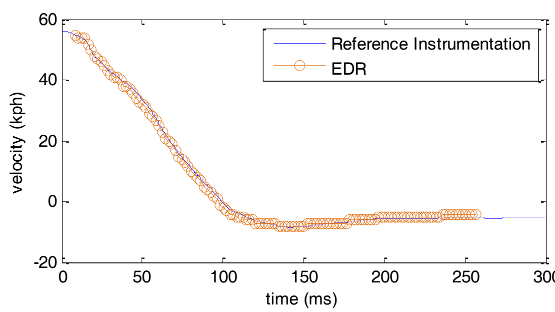
2012 Scion iQ (NHTSA test no. 7729): Crash Test (channel 99 & 100) vs. EDR (shifted -3ms to align to reference) longitudinal ΔV



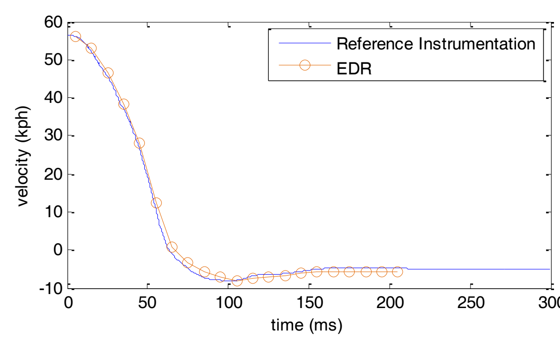
2012 Honda CR-V (NHTSA test no. 7732): Crash Test (channel 93 & 94) vs. EDR (shifted 24.3ms to align to reference) longitudinal ΔV



2012 Toyota RAV4 (NHTSA test no. 7744): Crash Test (channel 94 & 99) vs. EDR (shifted 4ms to align to reference) longitudinal ΔV



2012 Ram 2500 Crew Cab (NHTSA test no. 7747): Crash Test (channel 93 & 94) vs. EDR (shifted 8.4ms to align to reference) longitudinal ΔV



2012 Toyota 4Runner (NHTSA test no. 7755): Crash Test (channel 93 & 94) vs. EDR (shifted 5.2ms to align to reference) longitudinal ΔV

Figure A.1 (Cont'd) Overlay of EDR and crash test ΔV versus time after velocity and time shift (full-frontal crash test study)

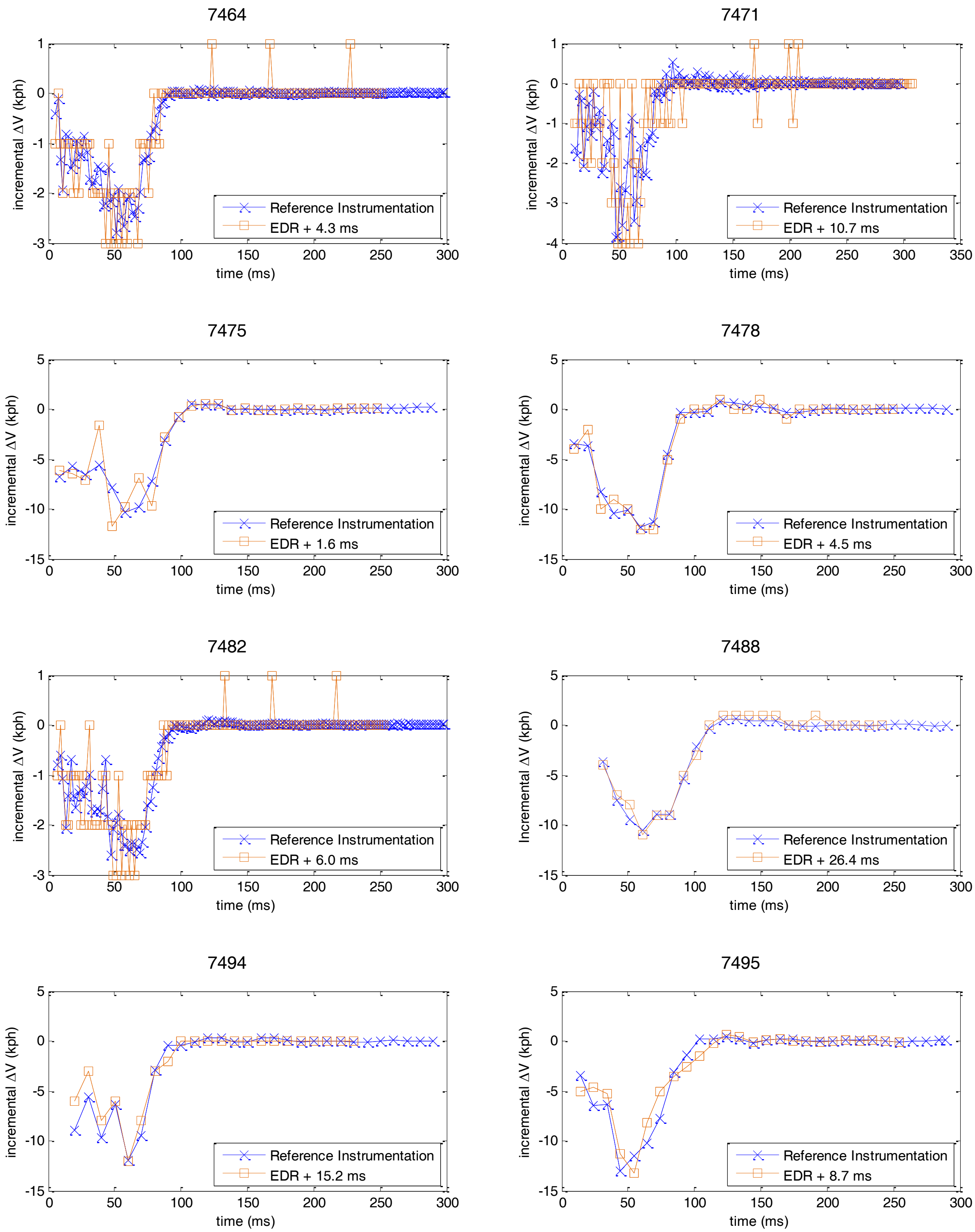


Figure A.2 Overlay of EDR and reference instrumentation incremental ΔV as optimized by the time shift algorithm for tests that do not overlap in velocity (full-frontal crash test study)

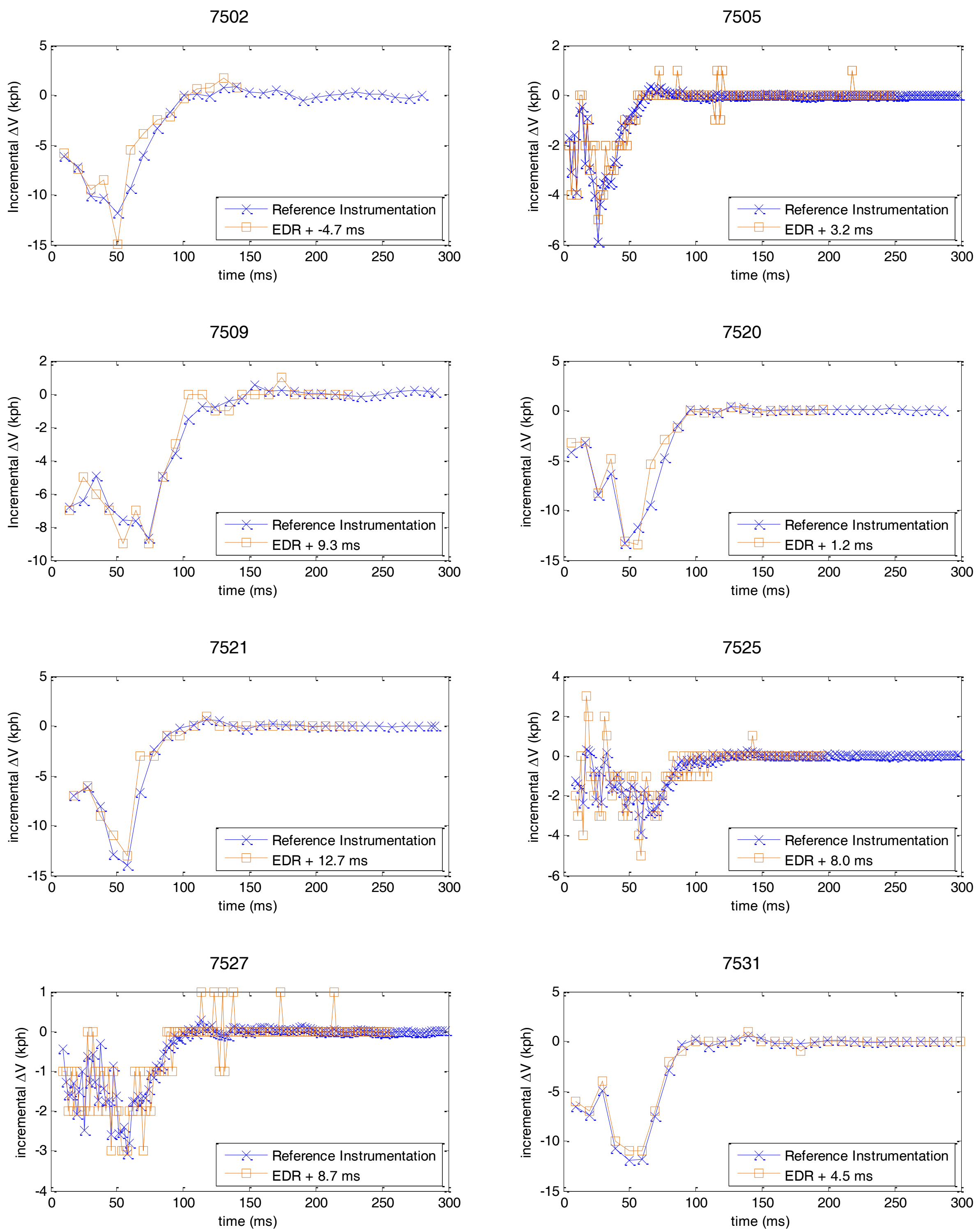


Figure A.2 (Cont'd) Overlay of EDR and reference instrumentation incremental ΔV as optimized by the time shift algorithm for tests that do not overlap in velocity (full-frontal crash test study)

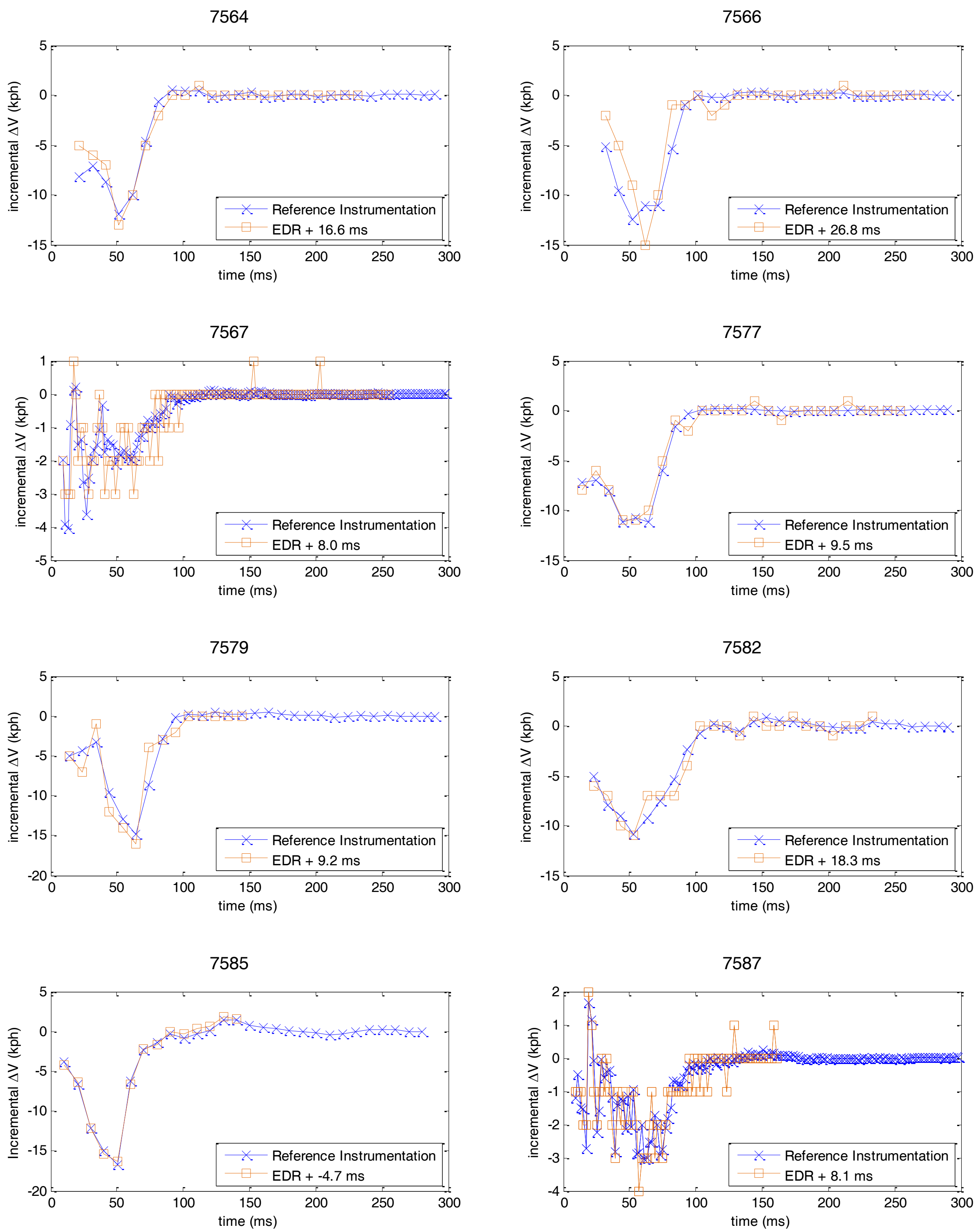


Figure A.2 (Cont'd) Overlay of EDR and reference instrumentation incremental ΔV as optimized by the time shift algorithm for tests that do not overlap in velocity (full-frontal crash test study)

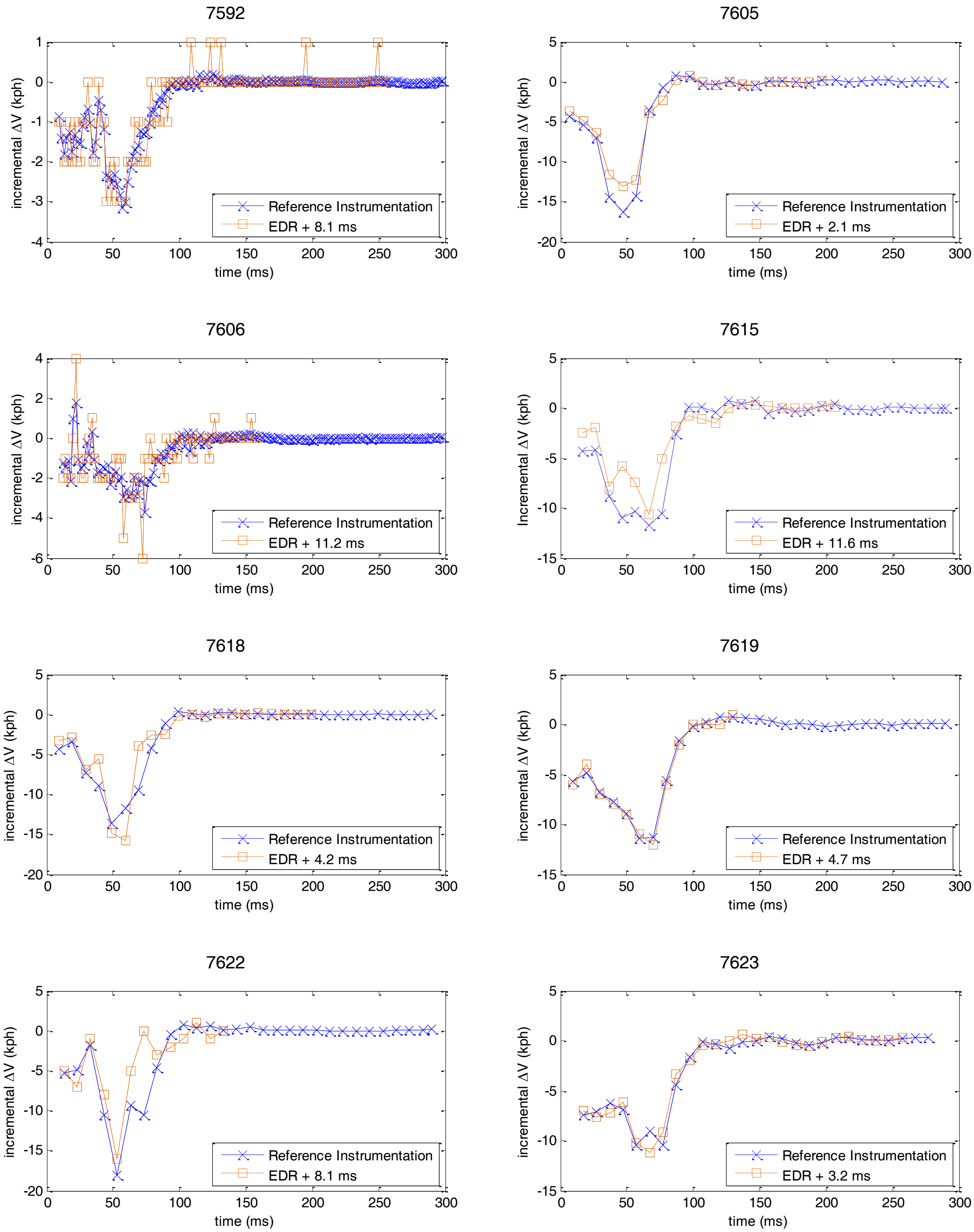


Figure A.2 (Cont'd) Overlay of EDR and reference instrumentation incremental ΔV as optimized by the time shift algorithm for tests that do not overlap in velocity (full-frontal crash test study)

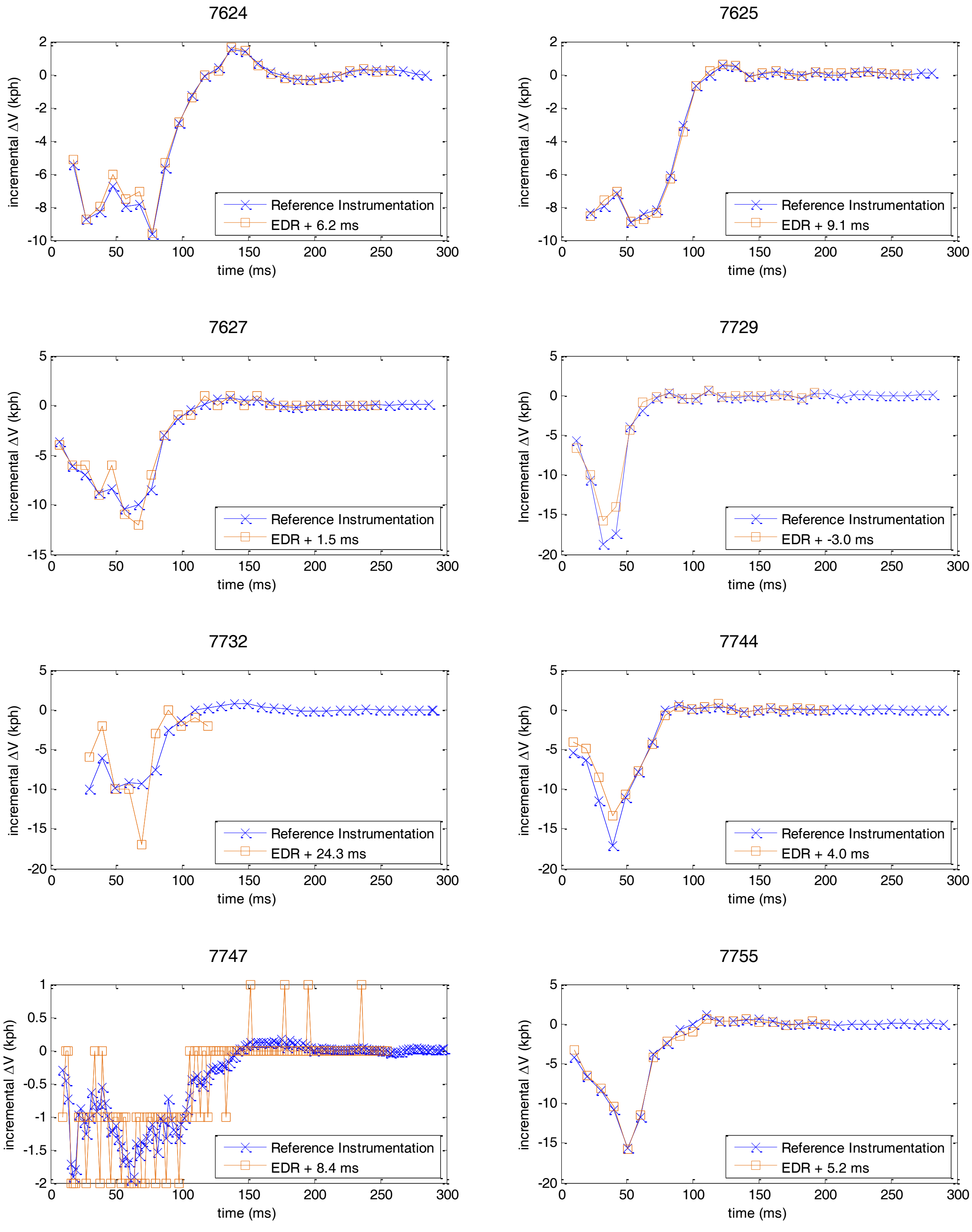


Figure A.2 (Cont'd) Overlay of EDR and reference instrumentation incremental ΔV as optimized by the time shift algorithm for tests that do not overlap in velocity (full-frontal crash test study)

Table A.6 Description of dataset EDR and reference instrumentation parameters (SINCAP crash test study)

Test No.	Make & Model	Model Year	EDR Recording Properties Freq (Hz)	t(0)	t(end)	total (ms)	Bosch CDR Tool EDR Module Type	Bosch CDR Tool EDR Indicated Location	EDR Recording Complete Status
6652	Ford Mustang	2010	100	0	250	250	FordRC6_2010	Center tunnel	Complete
6653	Ford Mustang	2010	100	0	250	250	FordRC6_2010	Center tunnel	Complete
6734	Ford Mustang	2010	100	0	250	250	FordRC6_2010	Center tunnel	Complete
6737	Ford Mustang	2010	100	0	250	250	FordRC6_2010	Center tunnel	Complete
6743	Ford Fusion	2010	100	0	250	250	FordRC6_2010	Center tunnel	Complete
6746	Chevrolet Camaro	2010	100	-70	220	290	SDM10	Center tunnel	Complete
6789	Chevrolet Equinox	2010	100	-70	220	290	SDM10	Center tunnel	Complete
6792	Buick Lacrosse	2010	100	-70	220	290	SDM10	Center tunnel	Complete
6798	Ford Taurus	2010	100	0	250	250	FordRC6_2010	Center tunnel	Complete
6813	Dodge Avenger	2010	500	0	298	298	CHRY0305	Center stack	Complete
6827	Cadillac SRX	2010	100	-70	220	290	SDM10	Center tunnel	Complete
6861	Toyota 4Runner	2010	250	-23	69	92	TOYOTA001	Under center stack	Complete
6944	Toyota Sienna	2011	250	-24	68	92	TOYOTA001	Under center stack	Complete
6952	Toyota Camry	2011	250	-21	71	92	TOYOTA001	Under center stack	Complete
6988	Chevrolet Traverse	2011	100	-70	220	290	SDM10	Center tunnel	Complete
7000	Chevrolet Malibu	2011	100	-70	220	290	Epsilon2006	Center tunnel	Complete
7036	Jeep Grand Cherokee	2011	500	0	298	298	CHRY0305	Center stack	Complete
7070	Buick Lucerne	2011	100	-70	220	290	SDMC2008V	Center tunnel	Complete
7103	Toyota Tacoma	2011	167	-24	54	78	TOYOTA001	Under center stack	Not Supported
7111	Ram 1500 Crew	2011	500	0	298	298	CHRY0403	Under center front seat or console	Complete
7117	Ford Escape	2011	100	3	253	250	FordRC6_2011	Center tunnel	Complete
7129	Ram 1500 Quad	2011	500	0	298	298	CHRY0403	Under center front seat or console	Complete
7130	Ford Fusion	2011	100	8	258	250	FordRC6_2011	Center tunnel	Complete
7138	Toyota RAV4	2011	250	-24	72	96	TOYOTA001	Under center console	Complete
7146	Lexus RX350	2011	250	-23	69	92	TOYOTA001	Under center stack	Complete
7151	Ford Edge	2011	100	7	257	250	FordRC62011CGEAB	Center tunnel	Complete
7160	Chevrolet Cruze	2011	100	-70	220	290	SDM10	Center tunnel	Complete
7177	Toyota Venza	2011	250	-24	68	92	TOYOTA001	Under center stack	Complete
7181	Toyota Highlander	2011	250	-23	69	92	TOYOTA001	Under center stack	Complete
7193	Dodge Caliber	2011	500	0	298	298	CHRY0305	Center tunnel before/aft of shifter or center stack	Complete
7259	Toyota Camry	2011	250	-21	71	92	TOYOTA001	Under center stack	Complete
7341	Ford Ranger	2011	100	0	250	250	FordRC6_2011	Center tunnel	Complete
7343	Toyota Tundra Double Cab	2011	167	-24	54	78	TOYOTA001	Under center stack	Not Supported
7352	Ford F150 Super Crew	2011	100	3	253	250	FordRC62011CGEAC	Center tunnel	Complete
7353	Toyota Corolla	2011	167	-24	54	78	TOYOTA001	Under center stack	Not Supported
7355	Ford F150 Super Cab	2011	100	8	258	250	FordRC62011CGEAC	Center tunnel	Complete
7363	Buick Lucerne	2011	100	-70	220	290	SDMC2008V	Center tunnel	Complete

Table A.6 (Cont'd) Description of dataset EDR and reference instrumentation parameters (SINCAP crash test study)

Test No.	Make & Model	Model Year	EDR Recording Properties Freq (Hz)	t(0)	t(end)	total (ms)	Bosch CDR Tool EDR Module Type	Bosch CDR Tool EDR Indicated Location	EDR Recording Complete Status
7364	Toyota Scion tC	2011	250	-24	68	92	TOYOTA001	Under center stack	Complete
7367	Buick Lacrosse	2011	100	-70	220	290	SDM10	Center tunnel	Complete
7392	Chevrolet Volt	2011	100	-70	220	290	SDM10	Center tunnel	Complete
7448	Mazda Mazda3	2012	100	0	250	250	MAZDA001	Center tunnel aft of shifter	Complete
7465	Ford Mustang	2012	100	8	258	250	FordRC6_2011	Center tunnel	Complete
7469	Dodge Avenger	2012	500	0	298	298	CHRY0305	Center stack	Complete
7470	Ford Focus	2012	100	0	250	250	FordAB10	Center tunnel	Complete
7473	Dodge Journey	2012	500	0	298	298	CHRY4101	Center stack	Complete
7484	Chrysler 200	2012	500	0	298	298	CHRY0305	Center stack	Complete
7486	Chevrolet Impala	2012	100	-70	220	290	SDM11_AUTOLIVNEW	Under RF seat	Complete
7492	Ford Explorer	2012	100	6	256	250	FordRC62011CGEAD	Center tunnel	Complete
7493	Chevrolet Camaro	2012	100	-70	220	290	SDM10	Center tunnel	Complete
7507	Fiat 500	2012	500	0	298	298	CHRY0000	Center stack	Complete
7510	Chevrolet Suburban 1500	2012	100	-70	220	290	SDM10	Center tunnel	Complete
7517	Toyota Camry	2012	250	-23	69	92	TOYOTA001	Under center stack	Complete
7519	Cadillac CTS	2012	100	-70	220	290	SDM10	Center tunnel	Complete
7528	Dodge Durango	2012	500	0	298	298	CHRY0305	Center stack	Complete
7534	Cadillac SRX	2012	100	10	300	290	SDM10P	Center tunnel	Complete
7537	Mazda Mazda6	2012	100	0	250	250	MAZDA002	Center tunnel, below instrument panel	Complete
7541	Ford Expedition	2012	100	2	252	250	FordRC6_2011	Center tunnel	Complete
7563	Chevrolet Sonic	2012	100	-70	220	290	SDM10	Center tunnel	Complete
7561	Jeep Liberty	2012	100	0	298	298	CHRY0305	Center stack	Complete
7576	Honda Fit	2012	100	0	298	298	HONDA001	Under dashboard, center	Complete
7586	Toyota Tundra	2012	166.7	0	250	250	TOYOTA001	Under center stack	Not Supported
7593	Chrysler 300	2012	500	0	298	298	CHRY4005	Center stack	Complete
7602	Toyota Yaris	2012	250	-21	71	92	TOYOTA001	Under center stack	Complete
7604	Dodge Charger	2012	500	0	298	298	CHRY4005	Center stack	Complete
7640	Lexus ES350	2012	250	-23	69	92	TOYOTA001	Under center stack	Complete
7648	Honda Civic	2012	100	0	250	250	HONDA001	Under dashboard, center	Complete
7650	Ford F250 Super Crew	2012	100	4	254	250	FordRC62011CGEAD	Center tunnel	Complete
7713	Honda Civic IMA	2012	100	0	250	250	HONDA001	Under dashboard, center	Complete
7733	Scion iQ	2012	250	-24	68	92	TOYOTA001	Under center console	Complete
7738	Toyota RAV4	2012	250	-24	72	96	TOYOTA001	Under center console	Complete
7745	Ram 2500 Crew Cab	2012	500	0	298	298	CHRY0403	Under center front seat or console	Complete
7749	Toyota Corolla	2012	166.7	-24	54	78	TOYOTA001	Under center stack	Not Supported
7750	Honda CR-V	2012	100	0	250	250	HONDA001	Under dashboard, center	Complete
7753	Toyota 4Runner	2012	250	-24	68	92	TOYOTA001	Under center stack	Complete
7768	Fiat 500	2012	500	0	298	298	CHRY0000	Center stack	Complete

Table A.7 Comparison of lateral EDR and reference instrumentation delta-v by arithmetic error (SINCAP crash test study)

Test No.	Make & Model	Time Shift (ms)	Peak Reference Acceleration > 50G After CFC 180		Sensors Averaged		EDR Time Series Max (kph)				EDR Report Single Max (kph)			
							EDR	REF	ERR	% ERR	EDR	REF	ERR	% ERR
6652	Ford Mustang	4.9	☐	—	T-C	—	27.6	26.5	1.0	3.9%	27.6	26.5	1.0	3.9%
6653	Ford Mustang	5.0	☐	—	F-R	F-C	26.6	25.1	1.5	6.1%	26.7	25.1	1.6	6.2%
6734	Ford Mustang	11.8	☐	—	F-T	—	25.6	24.8	0.8	3.4%	25.7	24.8	0.9	3.5%
6737	Ford Mustang	11.0	☐	—	F-R	T-C	26.2	26.4	-0.3	-1.1%	26.2	26.4	-0.2	-0.7%
6743	Ford Fusion	17.1	☐	—	F-C	R-T	21.1	27.9	-6.8	-24.3%	21.1	27.9	-6.7	-24.1%
6746	Chevrolet Camaro	12.9	☐	—	R-C	—	25.0	25.2	-0.2	-0.6%	25.0	25.2	-0.2	-0.6%
6789	Chevrolet Equinox	11.2	☑	53.8	R-T	—	23.0	24.0	-1.0	-4.0%	23.0	24.0	-1.0	-4.0%
6792	Buick Lacrosse	13.3	☐	—	F-R	F-C	23.0	23.8	-0.8	-3.2%	21.0	23.8	-2.8	-11.6%
6798	Ford Taurus	12.5	☐	—	F-R	F-T	22.8	24.0	-1.1	-4.7%	22.9	24.0	-1.1	-4.5%
6813	Dodge Avenger	5.8	☐	—	R-C	T-C	20.1	25.1	-5.0	-19.9%	—	—	—	—
6827	Cadillac SRX	13.4	☐	—	F-T	F-C	21.0	23.3	-2.3	-9.9%	21.0	23.3	-2.3	-9.9%
6861	Toyota 4Runner	1.5	☑	53.4	R-T	—	16.3	24.3	-8.1	-33.2%	—	—	—	—
6944	Toyota Sienna	2.8	☐	—	F-C	R-C	16.9	23.2	-6.3	-27.2%	—	—	—	—
6952	Toyota Camry	-0.5	☐	—	F-T	F-C	19.5	27.2	-7.8	-28.5%	—	—	—	—
6988	Chevrolet Traverse	18.7	☐	—	T-C	—	19.0	22.9	-3.9	-17.1%	19.0	22.9	-3.9	-17.1%
7000	Chevrolet Malibu	20.0	☐	—	F-T	R-C	25.1	25.9	-0.8	-3.1%	—	—	—	—
7036	Jeep Grand Cherokee	4.8	☐	—	F-T	R-C	23.0	23.0	0.0	0.0%	—	—	—	—
7070	Buick Lucerne	11.1	☐	—	R-T	R-C	24.1	22.6	1.5	6.5%	—	—	—	—
7103	Toyota Tacoma	0.0	☑	51.5	F-C	R-C	17.2	26.0	-8.8	-33.8%	—	—	—	—
7111	Ram 1500 Crew	12.0	☐	—	R-T	—	14.2	23.8	-9.6	-40.5%	14.0	23.8	-9.8	-41.2%
7117	Ford Escape	6.1	☐	—	F-T	—	20.4	23.6	-3.2	-13.5%	20.5	23.6	-3.1	-13.3%
7129	Ram 1500 Quad	10.7	☐	—	F-R	T-C	16.1	24.6	-8.5	-34.6%	16.0	24.6	-8.6	-35.0%
7130	Ford Fusion	1.9	☐	—	F-R	—	22.4	26.2	-3.8	-14.7%	22.4	26.2	-3.8	-14.7%
7138	Toyota RAV4	8.6	☐	—	F-R	R-C	19.3	26.2	-6.9	-26.2%	—	—	—	—
7146	Lexus RX350	1.1	☑	50.4	F-R	T-C	17.2	22.5	-5.3	-23.4%	17.7	22.5	-4.8	-21.2%
7151	Ford Edge	-0.2	☑	67.0	R-C	T-C	20.1	24.3	-4.2	-17.3%	20.1	24.3	-4.1	-17.1%
7160	Chevrolet Cruze	10.7	☐	—	F-T	—	24.0	26.4	-2.4	-9.0%	24.0	26.4	-2.4	-9.0%
7177	Toyota Venza	2.4	☐	—	F-R	T-C	19.6	27.2	-7.6	-27.9%	—	—	—	—
7181	Toyota Highlander	2.6	☑	59.5	F-C	R-C	18.5	24.9	-6.4	-25.7%	20.9	24.9	-4.0	-16.0%
7193	Dodge Caliber	6.8	☐	—	R-T	T-C	21.2	27.6	-6.3	-22.9%	—	—	—	—
7259	Toyota Camry	1.0	☐	—	F-R	T-C	20.4	26.7	-6.2	-23.3%	—	—	—	—
7341	Ford Ranger	6.8	☑	50.8	R-C	—	20.9	28.3	-7.5	-26.4%	20.9	28.3	-7.4	-26.3%
7343	Toyota Tundra Double Cab	2.6	☑	61.0	F-C	R-C	15.1	22.6	-7.5	-33.2%	—	—	—	—
7352	Ford F150 Super Crew	4.3	☐	—	F-T	R-C	22.3	22.6	-0.2	-1.1%	22.4	22.6	-0.2	-0.8%
7353	Toyota Corolla	3.5	☑	51.5	F-R	R-C	25.3	28.2	-2.9	-10.3%	—	—	—	—
7355	Ford F150 Super Cab	3.0	☑	51.8	F-R	R-C	22.1	23.7	-1.5	-6.5%	22.2	23.7	-1.5	-6.4%
7363	Buick Lucerne	0.0	☐	—	F-C	T-C	25.2	19.7	5.5	27.9%	—	—	—	—
7364	Toyota Scion tC	-3.5	☑	89.2	R-C	T-C	19.8	25.2	-5.4	-21.4%	22.5	25.2	-2.7	-10.7%

Table A.7 (Cont'd) Comparison of lateral EDR and reference instrumentation delta-v by arithmetic error (SINCAP crash test study)

Test No.	Make & Model	Time Shift (ms)	Peak Reference Acceleration > 50G After CFC 180		Sensors Averaged		EDR Time Series Max (kph)				EDR Report Single Max (kph)			
							EDR	REF	ERR	% ERR	EDR	REF	ERR	% ERR
7367	Buick Lacrosse	11.4	☐	—	F-C	F-T	22	24.7	-2.7	-10.8%	23.0	24.7	-1.7	-6.7%
7392	Chevrolet Volt	10.0	☐	—	T-C	R-C	24	22.2	1.8	8.0%	24.0	22.2	1.8	8.0%
7448	Mazda Mazda3	5.4	☐	—	T-C	F-R	19	23.6	-4.6	-19.6%	27	23.6	3.4	14.2%
7465	Ford Mustang	4.6	☐	—	R-C	T-C	21	24.0	-3.0	-12.5%	28.21	24.0	4.2	17.5%
7469	Dodge Avenger	4.4	☐	—	R-T	—	22	26.0	-4.0	-15.5%	—	—	—	—
7470	Ford Focus	2.4	☐	—	F-T	—	26	32.2	-6.2	-19.2%	—	—	—	—
7473	Dodge Journey	0.0	☐	—	F-R	R-C	22	25.8	-3.8	-14.7%	21	25.8	-4.8	-18.6%
7484	Chrysler 200	5.1	☐	—	R-C	F-C	20	24.8	-4.8	-19.4%	—	—	—	—
7486	Chevrolet Impala	14.4	☐	—	F-T	T-C	24	24.2	-0.2	-0.7%	24	24.2	-0.2	-0.7%
7492	Ford Explorer	5.4	☐	—	T-C	F-R	24	25.6	-1.6	-6.2%	21.94	25.6	-3.6	-14.2%
7493	Chevrolet Camaro	7.2	☑	56.0	T-C	R-C	15	22.4	-7.4	-33.2%	27	22.4	4.6	20.3%
7507	Fiat 500	3.9	☐	—	F-R	T-C	25	30.9	-5.9	-19.0%	26	30.9	-4.9	-15.8%
7510	Chevrolet Suburban 1500	14.9	☐	—	F-R	—	28.11	30.8	-2.7	-8.7%	18	30.8	-12.8	-41.5%
7517	Toyota Camry	0.2	☐	—	F-C	R-C	26	29.3	-3.3	-11.2%	—	—	—	—
7519	Cadillac CTS	11.6	☐	—	F-R	—	21.91	22.0	0.0	-0.2%	24	22.0	2.0	9.3%
7528	Dodge Durango	5.4	☑	58.4	F-T	R-T	18.84	20.9	-2.0	-9.7%	—	—	—	—
7534	Cadillac SRX	4.4	☐	—	T-C	—	18.83	20.1	-1.3	-6.5%	21	20.1	0.9	4.3%
7537	Mazda Mazda6	6.8	☐	—	F-T	—	23	24.2	-1.2	-4.8%	22	24.2	-2.2	-8.9%
7541	Ford Expedition	2.3	☐	—	R-C	T-C	27	25.6	1.4	5.3%	18.87	25.6	-6.8	-26.4%
7563	Chevrolet Sonic	9.3	☐	—	F-C	F-T	18	20.5	-2.5	-12.4%	24	20.5	3.5	16.8%
7571	Jeep Liberty	16.3	☐	—	F-T	—	21.2	24.8	-3.6	-14.4%	—	—	—	—
7576	Honda Fit	1.4	☐	—	F-R	F-T	21	22.2	-1.2	-5.3%	24	22.2	1.8	8.2%
7586	Toyota Tundra	3.0	☐	—	F-T	T-C	24	28.7	-4.7	-16.4%	—	—	—	—
7593	Chrysler 300	4.4	☐	—	F-C	F-R	24	25.7	-1.7	-6.7%	24	30.5	-0.9	-3.60%
7602	Toyota Yaris	1.8	☑	53.9	F-T	F-C	22	30.5	-8.5	-27.8%	—	—	—	—
7604	Dodge Charger	5.8	☐	—	R-C	T-C	22	28.4	-6.4	-22.5%	24	24.1	-0.1	-0.4%
7640	Lexus ES350	1.2	☑	55.6	F-T	R-C	23	24.1	-1.1	-4.5%	—	—	—	—
7648	Honda Civic	4.6	☑	50.0	F-T	F-C	27	27.3	-0.3	-1.2%	22	26.3	-4.3	-16.5%
7650	Ford F250 Super Crew	15.2	☐	—	T-C	F-T	22	26.3	-4.3	-16.5%	18.91	24.5	-5.6	-22.8%
7713	Honda Civic IMA	0.9	☐	—	T-C	F-C	20.1	24.5	-4.4	-17.9%	22	22.6	-0.6	-2.7%
7733	Scion iQ	1.7	☑	56.6	F-C	R-C	14.1	22.6	-8.5	-37.6%	—	—	—	—
7738	Toyota RAV4	2.8	☐	—	R-T	—	25.2	33.3	-8.1	-24.3%	—	—	—	—
7745	Ram 2500 Crew Cab	14.7	☑	61.4	T-C	F-R	18.9	24.5	-5.6	-22.8%	15	33.4	-18.4	-55.1%
7749	Toyota Corolla	2.2	☐	—	R-C	T-C	27.6	33.4	-5.8	-17.3%	—	—	—	—
7750	Honda CR-V	0.0	☑	70.8	T-C	F-R	20.1	26.0	-5.9	-22.7%	23	30.1	-7.1	-23.6%
7753	Toyota 4Runner	1.3	☑	75.6	R-C	T-C	26.6	30.1	-3.5	-11.6%	—	—	—	—
7768	Fiat 500	3.6	☐	—	R-T	—	15.7	23.4	-7.7	-33.0%	25	23.4	1.6	6.7%

Table A.8 Comparison of EDR reported seat belt buckle status and airbag deployment to reference instrumentation parameters (SINCAP crash test study)

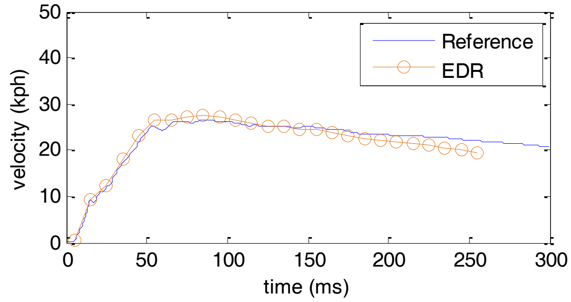
Test No.	Make & Model	Seatbelt Buckle Status				Airbag Deployment					
		Driver		Front Passenger		Front (Driver)		Side/Torso		Curtain	
		EDR	Reference	EDR	Reference	EDR (ms)	Reference	EDR (ms)	Reference	EDR (ms)	Reference
6652	Ford Mustang	☑	☑	☐	☐	NR	☐	☑ 1.5	☑	NR	NE
6653	Ford Mustang	☑	☑	☐	☐	NR	☐	☑ 1.5	☑	NR	NE
6734	Ford Mustang	☑	☑	☐	☐	NR	☐	☑ 2	☑	NR	NE
6737	Ford Mustang	☑	☑	☐	☐	NR	☐	☑ 1.5	☑	NR	NE
6743	Ford Fusion	☑	☑	☐	☐	NR	☐	☑ 0.5	☑	☑ 0.5	☑
6746	Chevrolet Camaro	☑	☑	☐	☐	☐	☐	☑ 0	☑	☑ 0	☑
6789	Chevrolet Equinox	☑	☑	☐	☐	☐	☐	☑ 0	☑	☑ 0	☑
6792	Buick Lacrosse	☑	☑	☐	☐	☐	☐	☑ 0	☑	☑ 0	☑
6798	Ford Taurus	☑	☑	☐	☐	NR	☐	☑ 2	☑	☑ 2	☑
6813	Dodge Avenger	NC	☑	NC	☐	☐	☐	☑	☑	☑	☑
6827	Cadillac SRX	☑	☑	☐	☐	☐	☐	☑	☑	☑	☑
6861	Toyota 4Runner	☑	☑	☐	☐	☑	☑	☑	☑	☑	☑
6944	Toyota Sienna	☑	☑	☐	☐	NR	☐	☑	☑	☑	☑
6952	Toyota Camry	☑	☑	☐	☐	NR	☐	☑	☑	☑	☑
6988	Chevrolet Traverse	☑	☑	☐	☐	☐	☐	☑ 0	☑	☑ 0	☑
7000	Chevrolet Malibu	☑	☑	☐	☐	☐	☐	☑ 2	☑	☑ 2	☑
7036	Jeep Grand Cherokee	☑	☑	☐	☐	☐	☐	☑	☑	☑	☑
7070	Buick Lucerne	☑	☑	☐	☐	☐	☐	☑	☑	☑	☑
7103	Toyota Tacoma	NR	☑	NR	☐	NR	☑	NR	☑	NR	☑
7111	Ram 1500 Crew	☑	☑	☐	☐	☐	☐	NC	NE	☑	☑
7117	Ford Escape	☑	☑	☐	☐	NR	☐	☑ 1	☑	☑ 1	☑
7129	Ram 1500 Quad	☑	☑	NC	☐	☐	☐	NC	NE	☑	☑
7130	Ford Fusion	☑	☑	☐	☐	NR	☐	☑ 2	☑	☑ 2	☑
7138	Toyota RAV4	☑	☑	☐	☐	NR	☐	☑	☑	☑	☑
7146	Lexus RX350	☑	☑	☐	☐	NR	☐	☑	☑	☑	☑
7151	Ford Edge	☑	☑	☐	☐	NR	☐	☑ 1	☑	☑ 1	☑
7160	Chevrolet Cruze	☑	☑	☐	☐	☐	☐	☑ 0	☑	☑ 0	☑
7177	Toyota Venza	☑	☑	☐	☐	NR	☐	☑	☑	☑	☑
7181	Toyota Highlander	☑	☑	☐	☐	NR	☐	☑	☑	☑	☑
7193	Dodge Caliber	NC	☑	☐	☐	☐	☐	NC	NE	☑	☑
7259	Toyota Camry	☑	☑	☐	☐	NR	☐	☑	☑	☑	☑
7341	Ford Ranger	☑	☑	☑	☑	NR	☐	☑	☑	NR	NE
7343	Toyota Tundra Double Cab	NR	☑	NR	☐	NR	☑	NR	☑	NR	☑
7352	Ford F150 Super Crew	☑	☑	☐	☐	NR	☐	☑ 3.5	☑	☑ 1.5	☑
7353	Toyota Corolla	NR	☑	NR	☐	NR	☐	NR	☑	NR	☑
7355	Ford F150 Super Cab	☑	☑	☐	☐	NR	☐	☑ 3.5	☑	☑ 1.5	☑
7363	Buick Lucerne	☑	☑	☐	☐	☐	☐	☑	☑	☑	☑
7364	Toyota Scion tC	☑	☑	☐	☐	NR	☐	☑	☑	☑	☑

(NC) Report indicated the module was not configured to record; (NE) Not equipped with this feature; (✓) Honda verified airbag deployment; (NR) No relevant information available in report

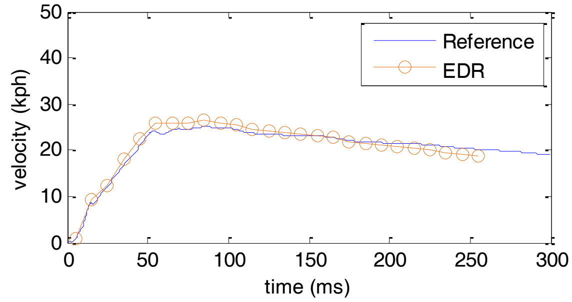
Table A.8 (Cont'd) Comparison of EDR reported seat belt buckle status and airbag deployment to reference instrumentation parameters (SINCAP crash test study)

Test No.	Make & Model	Seatbelt Buckle Status				Airbag Deployment					
		Driver		Front Passenger		Front (Driver)		Side/Torso		Curtain	
		EDR	Reference	EDR	Reference	EDR (ms)	Reference	EDR (ms)	Reference	EDR (ms)	Reference
7367	Buick Lacrosse	☑	☑	☐	☐	☐	☐	☑ 0	☑	☑ 0	☑
7392	Chevrolet Volt	☑	☑	☐	☐	☐	☐	☑ 0	☑	☑ 0	☑
7448	Mazda Mazda3	☑	☑	☐	☐	☐	☐	NR	☑	NR	☑
7465	Ford Mustang	☑	☑	☐	☐	NR	☐	☑ 1.5	☑	NR	NE
7469	Dodge Avenger	NC	☑	NC	☐	☐	☐	☑	☑	☑	☑
7470	Ford Focus	☑	☑	☐	☐	NR	☐	☑ 1	☑	☑ 1	☑
7473	Dodge Journey	☑	☑	☐	☐	☐	☐	☑	☑	☑	☑
7484	Chrysler 200	NC	☑	NC	☐	☐	☐	☑	☑	☑	☑
7486	Chevrolet Impala	☑	☑	☐	☐	☐	☐	☑ 6	☑	☑ 6	☑
7492	Ford Explorer	☑	☑	☐	☐	NR	☐	☑ 2.5	☑	☑ 2.5	☑
7493	Chevrolet Camaro	☑	☑	☐	☐	☐	☐	☑ 0	☑	☑ 0	☑
7507	Fiat 500	☑	☑	☐	☐	☐	☐	☑	☑	☑	☑
7510	Chevrolet Suburban 1500	☑	☑	☐	☐	☐	☐	☑ 3	☑	☑ 3	☑
7517	Toyota Camry	☑	☑	☐	☐	NR	☐	☑	☑	☑	☑
7519	Cadillac CTS	☑	☑	☐	☐	☐	☐	☑ 3	☑	☑ 3	☑
7528	Dodge Durango	☑	☑	☐	☐	☐	☐	☑	☑	☑	☑
7534	Cadillac SRX	☑	☑	☐	☐	☐	☐	☑ 1	☑	☑ 1	☑
7537	Mazda Mazda6	☑	☑	☐	☐	☐	☐	☑ 1	☑	☑ 1	☑
7541	Ford Expedition	☑	☑	☐	☐	NR	☐	☑ 1.5	☑	☑ 1.5	☑
7563	Chevrolet Sonic	☑	☑	☐	☐	☐	☐	☑ 0	☑	☑ 0	☑
7571	Jeep Liberty	NC	☑	☐	☐	☐	☐	☑	NE	☑	☑
7576	Honda Fit	☑	☑	☐	☐	☐	☐	✓ 0	☑	✓ 0	☑
7586	Toyota Tundra	NR	☑	NR	☐	NR	☑	☑	☑	☑	☑
7593	Chrysler 300	☑	☑	☐	☐	☐	☐	☑	☑	☑	☑
7602	Toyota Yaris	☑	☑	☐	☐	NR	☐	☑	☑	☑	☑
7604	Dodge Charger	☑	☑	☐	☐	☐	☐	☑	☑	☑	☑
7640	Lexus ES350	☑	☑	☐	☐	NR	☐	☑	☑	☑	☑
7648	Honda Civic	☑	☑	☐	☐	☐	☐	☑ 3	☑	☑ 3	☑
7650	Ford F250 Super Crew	☑	☑	NR	☐	NR	☐	☑ 5	☑	☑ 3	☑
7713	Honda Civic IMA	☑	☑	☐	☐	☐	☐	✓ 0	☑	✓ 0	☑
7733	Scion iQ	☑	☑	☐	☐	NR	☐	☑	☑	☑	☑
7738	Toyota RAV4	☑	☑	☐	☐	NR	☐	☑	☑	☑	☑
7745	Ram 2500 Crew Cab	☑	☑	NC	☐	☐	☐	☐	NE	☑	☑
7749	Toyota Corolla	NR	☑	NR	☐	NR	☐	☑	☑	☑	☑
7750	Honda CR-V	☑	☑	☐	☐	☐	☐	☑ 1	☑	☑ 1	☑
7753	Toyota 4Runner	☑	☑	☐	☐	☑ 2	☑	☑	☑	☑	☑
7768	Fiat 500	☑	☑	☐	☐	☐	☐	☑	☑	☑	☑

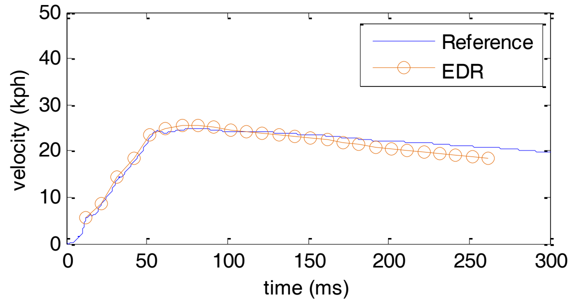
(NC) Report indicated the module was not configured to record; (NE) Not equipped with this feature; (✓) Honda verified airbag deployment; (NR) No relevant information available in report



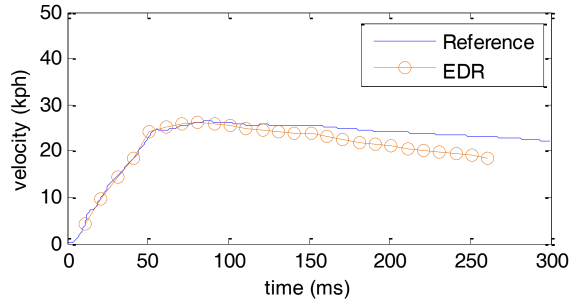
2010 Ford Mustang (test no. 6652): Rotation corrected reference velocity vs. EDR velocity (time shifted 4.9 ms)



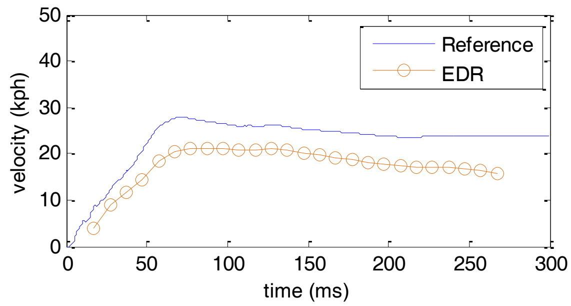
2010 Ford Mustang (test no. 6653): Rotation corrected reference velocity vs. EDR velocity (time shifted 5 ms)



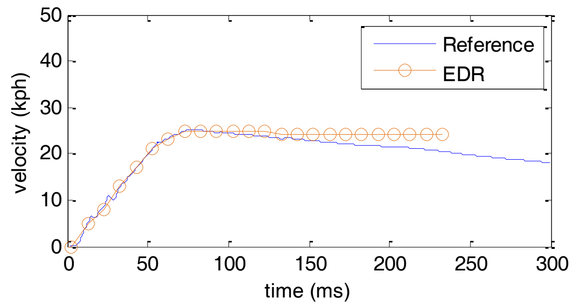
2010 Ford Mustang (test no. 6734): Rotation corrected reference velocity vs. EDR velocity (time shifted 11.8 ms)



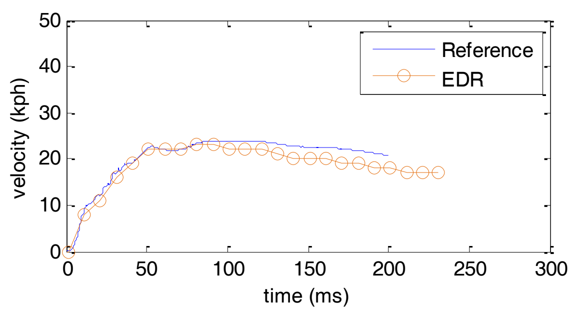
2010 Ford Mustang (test no. 6737): Rotation corrected reference velocity vs. EDR velocity (time shifted 11 ms)



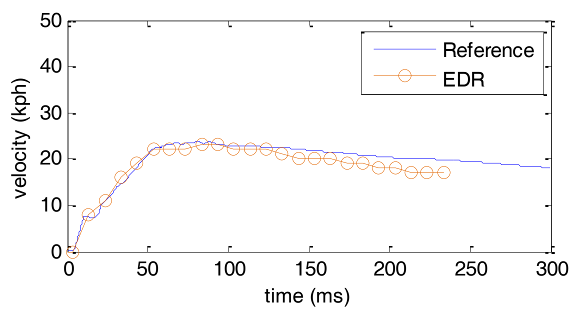
2010 Ford Fusion (test no. 6743): Rotation corrected reference velocity vs. EDR velocity (time shifted 17.1 ms)



2010 Chevrolet Camaro (test no. 6746): Rotation corrected reference velocity vs. EDR velocity (time shifted 12.9 ms)

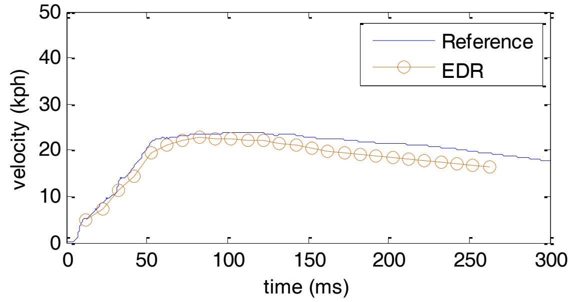


2010 Chevrolet Equinox (test no. 6789): Rotation corrected reference velocity vs. EDR velocity (time shifted 11.2 ms)

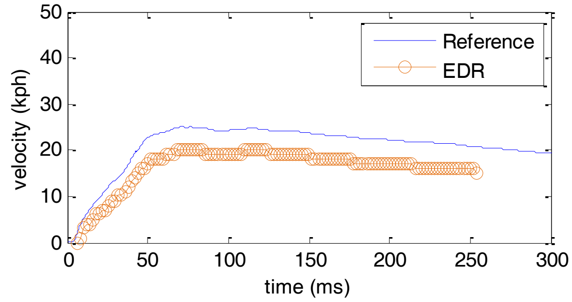


2010 Buick Lacrosse (test no. 6792): Rotation corrected reference velocity vs. EDR velocity (time shifted 13.3 ms)

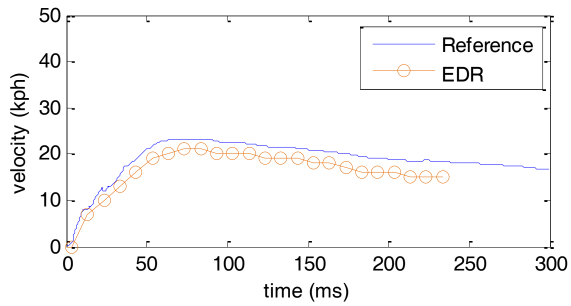
Figure A.3 Overlay of EDR and reference instrumentation lateral velocity versus time after a time shift (SINCAP crash test study)



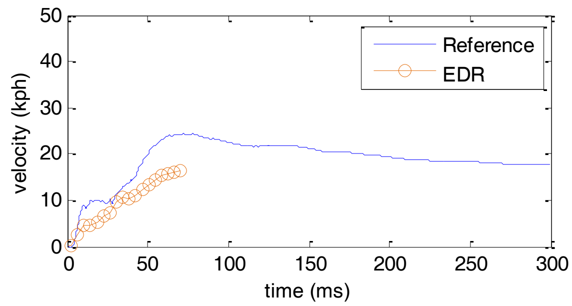
2010 Ford Taurus (test no. 6798): Rotation corrected reference velocity vs. EDR velocity (time shifted 12.5 ms)



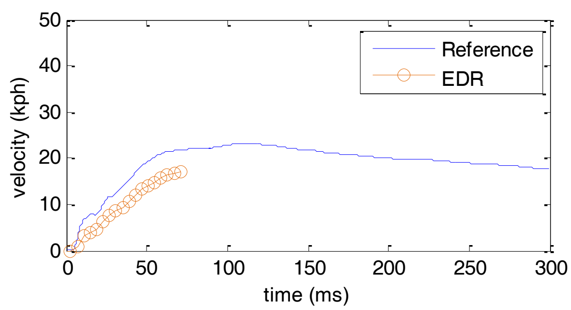
2010 Dodge Avenger (test no. 6813): Rotation corrected reference velocity vs. EDR velocity (time shifted 5.8 ms)



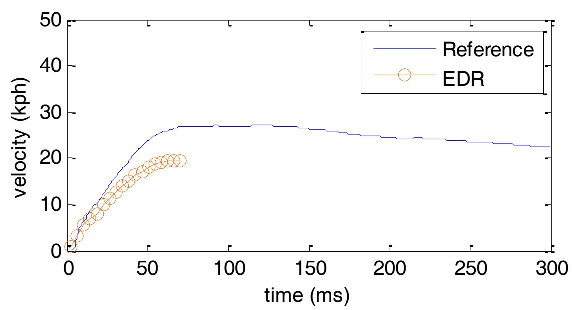
2010 Cadillac SRX (test no. 6827): Rotation corrected reference velocity vs. EDR velocity (time shifted 13.4 ms)



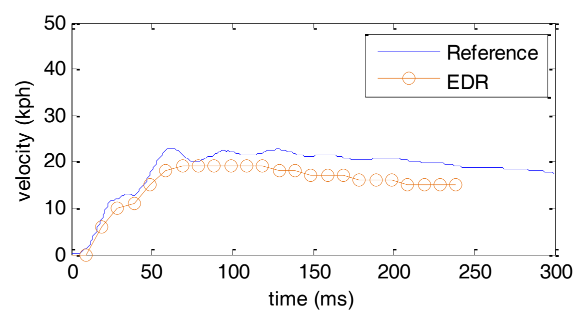
2010 Toyota 4Runner (test no. 6861): Rotation corrected reference velocity vs. EDR velocity (time shifted 1.5 ms)



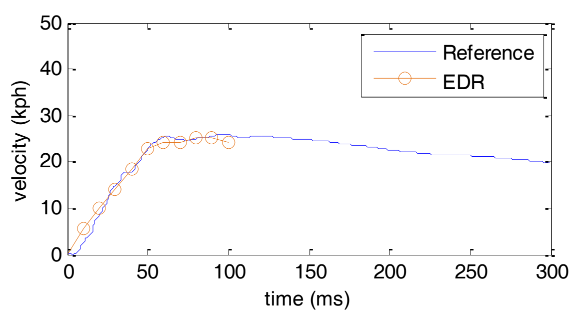
2011 Toyota Sienna (test no. 6944): Rotation corrected reference velocity vs. EDR velocity (time shifted 2.8 ms)



2011 Toyota Camry (test no. 6952): Rotation corrected reference velocity vs. EDR velocity (time shifted -0.5 ms)

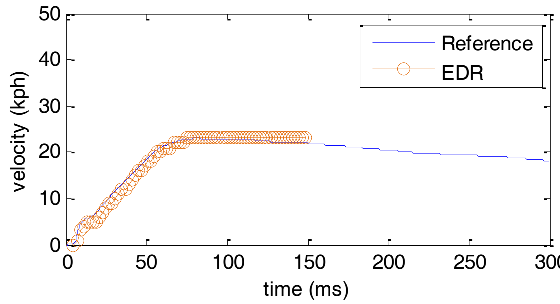


2011 Chevrolet Traverse (test no. 6988): Rotation corrected reference velocity vs. EDR velocity (time shifted 18.7 ms)

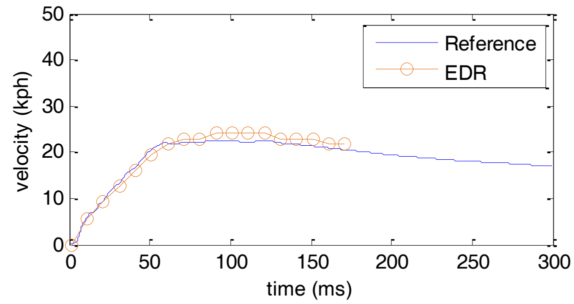


2011 Chevrolet Malibu (test no. 7000): Rotation corrected reference velocity vs. EDR velocity (time shifted 20 ms)

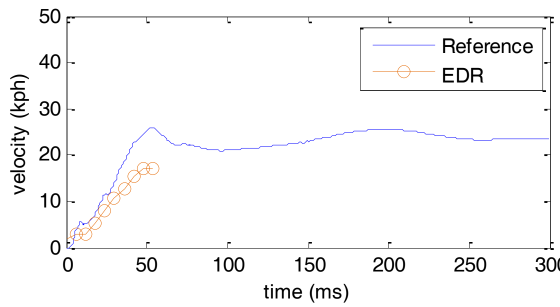
Figure A.3 (Cont'd) Overlay of EDR and reference instrumentation lateral velocity versus time after a time shift (SINCAP crash test study)



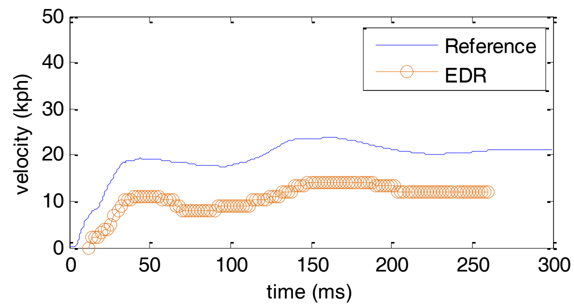
2011 Jeep Grand Cherokee (test no. 7036): Rotation corrected reference velocity vs. EDR velocity (time shifted 4.8 ms)



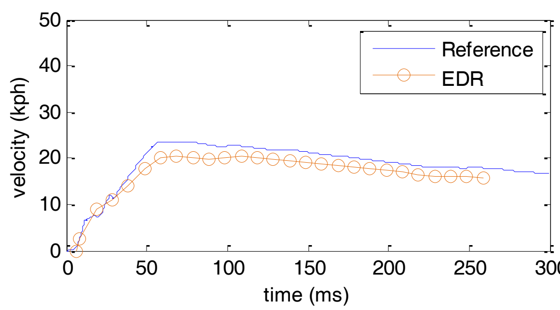
2011 Buick Lucerne (test no. 7070): Rotation corrected reference velocity vs. EDR velocity (time shifted 11.1 ms)



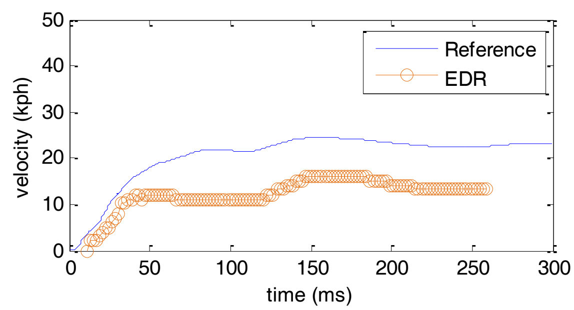
2011 Toyota Tacoma (test no. 7103): Rotation corrected reference velocity vs. EDR velocity (time shifted 0 ms)



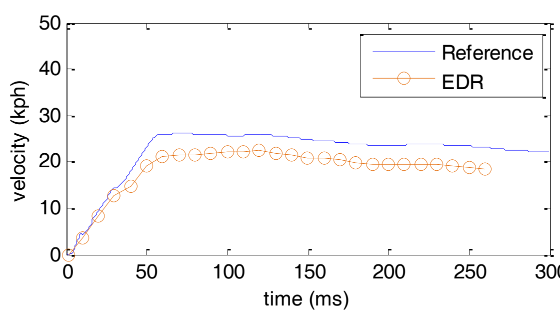
2011 Ram 1500 Crew (test no. 7111): Rotation corrected reference velocity vs. EDR velocity (time shifted 12 ms)



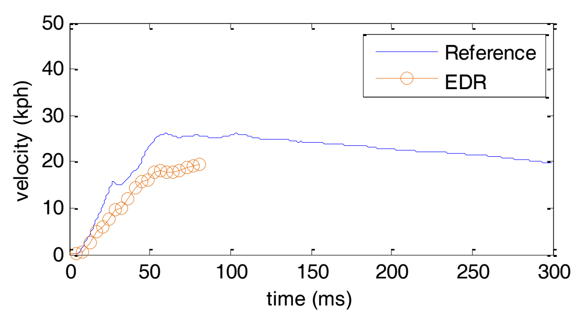
2011 Ford Escape (test no. 7117): Rotation corrected reference velocity vs. EDR velocity (time shifted 6.1 ms)



2011 Ram 1500 Quad (test no. 7129): Rotation corrected reference velocity vs. EDR velocity (time shifted 10.7 ms)

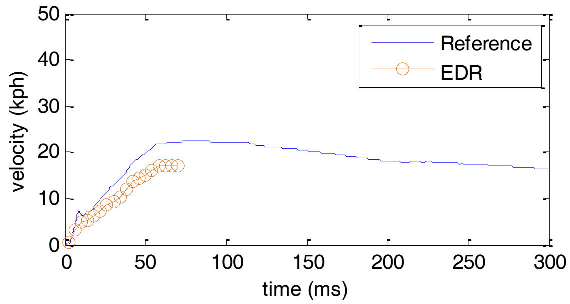


2011 Ford Fusion (test no. 7130): Rotation corrected reference velocity vs. EDR velocity (time shifted 1.9 ms)

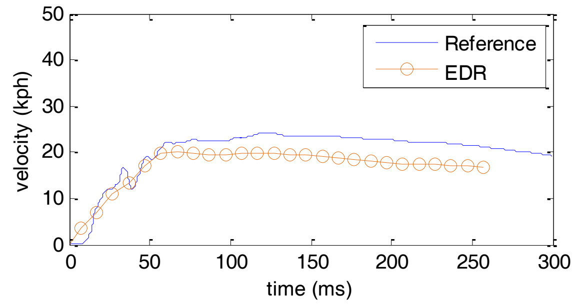


2011 Toyota RAV4 (test no. 7138): Rotation corrected reference velocity vs. EDR velocity (time shifted 8.6 ms)

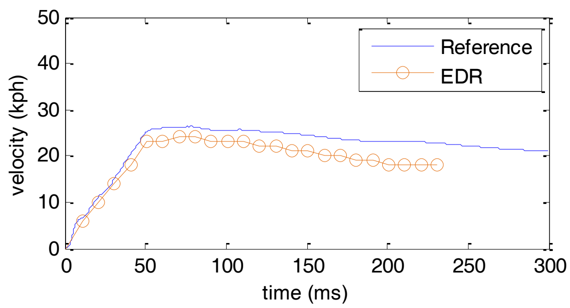
Figure A.3 (Cont'd) Overlay of EDR and reference instrumentation lateral velocity versus time after a time shift (SINCAP crash test study)



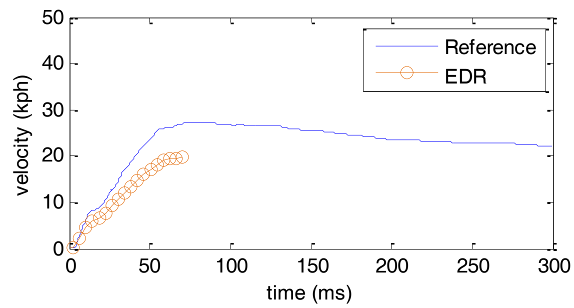
2011 Lexus RX350 (test no. 7146): Rotation corrected reference velocity vs. EDR velocity (time shifted 1.1 ms)



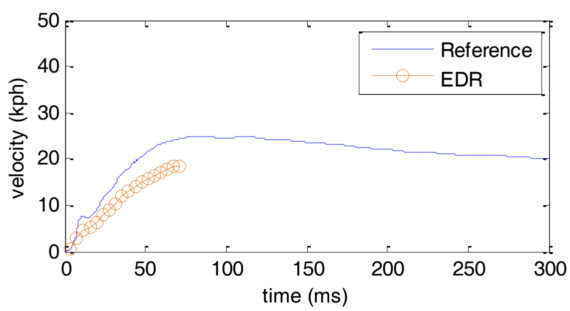
2011 Ford Edge (test no. 7151): Rotation corrected reference velocity vs. EDR velocity (time shifted -0.2 ms)



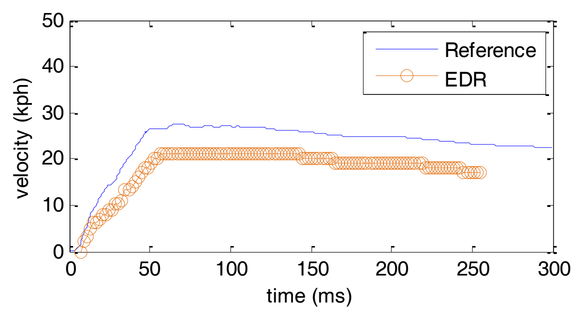
2011 Chevrolet Cruze (test no. 7160): Rotation corrected reference velocity vs. EDR velocity (time shifted 10.7 ms)



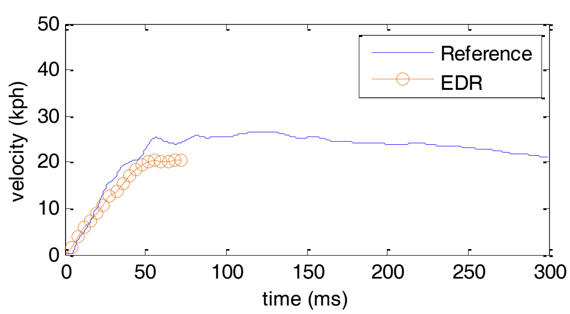
2011 Toyota Venza (test no. 7177): Rotation corrected reference velocity vs. EDR velocity (time shifted 2.4 ms)



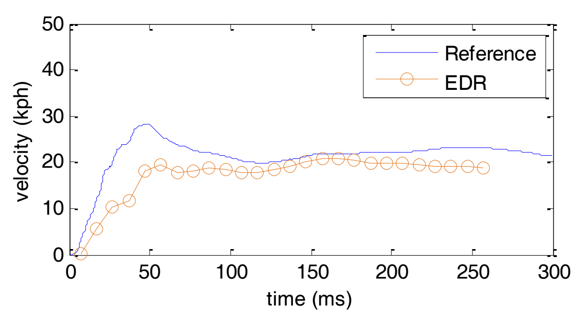
2011 Toyota Highlander (test no. 7181): Rotation corrected reference velocity vs. EDR velocity (time shifted 2.6 ms)



2011 Dodge Caliber (test no. 7193): Rotation corrected reference velocity vs. EDR velocity (time shifted 6.8 ms)

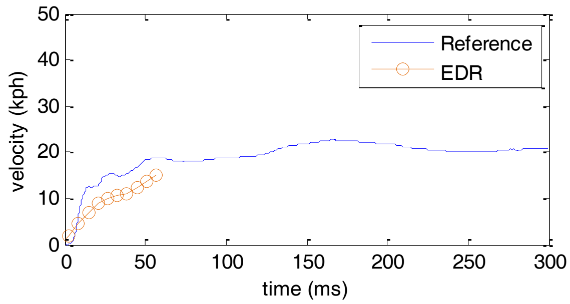


2011 Toyota Camry (test no. 7259): Rotation corrected reference velocity vs. EDR velocity (time shifted 1 ms)

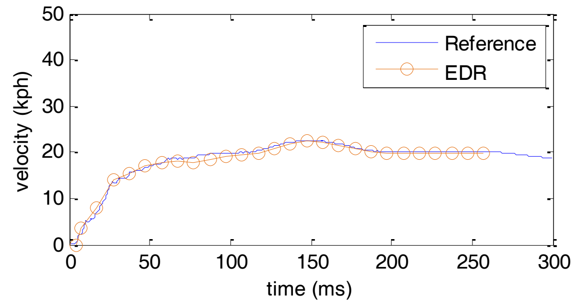


2011 Ford Ranger (test no. 7341): Rotation corrected reference velocity vs. EDR velocity (time shifted 6.8 ms)

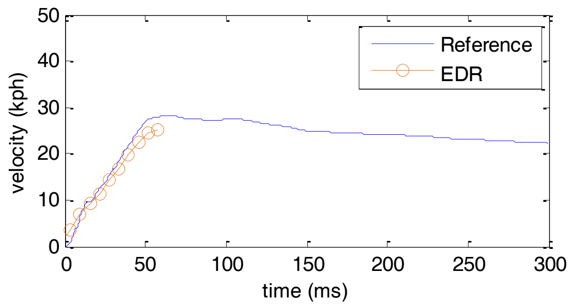
Figure A.3 (Cont'd) Overlay of EDR and reference instrumentation lateral velocity versus time after a time shift (SINCAP crash test study)



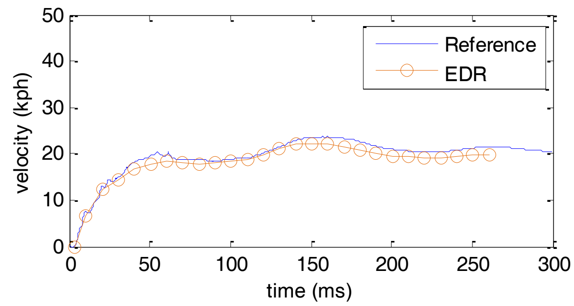
2011 Toyota Tundra Double Cab (test no. 7343): Rotation corrected reference velocity vs. EDR velocity (time shifted 2.6 ms)



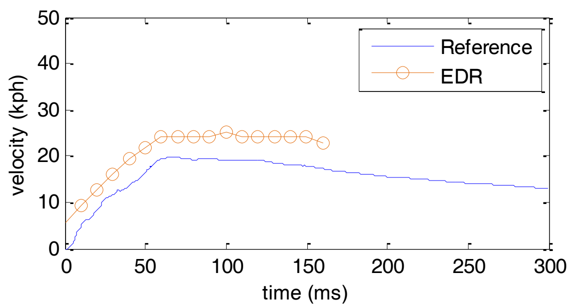
2011 Ford F150 Supercrew (test no. 7352): Rotation corrected reference velocity vs. EDR velocity (time shifted 4.3 ms)



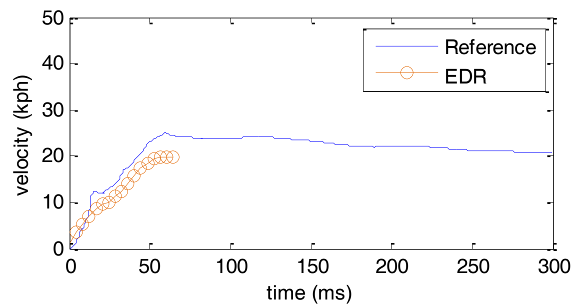
2011 Toyota Corolla (test no. 7353): Rotation corrected reference velocity vs. EDR velocity (time shifted 3.5 ms)



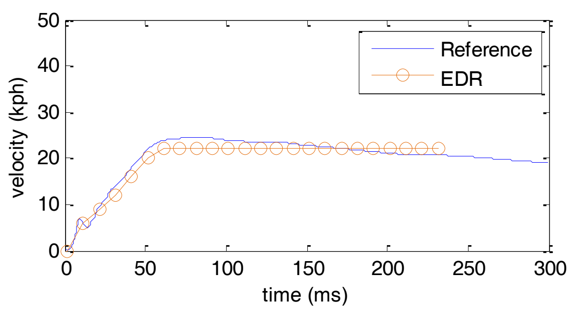
2011 Ford F150 Supercab (test no. 7355): Rotation corrected reference velocity vs. EDR velocity (time shifted 3 ms)



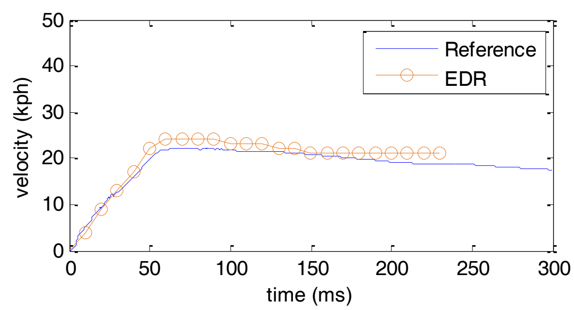
2011 Buick Lucerne (test no. 7363): Rotation corrected reference velocity vs. EDR velocity (time shifted 0 ms)



2011 Toyota Scion tC (test no. 7364): Rotation corrected reference velocity vs. EDR velocity (time shifted -3.5 ms)

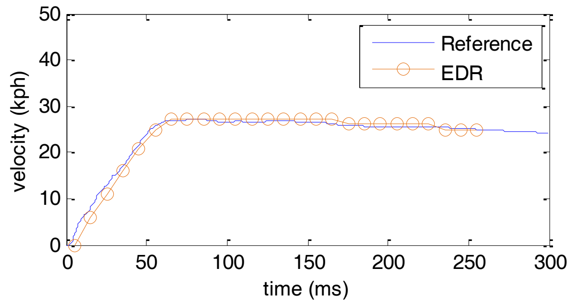


2011 Buick Lacrosse (test no. 7367): Rotation corrected reference velocity vs. EDR velocity (time shifted 11.4 ms)

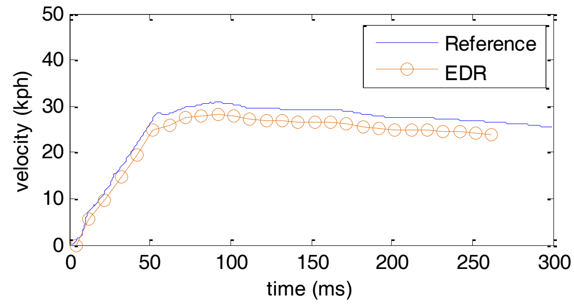


2011 Chevrolet Volt (test no. 7392): Rotation corrected reference velocity vs. EDR velocity (time shifted 10 ms)

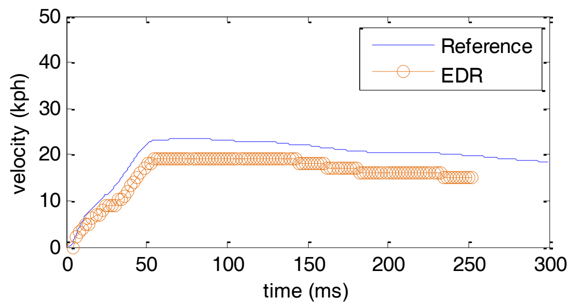
Figure A.3 (Cont'd) Overlay of EDR and reference instrumentation lateral velocity versus time after a time shift (SINCAP crash test study)



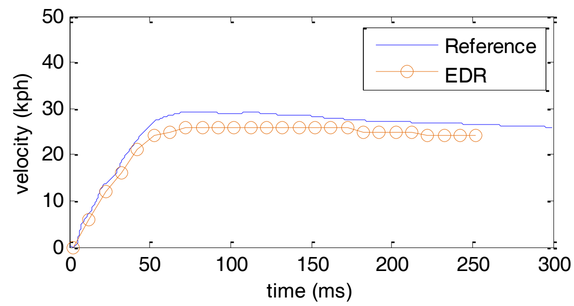
2012 Mazda Mazda3 (test no. 7448): Rotation corrected reference velocity vs. EDR velocity (time shifted 5.4ms)



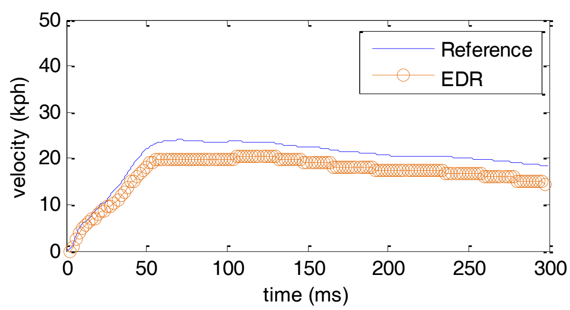
2012 Ford Mustang (test no. 7465): Rotation corrected reference velocity vs. EDR velocity (time shifted 4.6ms)



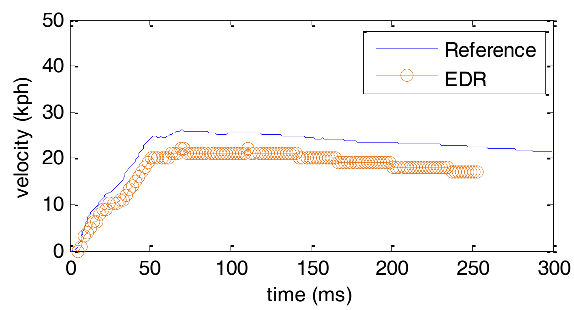
2012 Dodge Avenger (test no. 7469): Rotation corrected reference velocity vs. EDR velocity (time shifted 4.4ms)



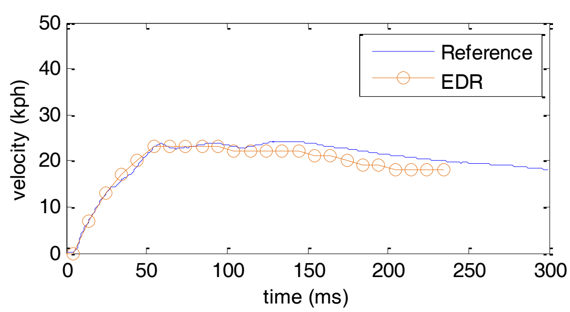
2012 Ford Focus (test no. 7470): Rotation corrected reference velocity vs. EDR velocity (time shifted 2.4ms)



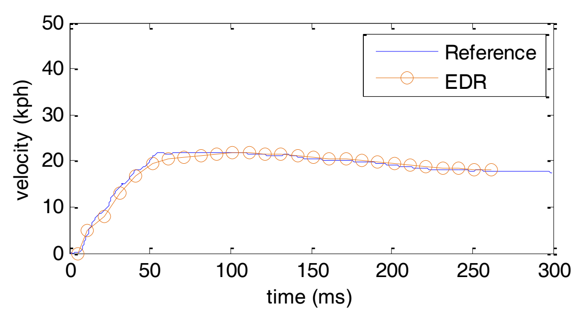
2012 Dodge Journey (test no. 7473): Rotation corrected reference velocity vs. EDR velocity (time shifted 0ms)



2012 Chrysler 200 (test no. 7484): Rotation corrected reference velocity vs. EDR velocity (time shifted 5.1ms)

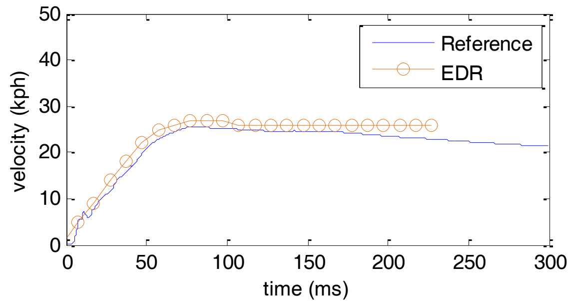


2012 Chevrolet Impala (test no. 7486): Rotation corrected reference velocity vs. EDR velocity (time shifted 14.4ms)

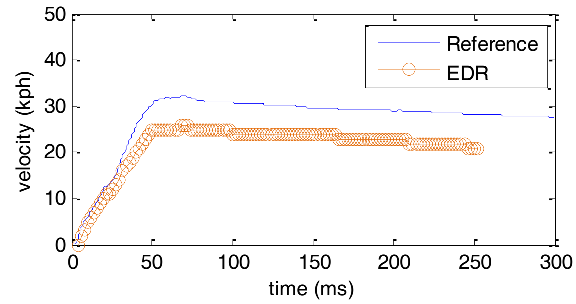


2012 Ford Explorer (test no. 7492): Rotation corrected reference velocity vs. EDR velocity (time shifted 5.4ms)

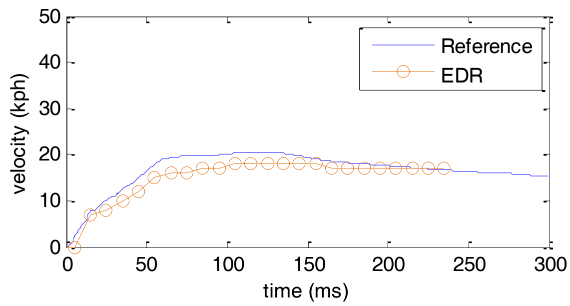
Figure A.3 (Cont'd) Overlay of EDR and reference instrumentation lateral velocity versus time after a time shift (SINCAP crash test study)



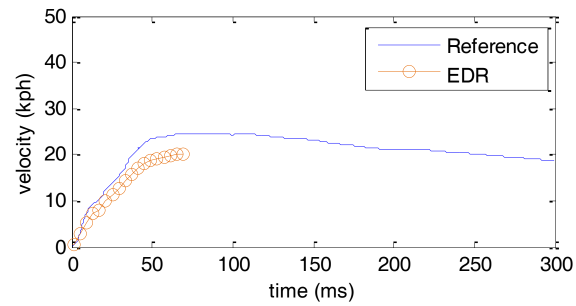
2012 Chevrolet Camaro (test no. 7493): Rotation corrected reference velocity vs. EDR velocity (time shifted 7.2ms)



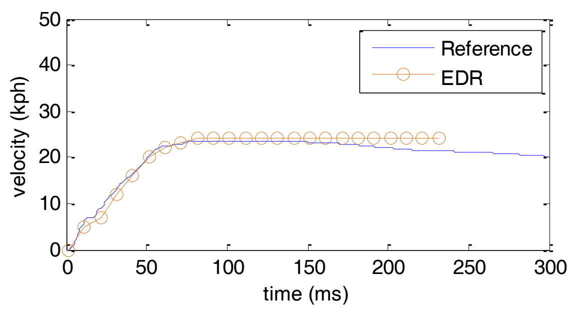
2012 Fiat 500 (test no. 7507): Rotation corrected reference velocity vs. EDR velocity (time shifted 3.9ms)



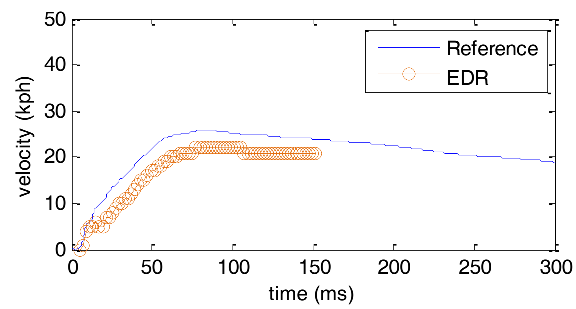
2012 Chevrolet Suburban 1500 (test no. 7510): Rotation corrected reference velocity vs. EDR velocity (time shifted 14.9ms)



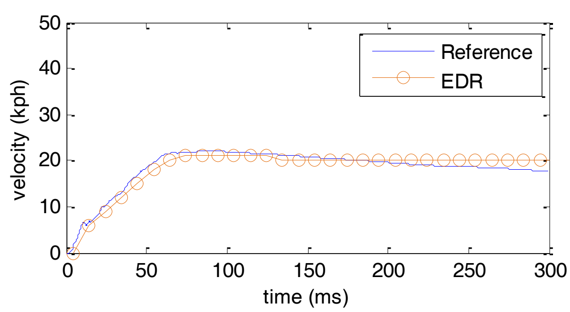
2012 Toyota Camry (test no. 7517): Rotation corrected reference velocity vs. EDR velocity (time shifted 0.2ms)



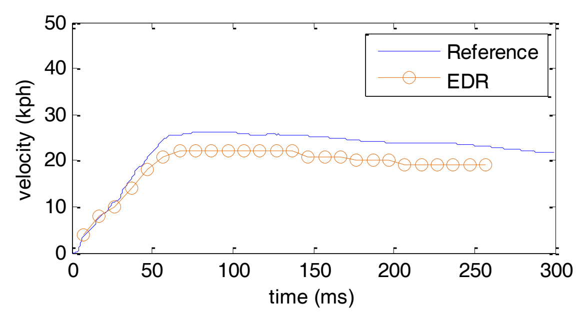
2012 Cadillac CTS (test no. 7519): Rotation corrected reference velocity vs. EDR velocity (time shifted 11.6ms)



2012 Dodge Durango (test no. 7528): Rotation corrected reference velocity vs. EDR velocity (time shifted 5.4ms)

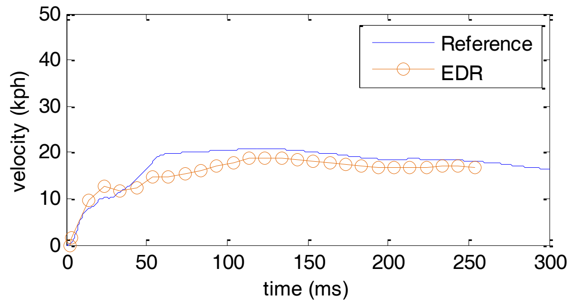


2012 Cadillac SRX (test no. 7534): Rotation corrected reference velocity vs. EDR velocity (time shifted 4.4ms)

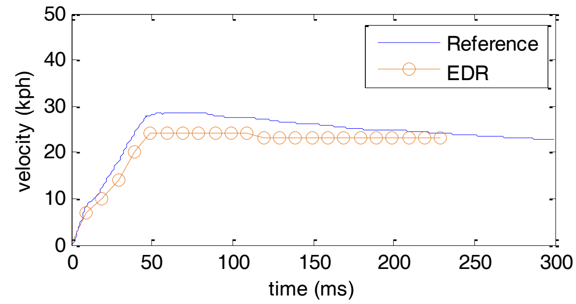


2012 Mazda Mazda6 (test no. 7537): Rotation corrected reference velocity vs. EDR velocity (time shifted 6.8ms)

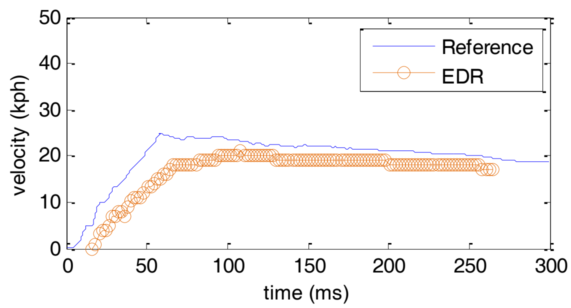
Figure A.3 (Cont'd) Overlay of EDR and reference instrumentation lateral velocity versus time after a time shift (SINCAP crash test study)



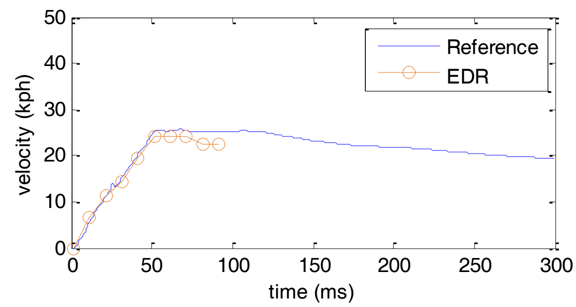
2012 Ford Expedition (test no. 7541): Rotation corrected reference velocity vs. EDR velocity (time shifted 2.3ms)



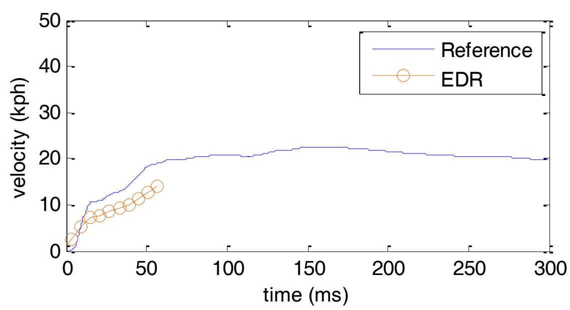
2012 Chevrolet Sonic (test no. 7563): Rotation corrected reference velocity vs. EDR velocity (time shifted 9.3ms)



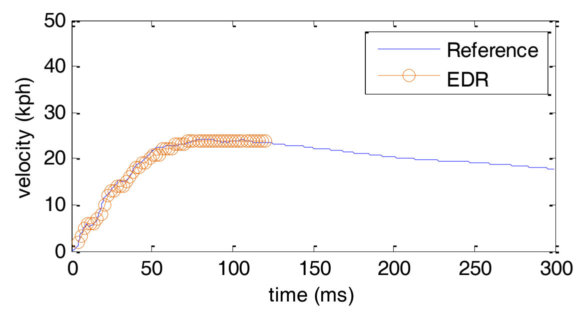
2012 Jeep Liberty (test no. 7571): Rotation corrected reference velocity vs. EDR velocity (time shifted 16.3 ms)



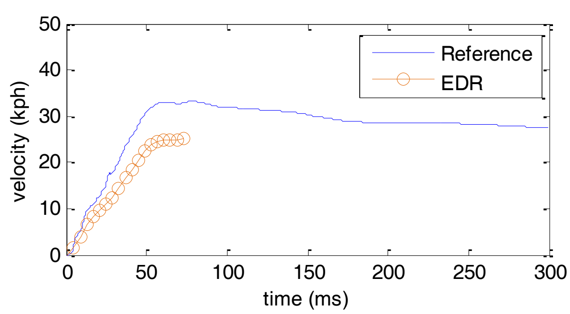
2012 Honda Fit (test no. 7576): Rotation corrected reference velocity vs. EDR velocity (time shifted 1.4ms)



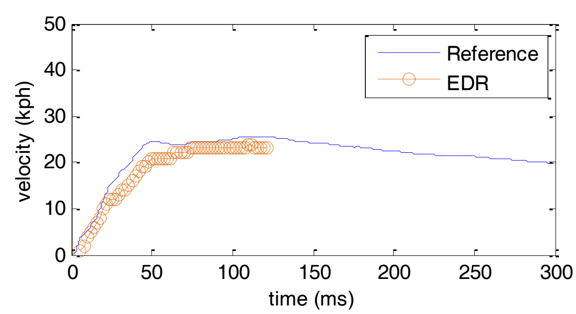
2012 Toyota Tundra (test no. 7586): Rotation corrected reference velocity vs. EDR velocity (time shifted 3ms)



2012 Chrysler 300 (test no. 7593): Rotation corrected reference velocity vs. EDR velocity (time shifted 4.4ms)

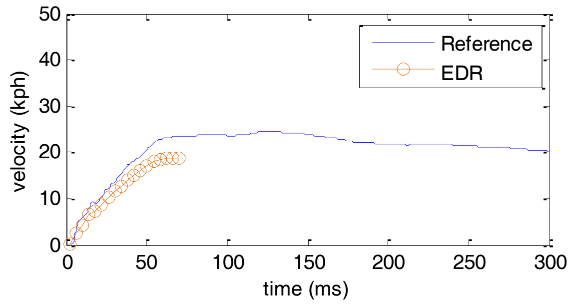


2012 Toyota Yaris (test no. 7602): Rotation corrected reference velocity vs. EDR velocity (time shifted 1.8ms)

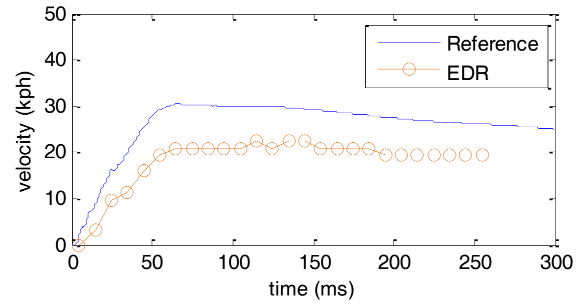


2012 Dodge Charger (test no. 7604): Rotation corrected reference velocity vs. EDR velocity (time shifted 5.8ms)

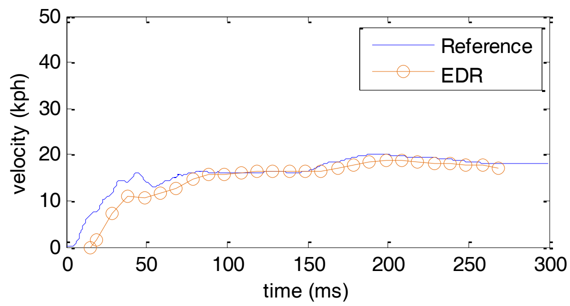
Figure A.3 (Cont'd) Overlay of EDR and reference instrumentation lateral velocity versus time after a time shift (SINCAP crash test study)



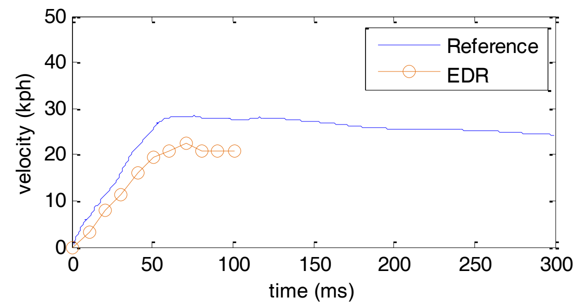
2012 Lexus ES350 (test no. 7640): Rotation corrected reference velocity vs. EDR velocity (time shifted 1.2ms)



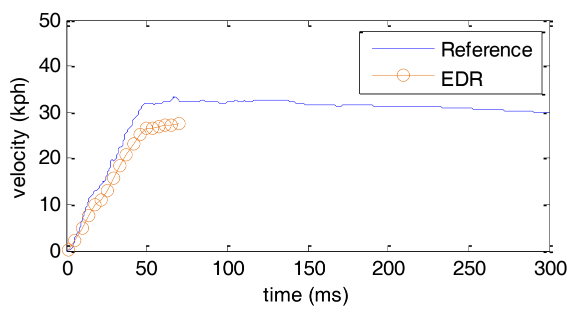
2012 Honda Civic (test no. 7648): Rotation corrected reference velocity vs. EDR velocity (time shifted 4.6ms)



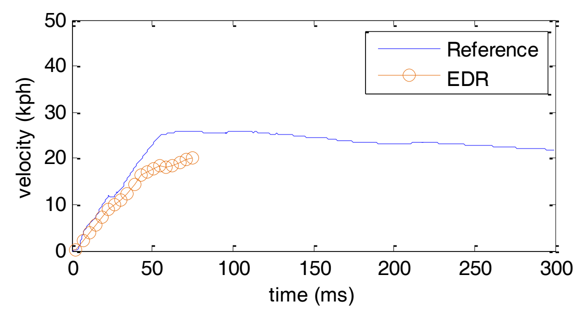
2012 Ford F250 Super Crew (test no. 7650): Rotation corrected reference velocity vs. EDR velocity (time shifted 15.2ms)



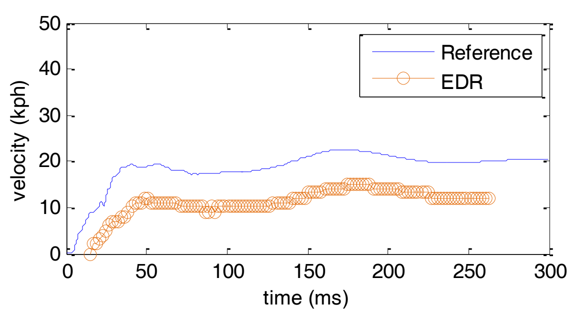
2012 Honda Civic IMA (test no. 7713): Rotation corrected reference velocity vs. EDR velocity (time shifted 0.9ms)



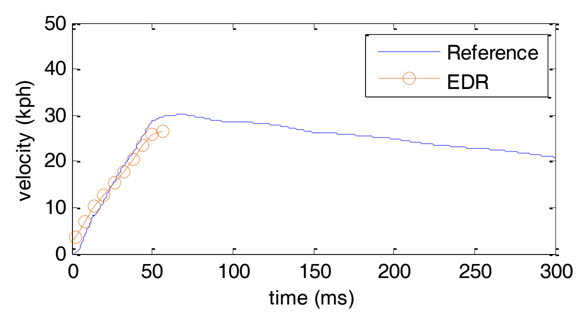
2012 Scion iQ (test no. 7733): Rotation corrected reference velocity vs. EDR velocity (time shifted 1.7ms)



2012 Toyota RAV4 (test no. 7738): Rotation corrected reference velocity vs. EDR velocity (time shifted 2.8ms)

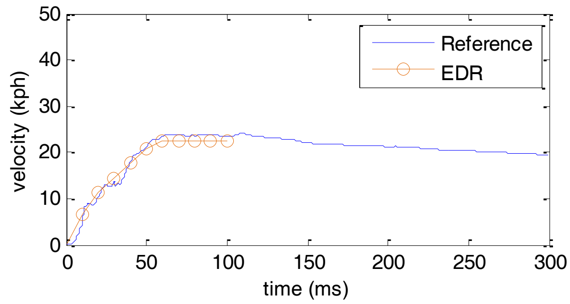


2012 Ram 2500 Crew Cab (test no. 7745): Rotation corrected reference velocity vs. EDR velocity (time shifted 14.7ms)

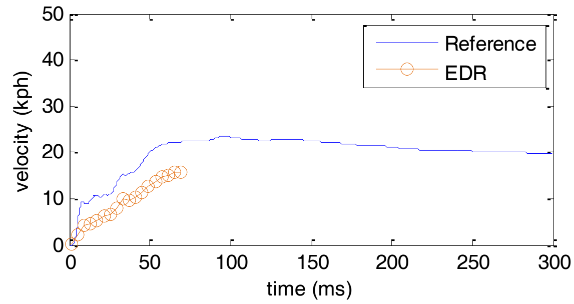


2012 Toyota Corolla (test no. 7749): Rotation corrected reference velocity vs. EDR velocity (time shifted 2.2ms)

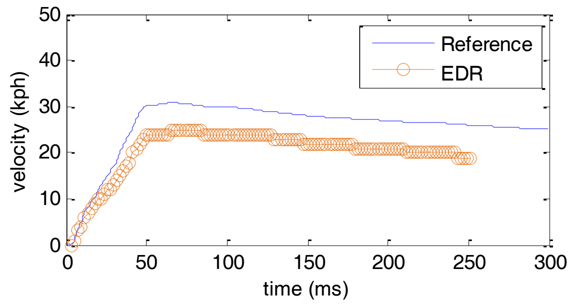
Figure A.3 (Cont'd) Overlay of EDR and reference instrumentation lateral velocity versus time after a time shift (SINCAP crash test study)



2012 Honda CR-V (test no. 7750): Rotation corrected reference velocity vs. EDR velocity (time shifted 0ms)

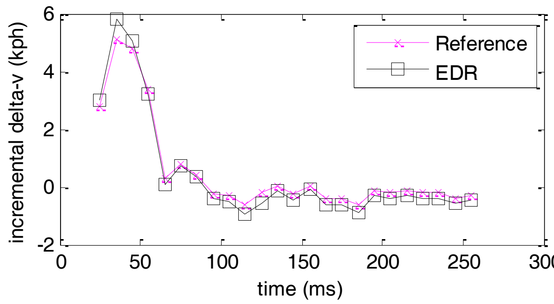


2012 Toyota 4Runner (test no. 7753): Rotation corrected reference velocity vs. EDR velocity (time shifted 1.3ms)

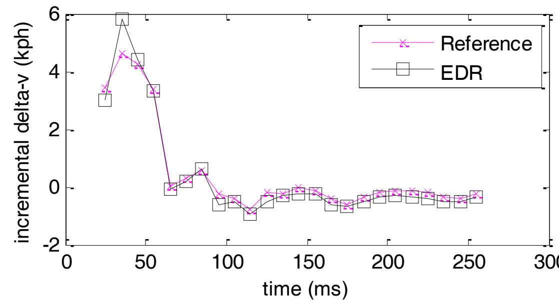


2012 Fiat 500 (test no. 7768): Rotation corrected reference velocity vs. EDR velocity (time shifted 3.6ms)

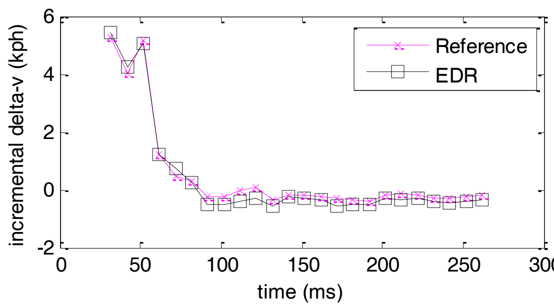
Figure A.3 (Cont'd) Overlay of EDR and reference instrumentation lateral velocity versus time after a time shift (SINCAP crash test study)



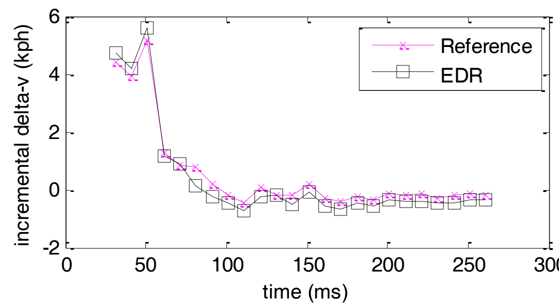
2010 Ford Mustang (test no. 6652) time shifted 4.9 ms)



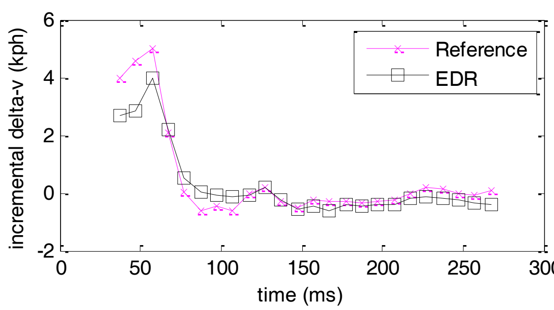
2010 Ford Mustang (test no. 6653) time shifted 5 ms)



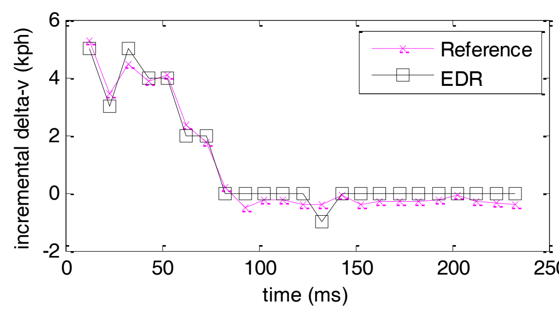
2010 Ford Mustang (test no. 6734) time shifted 11.8 ms)



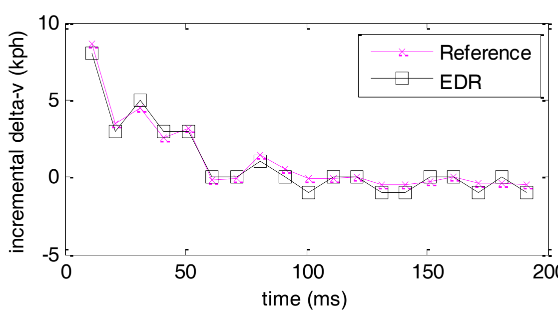
2010 Ford Mustang (test no. 6737) time shifted 11 ms)



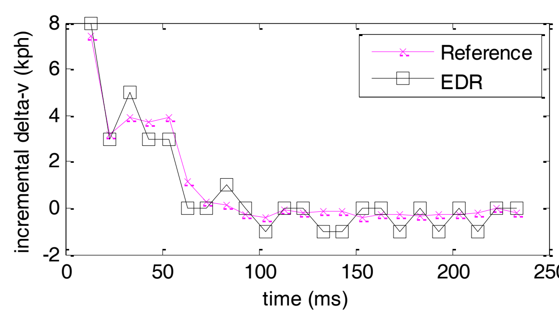
2010 Ford Fusion (test no. 6743) time shifted 17.1 ms)



2010 Chevrolet Camaro (test no. 6746) time shifted 12.9 ms)

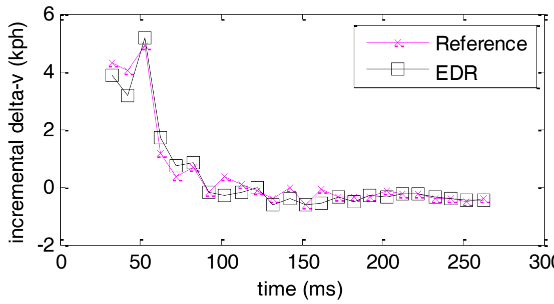


2010 Chevrolet Equinox (test no. 6789) time shifted 11.2 ms)

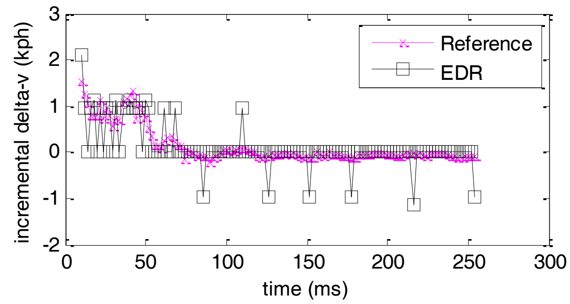


2010 Buick Lacrosse (test no. 6792) time shifted 13.3 ms)

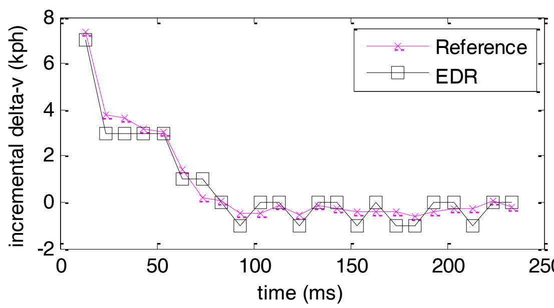
Figure A.4 Overlay of EDR and reference instrumentation lateral incremental delta-v versus time after optimization in time (SINCAP crash test study)



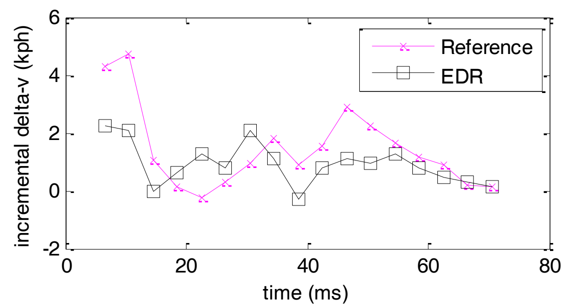
2010 Ford Taurus (test no. 6798) time shifted 12.5 ms)



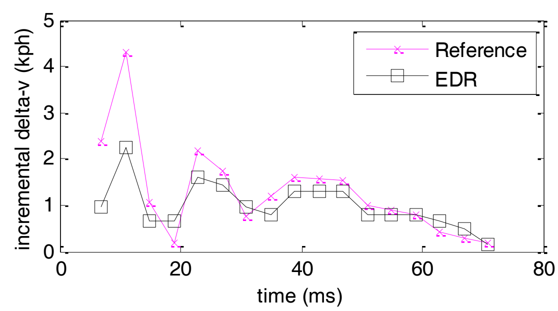
2010 Dodge Avenger (test no. 6813) time shifted 5.8 ms)



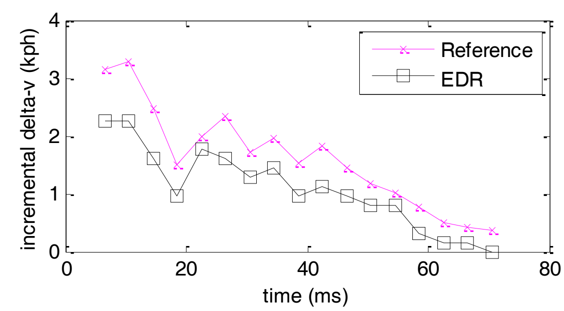
2010 Cadillac SRX (test no. 6827) time shifted 13.4 ms)



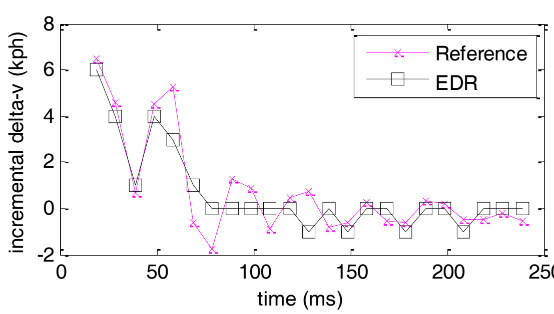
2010 Toyota 4Runner (test no. 6861) time shifted 1.5 ms)



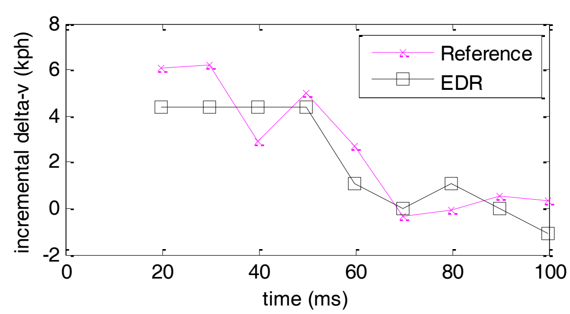
2011 Toyota Sienna (test no. 6944) time shifted 2.8 ms)



2011 Toyota Camry (test no. 6952) time shifted -0.5 ms)

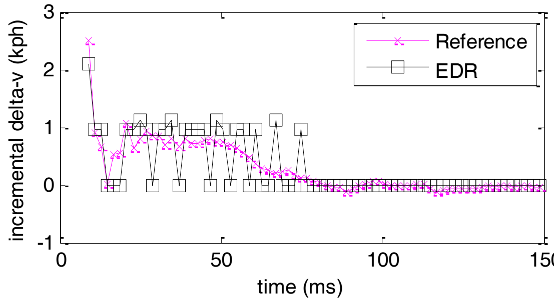


2011 Chevrolet Traverse (test no. 6988) time shifted 18.7 ms)

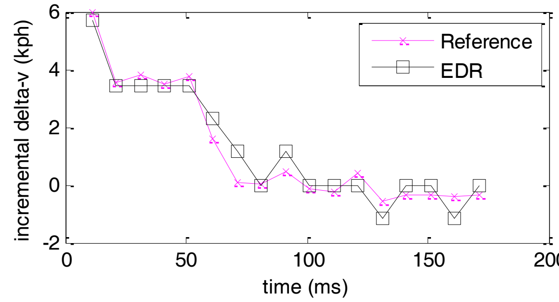


2011 Chevrolet Malibu (test no. 7000) time shifted 20 ms)

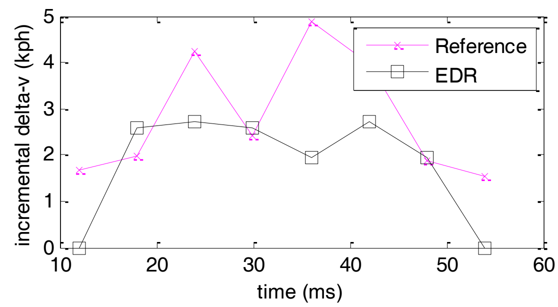
Figure A.4 (Cont'd) Overlay of EDR and reference instrumentation lateral incremental delta-v versus time after optimization in time (SINCAP crash test study)



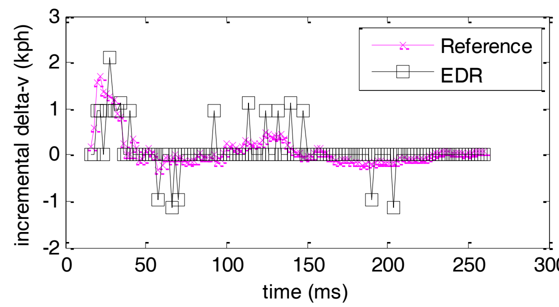
2011 Jeep Grand Cherokee (test no. 7036) time shifted 4.8 ms)



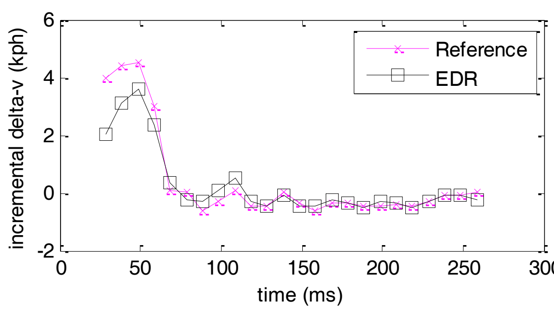
2011 Buick Lucerne (test no. 7070) time shifted 11.1 ms)



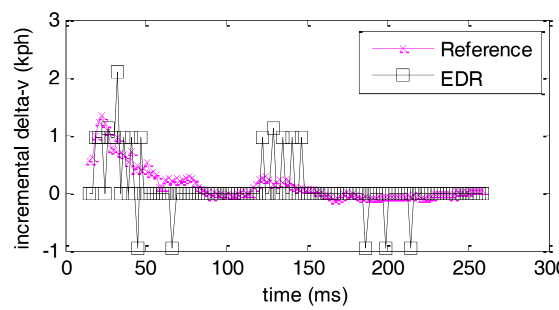
2011 Toyota Tacoma (test no. 7103) time shifted 0 ms)



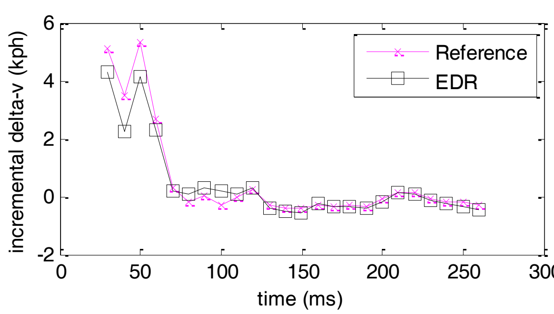
2011 Ram 1500 Crew (test no. 7111) time shifted 12 ms)



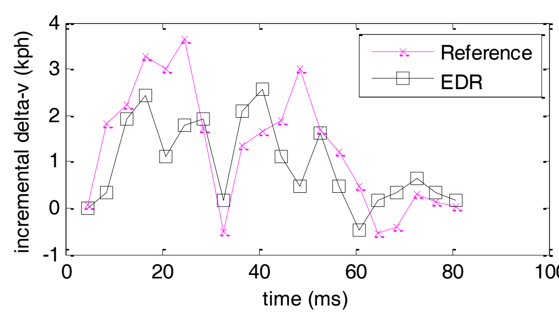
2011 Ford Escape (test no. 7117) time shifted 6.1 ms)



2011 Ram 1500 Quad (test no. 7129) time shifted 10.7 ms)

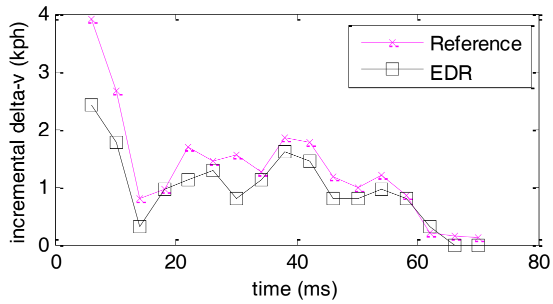


2011 Ford Fusion (test no. 7130) time shifted 1.9 ms)

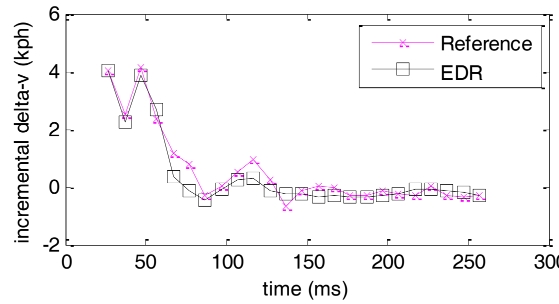


2011 Toyota RAV4 (test no. 7138) time shifted 8.6 ms)

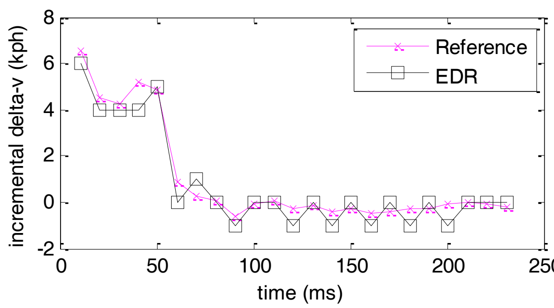
Figure A.4 (Cont'd) Overlay of EDR and reference instrumentation lateral incremental delta-v versus time after optimization in time (SINCAP crash test study)



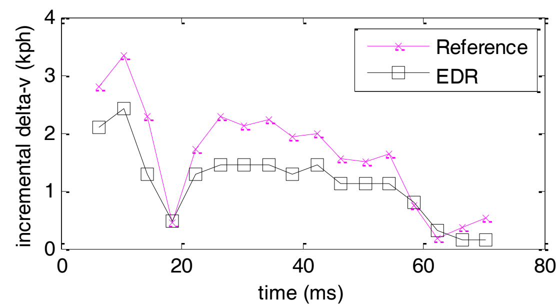
2011 Lexus RX350 (test no. 7146) time shifted 1.1 ms)



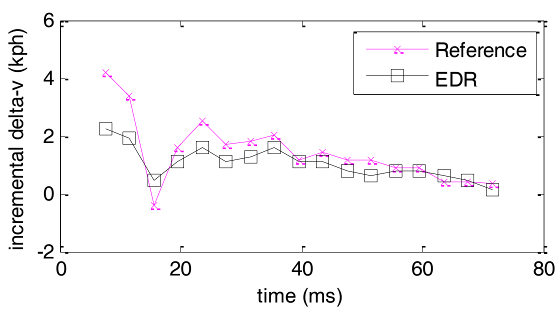
2011 Ford Edge (test no. 7151) time shifted -0.2 ms)



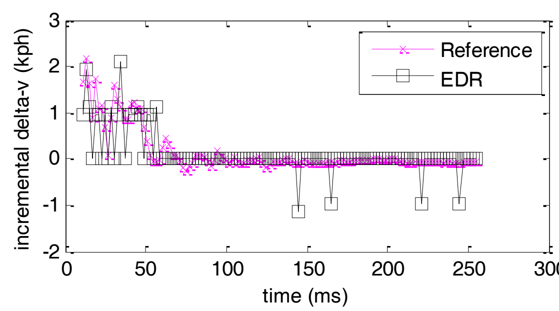
2011 Chevrolet Cruze (test no. 7160) time shifted 10.7 ms)



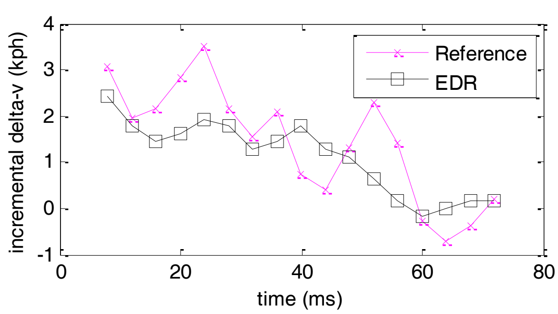
2011 Toyota Venza (test no. 7177) time shifted 2.4 ms)



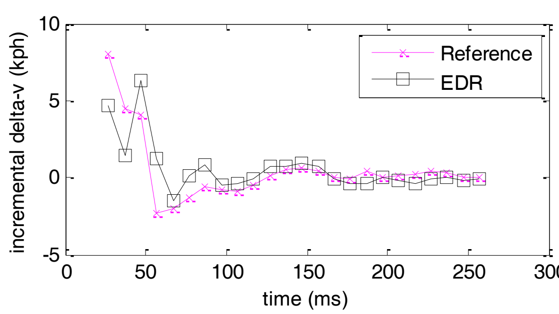
2011 Toyota Highlander (test no. 7181) time shifted 2.6 ms)



2011 Dodge Caliber (test no. 7193) time shifted 6.8 ms)

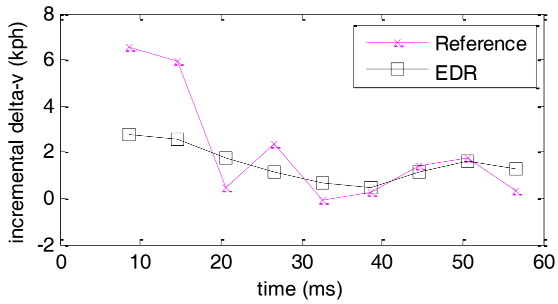


2011 Toyota Camry (test no. 7259) time shifted 1 ms)

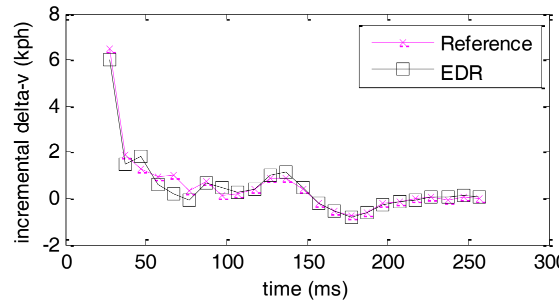


2011 Ford Ranger (test no. 7341) time shifted 6.8 ms)

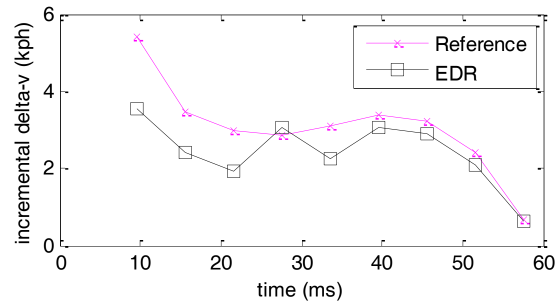
Figure A.4 (Cont'd) Overlay of EDR and reference instrumentation lateral incremental delta-v versus time after optimization in time (SINCAP crash test study)



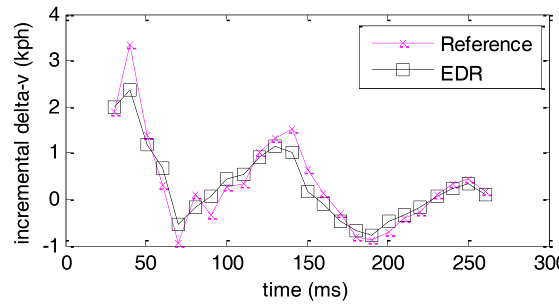
2011 Toyota Tundra Double Cab (test no. 7343) time shifted 2.6 ms)



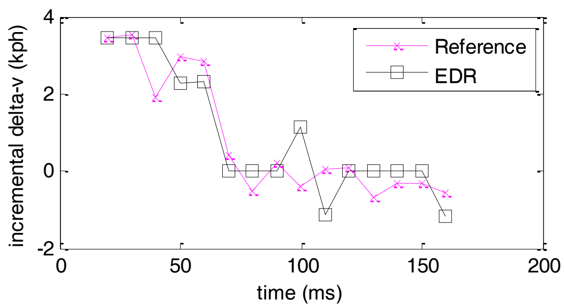
2011 Ford F150 Supercrew (test no. 7352) time shifted 4.3 ms)



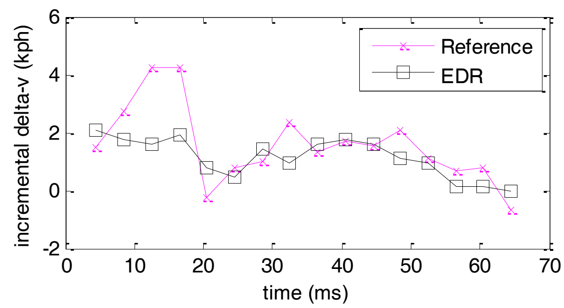
2011 Toyota Corolla (test no. 7353) time shifted 3.5 ms)



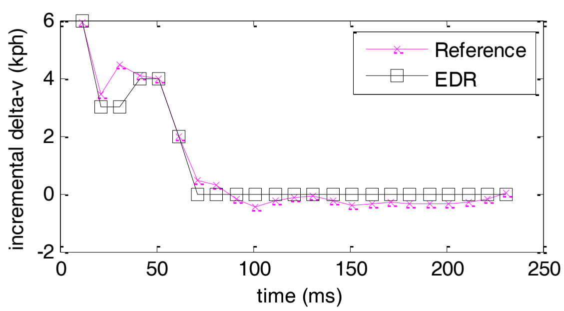
2011 Ford F150 Supercab (test no. 7355) time shifted 3 ms)



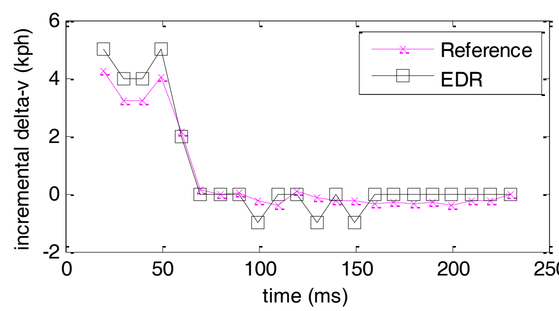
2011 Buick Lucerne (test no. 7363) time shifted 0 ms)



2011 Toyota Scion tC (test no. 7364) time shifted -3.5 ms)

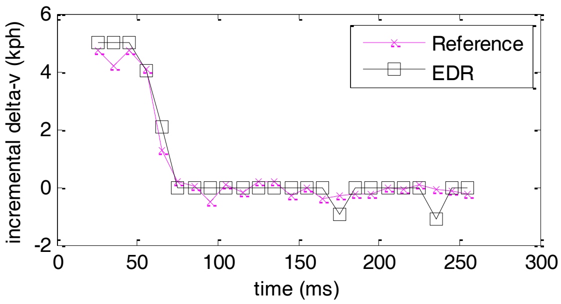


2011 Buick Lacrosse (test no. 7367) time shifted 11.4 ms)

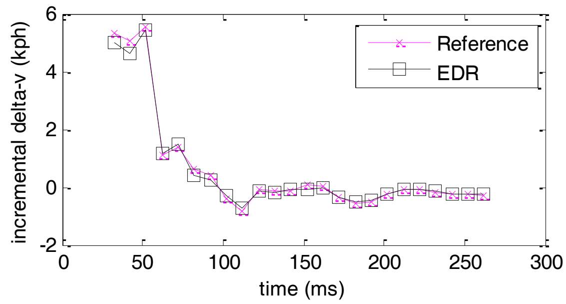


2011 Chevrolet Volt (test no. 7392) time shifted 10 ms)

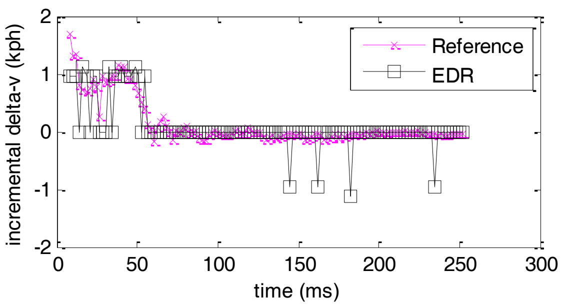
Figure A.4 (Cont'd) Overlay of EDR and reference instrumentation lateral incremental delta-v versus time after optimization in time (SINCAP crash test study)



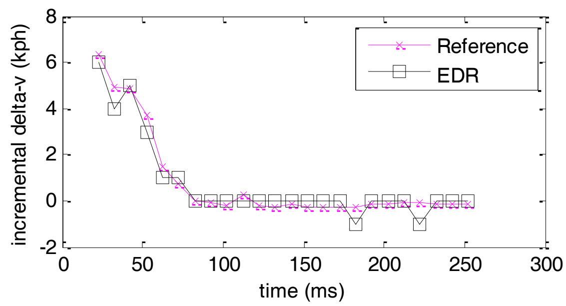
2012 Mazda Mazda3 (test no. 7448) time shifted 5.4ms



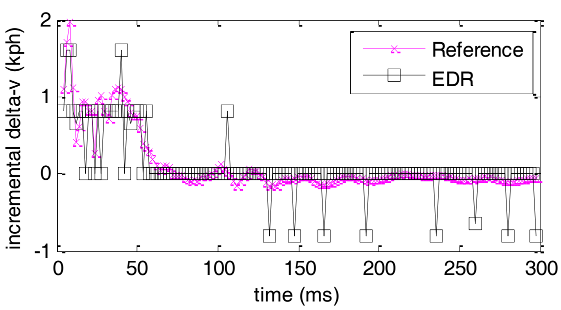
2012 Ford Mustang (test no. 7465) time shifted 4.6ms



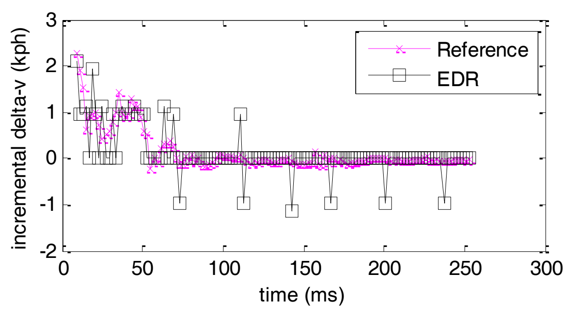
2012 Dodge Avenger (test no. 7469) time shifted 4.4ms



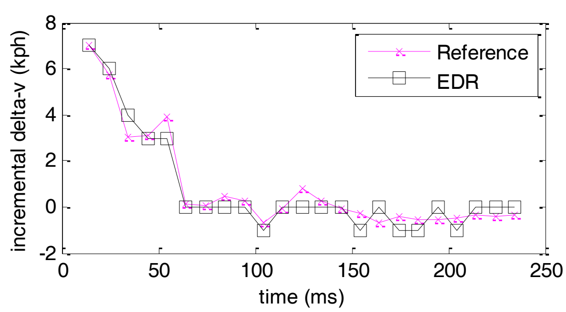
2012 Ford Focus (test no. 7470) time shifted 2.4ms



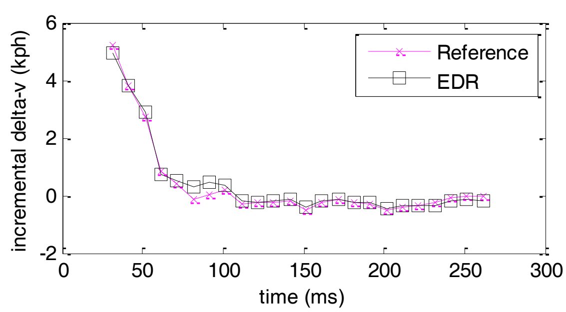
2012 Dodge Journey (test no. 7473) time shifted 0ms



2012 Chrysler 200 (test no. 7484) time shifted 5.1ms

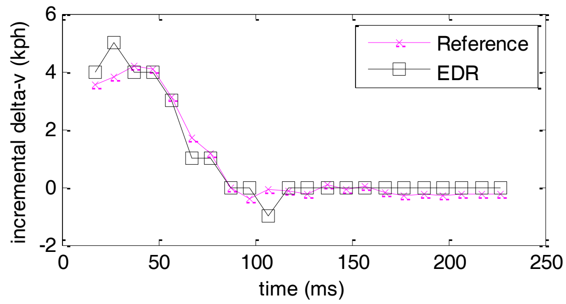


2012 Chevrolet Impala (test no. 7486) time shifted 14.4ms

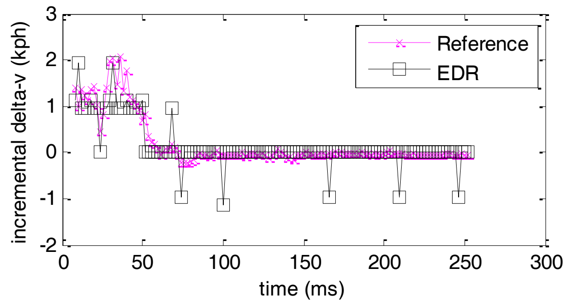


2012 Ford Explorer (test no. 7492) time shifted 5.4ms

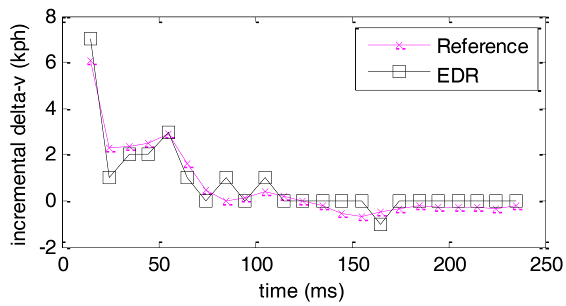
Figure A.4 (Cont'd) Overlay of EDR and reference instrumentation lateral incremental delta-v versus time after optimization in time (SINCAP crash test study)



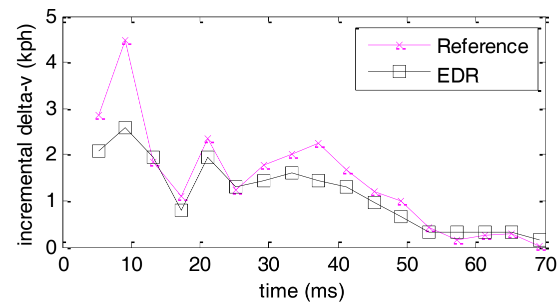
2012 Chevrolet Camaro (test no. 7493) time shifted 7.2ms



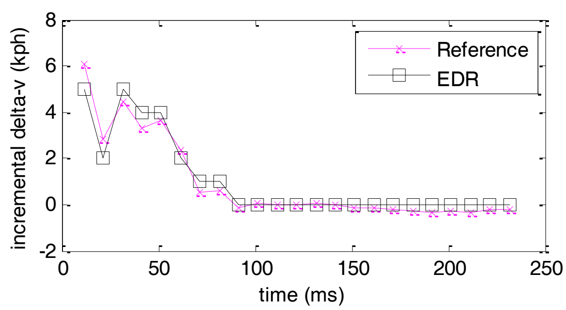
2012 Fiat 500 (test no. 7507) time shifted 3.9ms



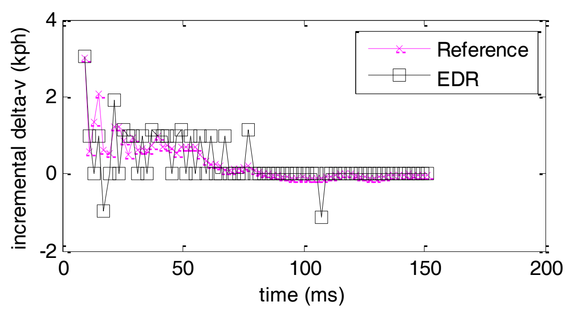
2012 Chevrolet Suburban 1500 (test no. 7510) time shifted 14.9ms



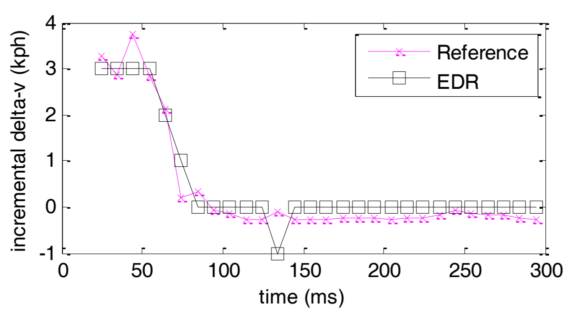
2012 Toyota Camry (test no. 7517) time shifted 0.2ms



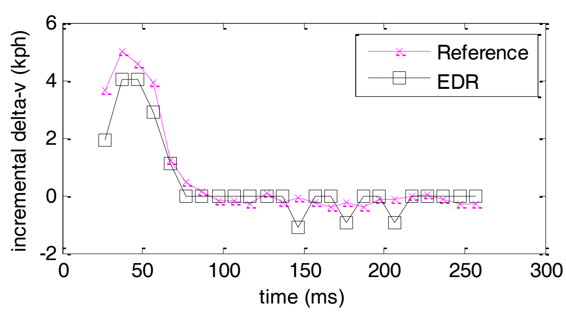
2012 Cadillac CTS (test no. 7519) time shifted 11.6ms



2012 Dodge Durango (test no. 7528) time shifted 5.4ms

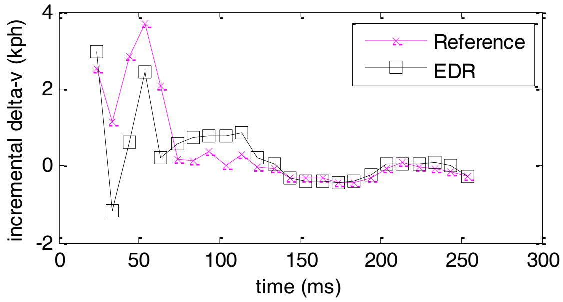


2012 Cadillac SRX (test no. 7534) time shifted 4.4ms

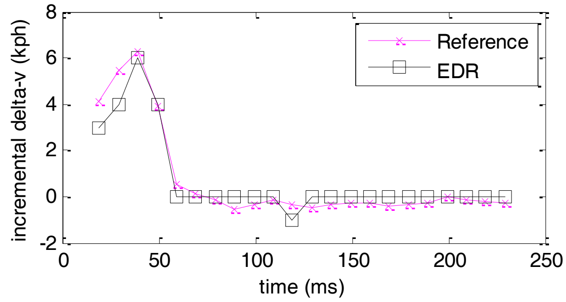


2012 Mazda Mazda6 (test no. 7537) time shifted 6.8ms

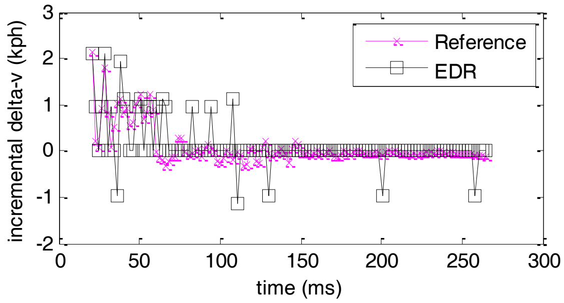
Figure A.4 (Cont'd) Overlay of EDR and reference instrumentation lateral incremental delta-v versus time after optimization in time (SINCAP crash test study)



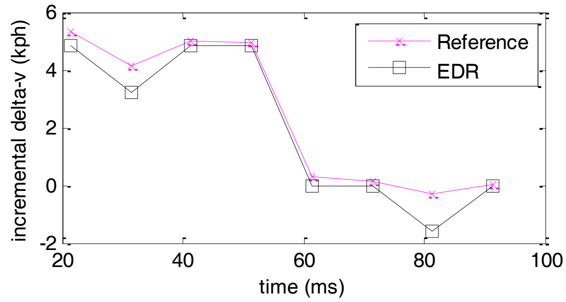
2012 Ford Expedition (test no. 7541) time shifted 2.3ms



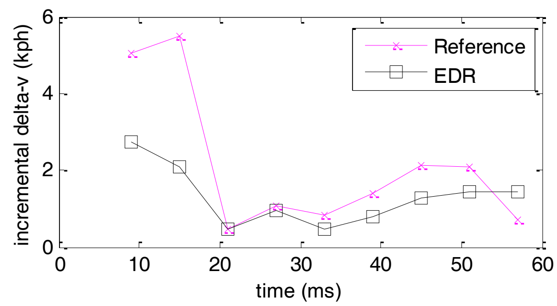
2012 Chevrolet Sonic (test no. 7563) time shifted 9.3ms



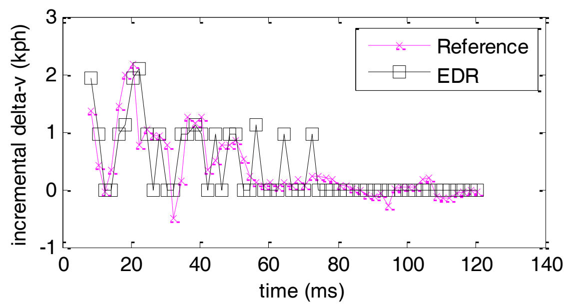
2012 Jeep Liberty (test no. 7571) time shifted 16.3 ms)



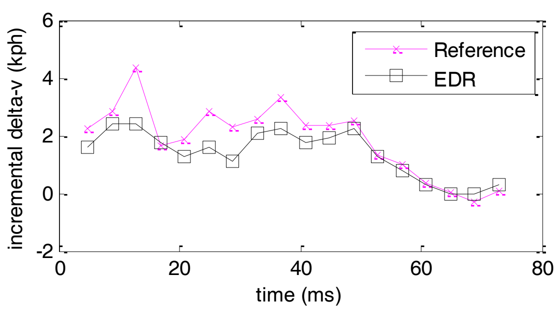
2012 Honda Fit (test no. 7576) time shifted 1.4ms



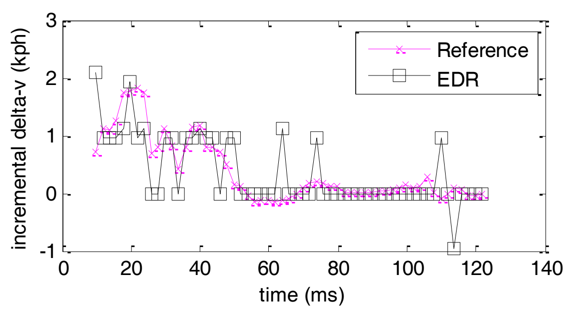
2012 Toyota Tundra (test no. 7586) time shifted 3ms



2012 Chrysler 300 (test no. 7593) time shifted 4.4ms

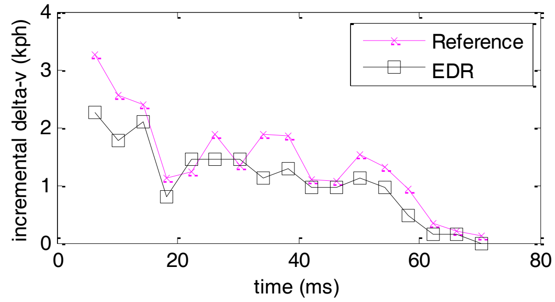


2012 Toyota Yaris (test no. 7602) time shifted 1.8ms

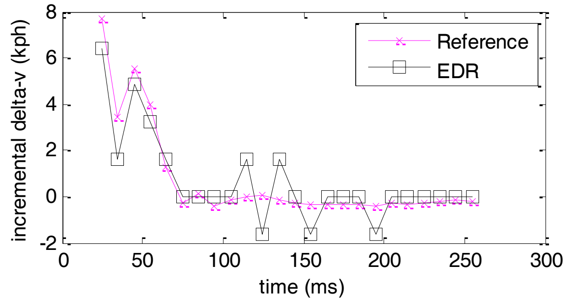


2012 Dodge Charger (test no. 7604) time shifted 5.8ms

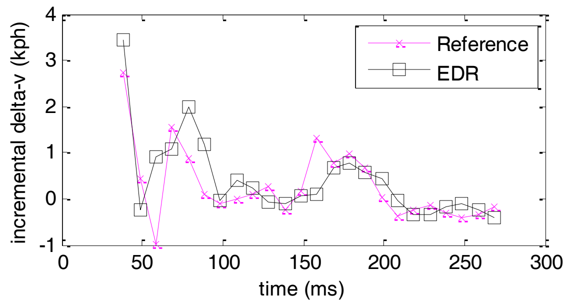
Figure A.4 (Cont'd) Overlay of EDR and reference instrumentation lateral incremental delta-v versus time after optimization in time (SINCAP crash test study)



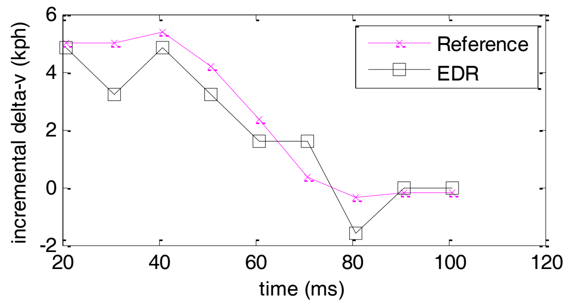
2012 Lexus ES350 (test no. 7640) time shifted 1.2ms



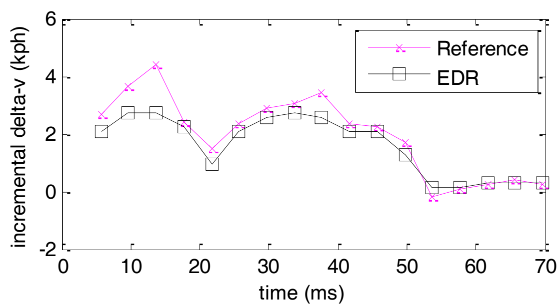
2012 Honda Civic (test no. 7648) time shifted 4.6ms



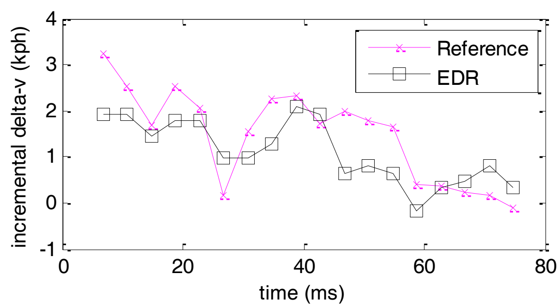
2012 Ford F250 Super Crew (test no. 7650) time shifted 15.2ms



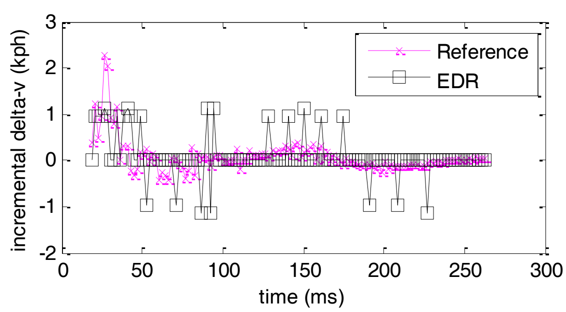
2012 Honda Civic IMA (test no. 7713) time shifted 0.9ms



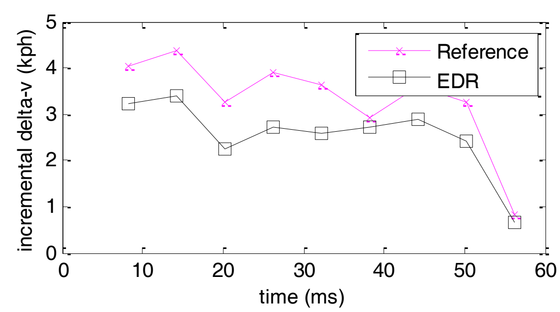
2012 Scion iQ (test no. 7733) time shifted 1.7ms



2012 Toyota RAV4 (test no. 7738) time shifted 2.8ms

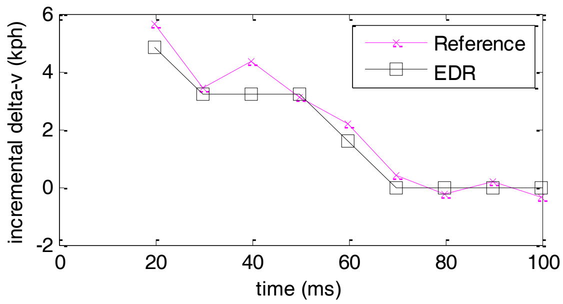


2012 Ram 2500 Crew Cab (test no. 7745) time shifted 14.7ms

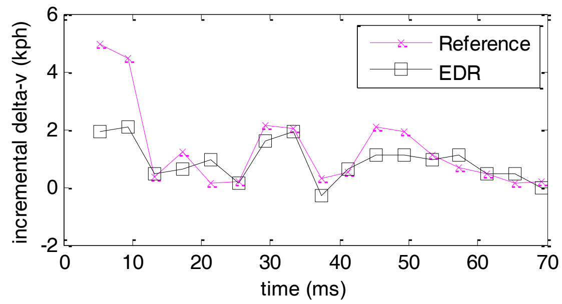


2012 Toyota Corolla (test no. 7749) time shifted 2.2ms

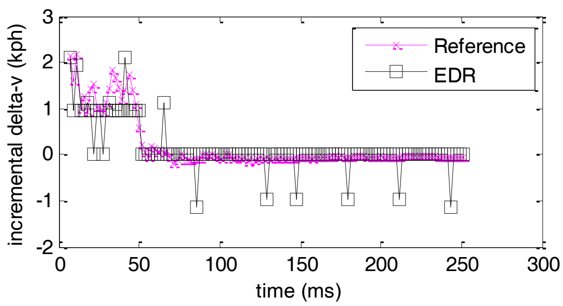
Figure A.4 (Cont'd) Overlay of EDR and reference instrumentation lateral incremental delta-v versus time after optimization in time (SINCAP crash test study)



2012 Honda CR-V (test no. 7750) time shifted 0ms



2012 Toyota 4Runner (test no. 7753) time shifted 1.3ms



2012 Fiat 500 (test no. 7768) time shifted 3.6ms

Figure A.4 (Cont'd) Overlay of EDR and reference instrumentation lateral incremental delta-v versus time after optimization in time (SINCAP crash test study)

Table A.9 Characteristics of the crash tests, EDRs, and analysis (small overlap crash test study)

Test ID	MY	Make & Model	Module Type	EDR Location	Test Type	Impact Speed (kph)	Overlap (%)	Impact Angle (°)	EDR Recording Complete	Sensors Averaged		Simplified Rotation	
												ω (rad/s)	α (rad/s²)
CEN1216	2012	Dodge Avenger	CHRY0305	Center Stack	VTB	64.3	25%	0	☑	—	—	-2.1	-37.5
CEN1321	2013	Dodge Dart	CHRY6001	Center Stack	VTB	64.13	25%	0	☑	—	—	-1.6	-42.5
CEN1322	2013	Dodge Dart	CHRY6001	Center Stack	VTB	64.31	25%	0	☑	—	—	-1.8	-16.9
CEN1325	2013	Fiat 500	CHRY0000a	Center Stack	VTB	64	25%	0	☑	—	—	-4.2	-89.9
CEN1404	2014	Jeep Grand Cherokee	†	Center Stack	VTB	64.2	25%	0	☑	—	—	-2.9	-29.9
CEN1414	2014	Fiat 500L	†	Center Stack	VTB	64.3	25%	0	☑	—	—	-3.4	-56.3
RB0330	2011	Dodge Ram1500	CHRY0403	Under center front seat or console	VTV	90	20%	353	☑	F-C	—	—	—
RC0528	2012	Fiat 500	CHRY0000	Center Stack	VTV	90	20%	353	☑	F-C	R-C	—	—
CEN1314	2013	Ford Focus	FordAB10BEV	Center Tunnel	VTB	64.3	25%	0	☑	—	—	-3.5	-57.2
CEN1326	2014	Honda Odyssey	HONDA002	Under Dashboard, Center	VTB	64.4	25%	0	☑	—	—	-2.6	-53.4
CEN1343	2014	Ford Fiesta	†	Center Tunnel	VTB	64.4	25%	0	☑	—	—	-3.6	-45.1
RA0220	2010	Ford Fusion	FordRC6_2010	Center Tunnel	VTV	90	20%	353	☑	F-C	R-C	—	—
RB0222	2011	Ford Explorer	FordRC62011CGEAD	Center Tunnel	VTV	90	20%	353	☑	F-C	R-C	—	—
RB0224	2011	Ford Fiesta	FordRC6_2011_EU	Center Tunnel	VTV	90	20%	353	☑	F-C	—	—	—
CEN1218	2013	Chevrolet Malibu	SDM10P_1	Center Tunnel	VTB	64.2	25%	0	☑	—	—	-1.1	-22.1
CEN1308	2013	Buick Encore	SDM10P_1	Center Tunnel	VTB	64.2	25%	0	☑	—	—	-3.6	-41.3
CEN1311	2013	Buick Encore	SDM10P_1	Center Tunnel	VTB	64.3	25%	0	☑	—	—	-4.3	-38.2
CEN1312	2013	Chevrolet Cruze	SDM10P_1	Center Tunnel	VTB	64.3	25%	0	☑	—	—	-1.5	-25.0
CEN1313	2013	Chevrolet Sonic	SDM10P_1	Center Tunnel	VTB	64.3	25%	0	☑	—	—	-2.6	-35.6
CEN1335	2013	Chevrolet Spark	SDM10P_1	Center Tunnel	VTB	64.2	25%	0	☑	—	—	-2.7	-39.2
CEN1401	2014	Chevrolet Equinox	SDM10P_1	Center Tunnel	VTB	64.5	25%	0	☑	—	—	-0.6	-4.3
CEN1412	2014	Chevrolet Malibu	SDM10P_1	Center Tunnel	VTB	64.4	25%	0	☑	—	—	-1.4	-23.8
RB0178	2011	Chevrolet Cruze	SDM10	Center Tunnel	VTV	91	20%	353	☑	F-C	R-C	—	—
RB0180	2011	Buick Lacrosse	SDM10	Center Tunnel	VTV	91	20%	353	☑	F-C	—	—	—
RB0182	2011	Chevrolet Cruze	SDM10	Center Tunnel	VTV	90	20%	353	☑	F-R	—	—	—
RB0183	2011	Chevrolet Cruze	SDM10	Center Tunnel	VTV	90	20%	353	☑	F-R	R-C	—	—
CEN1202	2012	Acura TSX	†	Under Dashboard, Center	VTB	64.2	25%	0	†	—	—	-1.7	-28.2
CEN1213	2012	Acura TSX	†	Under Dashboard, Center	VTB	64.2	25%	0	†	—	—	-2.3	-28.1
CEN1229	2013	Honda Accord	HONDA002	Under Dashboard, Center	VTB	64.3	25%	0	☑	—	—	-2.9	-40.8
CEN1301	2013	Honda Civic	HONDA001	Under Dashboard, Center	VTB	64.3	25%	0	☑	—	—	-3.2	-51.6
CEN1302	2013	Honda Civic	HONDA002	Under Dashboard, Center	VTB	64.32	25%	0	☑	—	—	-3.4	-43.3

(†) CDRx file not available; (‡) not Bosch CDR supported; (ω) yaw motion; (α) angular acceleration; (F) right front sill; (R) right rear sill; (T) trunk floor center; (C) vehicle center of gravity; (VTV) vehicle to vehicle, i.e. NHTSA crash test; (VTB) vehicle to barrier, i.e. IIHS crash test;

Table A.9 (Cont'd) Characteristics of the crash tests, EDRs, and analysis (small overlap crash test study)

Test ID	MY	Make & Model	Module Type	EDR Location	Test Type	Impact Speed (kph)	Overlap (%)	Impact Angle (°)	EDR Recording Complete	Sensors Averaged		Simplified Rotation	
												ω (rad/s)	α (rad/s²)
CEN1341	2014	Acura RLX	HONDA002	Under Dashboard, Center	VTB	64.2	25%	0	☑	—	—	-2.5	-48.6
CEN1405	2014	Honda Pilot	HONDA001	Under Dashboard, Center	VTB	64.2	25%	0	☑	—	—	-2.4	-16.8
CEN1237	2013	Hyundai Tucson	‡	‡	VTB	64.3	25%	0	☑	—	—	-3.7	-49.4
CEN1310	2013	Hyundai Elantra	‡	‡	VTB	64.3	25%	0	☑	—	—	-4.0	-46.5
CEN1317	2013	Kia Soul	‡	‡	VTB	64.3	25%	0	☑	—	—	-3.6	-33.7
CEN1318	2014	Kia Forte	‡	‡	VTB	64.4	25%	0	☑	—	—	-3.4	-36.7
CEN1330	2013	Kia Rio	‡	‡	VTB	64.2	25%	0	☑	—	—	-2.2	-28.8
CEN1220	2012	Mazda Mazda6	MAZDA002	Center tunnel, below instrument panel	VTB	64.3	25%	0	☑	—	—	-1.3	-49.8
CEN1306	2013	Mazda CX5	MAZDA002	Center Tunnel Aft of Shifter	VTB	64.1	25%	0	☑	—	—	-3.4	-36.1
CEN1324	2013	Mazda Mazda2	MAZDA002	Center Tunnel Aft of Shifter	VTB	64.6	25%	0	☑	—	—	-2.6	-27.8
CEN1345	2014	Mazda CX-5	†	Center Tunnel Aft of Shifter	VTB	64.3	25%	0	☑	—	—	-2.7	-39.2
CEN1346	2014	Mazda Mazda3	†	Center Tunnel Aft of Shifter	VTB	64.4	25%	0	☑	—	—	-3.5	-50.0
CEN1408	2014	Mazda CX-9	†	Center tunnel, below instrument panel	VTB	64.3	25%	0	☐	—	—	-1.8	-28.0
CEN1424	2014	Mazda Mazda5	MAZDA001	Center tunnel, below instrument panel	VTB	64.3	25%	0	☑	—	—	-3.2	-37.9
CEN1334	2014	Nissan Versa	NISSAN02	Center Tunnel, Between Front Seats	VTB	64.3	25%	0	☑	—	—	-2.0	-25.3
CEN1407	2014	Nissan Rogue	†	Under the front row passenger seat	VTB	64.4	25%	0	☑	—	—	-1.2	-24.3
CEN1416	2014	Nissan Juke	NISSAN02B	Center Tunnel, Between Front Seats	VTB	64.5	25%	0	☑	—	—	-2.5	-33.2
CEN1215	2012	Toyota Camry	TOYOTA001	Under Center Stack	VTB	64.3	25%	0	☑	—	—	-2.4	-52.3
CEN1319	2013	Toyota RAV4	TOYOTA001	Under Center Console	VTB	64.3	25%	0	☑	—	—	-2.7	-39.8
CEN1320	2014	Scion tC	TOYOTA001	Under Center Stack	VTB	64.3	25%	0	☑	—	—	-2.3	-16.4
CEN1328	2013	Toyota Prius C	TOYOTA001	Under Center Stack	VTB	64.2	25%	0	☑	—	—	-3.4	-56.4
CEN1331	2013	Toyota Yaris	TOYOTA001	Under Center Stack	VTB	64.2	25%	0	☑	—	—	-4.1	-58.2
CEN1332	2014	Toyota Corolla	TOYOTA001	Under Center Stack	VTB	64.4	25%	0	☑	—	—	-3.2	-46.1
CEN1347	2014	Toyota Prius	TOYOTA001	Under Center Stack	VTB	64.5	25%	0	☑	—	—	-1.7	-15.3
CEN1349	2014	Toyota Camry	TOYOTA001	Under Center Stack	VTB	64.4	25%	0	☑	—	—	-2.2	-32.0
RA5135	2010	Toyota Yaris	TOYOTA001	Under Center Stack	VTV	87	20%	353	☑	F-C	R-C	—	—
RB5137	2010	Toyota Yaris	TOYOTA001	Under Center Stack	VTV	90	20%	353	☑	F-C	R-C	—	—
CEN1304	2013	Volvo XC60	VOLVO001	Center Tunnel, Under Console	VTB	64.28	25%	0	☑	—	—	-1.1	-13.4
CEN1344	2014	Volvo S80	†	Center Tunnel, Under Console	VTB	64.2	25%	0	☑	—	—	-0.7	-17.8

(†) CDRx file not available; (‡) not Bosch CDR supported; (ω) yaw motion; (α) angular acceleration; (F) right front sill; (R) right rear sill; (T) trunk floor center; (C) vehicle center of gravity; (VTV) vehicle to vehicle, i.e. NHTSA crash test; (VTB) vehicle to barrier, i.e. IIHS crash test;

Table A.10 Comparison of EDR and crash test precrash speed (small overlap crash test study)

Test ID	Make & Model	EDR	TEST	ERR	ABS	% ERR	% ABS
CEN1216	Dodge Avenger	65	64.3	0.7	0.70	1.1%	1.1%
CEN1321	Dodge Dart	64	64.1	-0.1	0.13	-0.2%	0.2%
CEN1322	Dodge Dart	65	64.3	0.7	0.69	1.1%	1.1%
CEN1325	Fiat 500	64	64.0	0.0	0.00	0.0%	0.0%
CEN1404	Jeep Grand Cherokee	65	64.2	0.8	0.80	1.2%	1.2%
CEN1414	Fiat 500L	64	64.3	-0.3	0.30	-0.5%	0.5%
RB0330	Dodge Ram1500	—	—	—	—	—	—
RC0528	Fiat 500	—	—	—	—	—	—
CEN1314	Ford Focus	63.8	64.3	-0.5	0.50	-0.8%	0.8%
CEN1326	Honda Odyssey	65	64.4	0.6	0.60	0.9%	0.9%
CEN1343	Ford Fiesta	64	64.4	-0.4	0.40	-0.6%	0.6%
RA0220	Ford Fusion	—	—	—	—	—	—
RB0222	Ford Explorer	—	—	—	—	—	—
RB0224	Ford Fiesta	—	—	—	—	—	—
CEN1218	Chevrolet Malibu	64	64.2	-0.2	0.20	-0.3%	0.3%
CEN1308	Buick Encore	64	64.2	-0.2	0.20	-0.3%	0.3%
CEN1311	Buick Encore	64	64.3	-0.3	0.30	-0.5%	0.5%
CEN1312	Chevrolet Cruze	64	64.3	-0.3	0.30	-0.5%	0.5%
CEN1313	Chevrolet Sonic	65	64.3	0.7	0.70	1.1%	1.1%
CEN1335	Chevrolet Spark	64	64.2	-0.2	0.20	-0.3%	0.3%
CEN1401	Chevrolet Equinox	64	64.5	-0.5	0.50	-0.8%	0.8%
CEN1412	Chevrolet Malibu	64	64.4	-0.4	0.40	-0.6%	0.6%
RB0178	Chevrolet Cruze	—	—	—	—	—	—
RB0180	Buick Lacrosse	—	—	—	—	—	—
RB0182	Chevrolet Cruze	—	—	—	—	—	—
RB0183	Chevrolet Cruze	—	—	—	—	—	—
CEN1202	Acura TSX	—	—	—	—	—	—
CEN1213	Acura TSX	—	—	—	—	—	—
CEN1229	Honda Accord	64	64.3	-0.3	0.30	-0.5%	0.5%
CEN1301	Honda Civic	64	64.3	-0.3	0.30	-0.5%	0.5%
CEN1302	Honda Civic	64	64.3	-0.3	0.31	-0.5%	0.5%
CEN1341	Acura RLX	64	64.2	-0.2	0.20	-0.3%	0.3%
CEN1405	Honda Pilot	64	64.2	-0.2	0.20	-0.3%	0.3%
CEN1237	Hyundai Tucson	63	64.3	-1.3	1.30	-2.0%	2.0%
CEN1310	Hyundai Elantra	63	64.3	-1.3	1.30	-2.0%	2.0%
CEN1317	Kia Soul	61	64.3	-3.3	3.30	-5.1%	5.1%
CEN1318	Kia Forte	62	64.4	-2.4	2.40	-3.7%	3.7%
CEN1330	Kia Rio	65	64.2	0.8	0.80	1.2%	1.2%

Table A.10 (Cont'd) Comparison of EDR and crash test precrash speed (small overlap crash test study)

Test ID	Make & Model	EDR	TEST	ERR	ABS	% ERR	% ABS
CEN1220	Mazda Mazda6	63	64.3	-1.3	1.30	-2.0%	2.0%
CEN1306	Mazda CX5	63	64.1	-1.1	1.10	-1.7%	1.7%
CEN1324	Mazda Mazda2	64	64.6	-0.6	0.60	-0.9%	0.9%
CEN1345	Mazda CX-5	64	64.3	-0.3	0.30	-0.5%	0.5%
CEN1346	Mazda Mazda3	64	64.4	-0.4	0.40	-0.6%	0.6%
CEN1408	Mazda CX-9	63	64.3	-1.3	1.30	-2.0%	2.0%
CEN1424	Mazda Mazda5	63	64.3	-1.3	1.30	-2.0%	2.0%
CEN1334	Nissan Versa	63	64.3	-1.3	1.30	-2.0%	2.0%
CEN1407	Nissan Rogue	64	64.4	-0.4	0.40	-0.6%	0.6%
CEN1416	Nissan Juke	64	64.5	-0.5	0.50	-0.8%	0.8%
CEN1215	Toyota Camry	62	64.3	-2.3	2.30	-3.6%	3.6%
CEN1319	Toyota RAV4	64	64.3	-0.3	0.30	-0.5%	0.5%
CEN1320	Scion tC	63	64.3	-1.3	1.30	-2.0%	2.0%
CEN1328	Toyota Prius C	64	64.2	-0.2	0.20	-0.3%	0.3%
CEN1331	Toyota Yaris	63	64.2	-1.2	1.20	-1.9%	1.9%
CEN1332	Toyota Corolla	64	64.4	-0.4	0.40	-0.6%	0.6%
CEN1347	Toyota Prius	64	64.5	-0.5	0.50	-0.8%	0.8%
CEN1349	Toyota Camry	62	64.4	-2.4	2.40	-3.7%	3.7%
RA5135	Toyota Yaris	—	—	—	—	—	—
RB5137	Toyota Yaris	—	—	—	—	—	—
CEN1304	Volvo XC60	63	64.3	-1.3	1.28	-2.0%	2.0%
CEN1344	Volvo S80	63	64.2	-1.2	1.20	-1.9%	1.9%

Table A.11 Comparison of EDR and crash test airbag and seat belt status (small overlap crash test study)

Test ID	Make & Model	Seatbelt Buckle Status				Airbag Deployment					
		Driver		Front Passenger		Front (Driver)		Side/Torso		Curtain	
		EDR	ref	EDR	ref	EDR (ms)	ref	EDR (ms)	ref	EDR (ms)	ref
CEN1216	Dodge Avenger	NC	☑	NC	☐	☑	☑	☑	☑	☑	☑
CEN1321	Dodge Dart	☑	☑	☐	☐	☑ 40	☑	☑	☑	☑	☑
CEN1322	Dodge Dart	☑	☑	☐	☐	☑ 39	☑	☑	☑	☑	☑
CEN1325	Fiat 500	☑	☑	☐	☐	☑ 29	☑	☑	☑	☑	☑
CEN1404	Jeep Grand Cherokee	☑	☑	☐	☐	☑ 22	☑	☑	☑	☑	☑
CEN1414	Fiat 500L	☑	☑	☐	☐	☑ 34	☑	☑	☑	☑	☑
RB0330	Dodge Ram1500	☑	☑	NC	☐	☑ 0	☑	NE	NE	☐	☐
RC0528	Fiat 500	☑	☑	☐	☐	☑ 15	☑	☑	☑	☑	☑
CEN1314	Ford Focus	☑	☑	☐	☐	☑ 40.5	☑	☑ 66.5	☑	☑ 41.0	☑
CEN1326	Honda Odyssey	☑	☑	☐	☐	☑ 16	☑	☑ 15	☑	☑ 15	☑
CEN1343	Ford Fiesta	☑	☑	☐	☐	☑ 56.5	☑	☐	☐	☑ 56.5	☑
RA0220	Ford Fusion	☑	☑	☐	☐	☑ 27.5	☑	☑ 30.5	☑	☑ 30.5	☑
RB0222	Ford Explorer	☑	☑	☐	☐	☑ 28.5	☑	☑ 33.0	☑	☑ 33.0	☑
RB0224	Ford Fiesta	☑	☑	☐	☐	☑ 25.5	☑	☑ 73.0	☑	☑ 73.0	☑
CEN1218	Chevrolet Malibu	☑	☑	☐	☐	☑ 13	☑	NE	NE	☑ 49	☑
CEN1308	Buick Encore	☑	☑	☐	☐	☑ 32	☑	☑ 19	☑	☑ 19	☑
CEN1311	Buick Encore	☑	☑	☐	☐	☑ 30	☑	☐	☐	☑ 110	☑
CEN1312	Chevrolet Cruze	☑	☑	☐	☐	☑ 21	☑	☑ 63	☑	☑ 63	☑
CEN1313	Chevrolet Sonic	☑	☑	☐	☐	☑ 46	☑	☐	☐	☑ 166	☑
CEN1335	Chevrolet Spark	☑	☑	☐	☐	☑ 15	☑	☐	☐	☑ 16	☑
CEN1401	Chevrolet Equinox	☑	☑	☐	☐	☑ 33	☑	☐	☐	☑ 36	☑
CEN1412	Chevrolet Malibu	☑	☑	☐	☐	☑ 11	☑	☐	☐	☑ 11	☑
RB0178	Chevrolet Cruze	☑	☑	☐	☐	☑ 27	☑	☑ 39	☑	☑ 39	☑
RB0180	Buick Lacrosse	☑	☑	☐	☐	☑ 21	☑	☐	☐	☑ 30	☑
RB0182	Chevrolet Cruze	☑	☑	☐	☐	☑ 30	☑	☐	☐	☑ 153	☑
RB0183	Chevrolet Cruze	☑	☑	☐	☐	☑ 30	☑	☑ 139	☑	☑ 139	☑
CEN1202	Acura TSX	†	☑	☐	☐	†	☑	†	☑	†	☑
CEN1213	Acura TSX	†	☑	☐	☐	†	☑	†	☑	†	☑
CEN1229	Honda Accord	☑	☑	☐	☐	☑ 39	☑	☑ 37	☑	☑ 37	☑
CEN1301	Honda Civic	☑	☑	☐	☐	☑ 16	☑	☑ 25	☑	☑ 25	☑
CEN1302	Honda Civic	☑	☑	☐	☐	☑ 13	☑	☑ 41	☑	☑ 41	☑

(†) CDRx file not available; (NC) not configured; (NE) not equipped; (NR) not reported; (SNA) signal not available; (Dis) disabled;

Table A.11 (Cont'd) Comparison of EDR and crash test airbag and seat belt status (small overlap crash test study)

Test ID	Make & Model	Seatbelt Buckle Status				Airbag Deployment					
		Driver		Front Passenger		Front (Driver)		Side/Torso		Curtain	
		EDR	ref	EDR	ref	EDR (ms)	ref	EDR (ms)	ref	EDR (ms)	ref
CEN1341	Acura RLX	☑	☑	☐	☐	☑ 37	☑	☑ 23	☑	☑ 23	☑
CEN1405	Honda Pilot	☑	☑	☐	☐	☑ 3	☑	☑ 51	☑	☑ 51	☑
CEN1237	Hyundai Tucson	☑	☑	☐	☐	☑ 32	☑	☐	☐	☐	☐
CEN1310	Hyundai Elantra	☑	☑	☐	☐	☑ 6	☑	☑ 34	☑	☑ 34	☑
CEN1317	Kia Soul	☑	☑	☐	☐	☑ 16	☑	☐	☐	☐	☐
CEN1318	Kia Forte	☑	☑	☐	☐	☑ 6	☑	☑ 38	☑	☑ 12	☑
CEN1330	Kia Rio	☑	☑	☐	☐	☑ 4	☑	☑ 34	☑	☑ 34	☑
CEN1220	Mazda Mazda6	☑	☑	☐	☐	☑ 43	☑	SNA	☐	SNA	☐
CEN1306	Mazda CX5	☑	☑	☐	☐	☑ 1	☑	SNA	☐	☑ 98	☑
CEN1324	Mazda Mazda2	☑	☑	☐	☐	☑ 48	☑	☑ 34	☑	☑ 34	☑
CEN1345	Mazda CX-5	☑	☑	☐	☐	☑ 31	☑	☑ 34	☑	☑ 34	☑
CEN1346	Mazda Mazda3	☑	☑	☐	☐	☑ 29	☑	☑ 34	☑	☑ 34	☑
CEN1408	Mazda CX-9	☑	☑	NR	☐	☑ 27	☑	☐	☐	☐	☐
CEN1424	Mazda Mazda5	☑	☑	☐	☐	☑ 35	☑	☐	☐	☐	☐
CEN1334	Nissan Versa	☑	☑	☐	☐	☑ 14	☑	☑ 63	☑	☑ 63	☑
CEN1407	Nissan Rogue	☑	☑	☐	☐	☑ 12	☑	☑ 14	☑	☑ 14	☑
CEN1416	Nissan Juke	☑	☑	☐	☐	☑ 2	☑	☑ 19	☑	☑ 19	☑
CEN1215	Toyota Camry	☑	☑	☐	☐	☑ 25	☑	NR	☑	NR	☑
CEN1319	Toyota RAV4	☑	☑	☐	☐	☑ 1	☑	☑ 71	☑	☑ 71	☑
CEN1320	Scion tC	☑	☑	☐	☐	☑ 1	☑	☑ 66	☑	☑ 1	☑
CEN1328	Toyota Prius C	☑	☑	☐	☐	☑ 27	☑	☑ 51	☑	☑ 77	☑
CEN1331	Toyota Yaris	☑	☑	☐	☐	☑ 6	☑	☐	☐	SNA	☐
CEN1332	Toyota Corolla	☑	☑	☐	☐	☑ 16	☑	☑ 16	☑	☑ 16	☑
CEN1347	Toyota Prius	☑	☑	☐	☐	☑ 0	☑	SNA	☐	☑ 0	☑
CEN1349	Toyota Camry	☑	☑	☐	☐	☑ 1	☑	SNA	☐	☑ 1	☑
RA5135	Toyota Yaris	☑	☑	☐	☐	☑ 8	☑	NE	NE	☐	Dis
RB5137	Toyota Yaris	☑	☑	☐	☐	☑ 6	☑	NE	NE	☐	☐
CEN1304	Volvo XC60	☑	☑	☐	☐	☑ 3	☑	☑ 33	☑	☑ 4	☑
CEN1344	Volvo S80	☑	☑	☐	☐	☑ 3	☑	☑ 25	☑	☑ 3	☑

(†) CDRx file not available; (NC) not configured; (NE) not equipped; (NR) not reported; (SNA) signal not available; (Dis) disabled;

Table A.12 Comparison of EDR and crash test maximum delta-v (small overlap crash test study)

Test ID	Make & Model	Longitudinal Maximum Delta-V (kph)				Lateral Maximum Delta-V (kph)			
		EDR	TEST	ERR	% ERR	EDR	TEST	ERR	% ERR
CEN1216	Dodge Avenger	51	52.0	-1.0	-2.0%	13	17.4	-4.4	-25.3%
CEN1321	Dodge Dart	41	36.1	4.9	13.7%	14	21.7	-7.7	-35.4%
CEN1322	Dodge Dart	42	43.4	-1.4	-3.1%	13	17.7	-4.7	-26.7%
CEN1325	Fiat 500	59	47.5	11.5	24.2%	11	16.0	-5.0	-31.1%
CEN1404	Jeep Grand Cherokee	55	55.9	-0.9	-1.6%	15	13.3	1.7	12.6%
CEN1414	Fiat 500L	51	50.1	0.9	1.8%	10	15.5	-5.5	-35.6%
RB0330	Dodge Ram1500	41.8	43.3	-1.5	-3.4%	15	18.4	-3.3	-17.7%
RC0528	Fiat 500	52.8	52.1	0.6	1.2%	15	18.6	-3.6	-19.6%
CEN1314	Ford Focus	58	48.9	9.1	18.7%	13	21.0	-8.0	-38.0%
CEN1326	Honda Odyssey	63	54.9	8.1	14.7%	13	14.4	-1.4	-9.9%
CEN1343	Ford Fiesta	55.6	50.8	4.8	9.4%	17	16.0	0.5	3.2%
RA0220	Ford Fusion	45.3	47.6	-2.3	-4.8%	18	22.2	-4.0	-17.8%
RB0222	Ford Explorer	40.6	41.6	-1.0	-2.5%	17	18.8	-1.7	-9.1%
RB0224	Ford Fiesta	51.7	52.5	-0.8	-1.6%	18	21.2	-2.7	-12.9%
CEN1218	Chevrolet Malibu	39	40.6	-1.6	-4.0%	14	17.4	-3.4	-19.6%
CEN1308	Buick Encore	50	51.5	-1.5	-2.9%	10	15.2	-5.2	-34.0%
CEN1311	Buick Encore	55	55.6	-0.6	-1.2%	10	17.6	-7.6	-43.2%
CEN1312	Chevrolet Cruze	44	45.4	-1.4	-3.0%	16	15.8	0.2	1.1%
CEN1313	Chevrolet Sonic	47	51.3	-4.3	-8.4%	13	19.2	-6.2	-32.4%
CEN1335	Chevrolet Spark	43	41.4	1.6	3.8%	19	19.0	0.0	-0.2%
CEN1401	Chevrolet Equinox	38	33.5	4.5	13.5%	19	16.6	2.4	14.3%
CEN1412	Chevrolet Malibu	46	48.8	-2.8	-5.6%	17	18.8	-1.8	-9.7%
RB0178	Chevrolet Cruze	46	49.3	-3.3	-6.7%	17	21.0	-4.0	-19.1%
RB0180	Buick Lacrosse	46	47.4	-1.4	-3.1%	15	19.7	-4.7	-24.0%
RB0182	Chevrolet Cruze	46	49.1	-3.1	-6.3%	15	16.5	-1.5	-9.1%
RB0183	Chevrolet Cruze	46	51.8	-5.8	-11.1%	16	13.1	2.9	22.1%
CEN1202	Acura TSX	51.5	51.3	0.2	0.5%	11	18.6	-7.3	-39.3%
CEN1213	Acura TSX	53.1	51.6	1.5	2.9%	13	21.6	-8.7	-40.4%
CEN1229	Honda Accord	58	56.8	1.2	2.1%	10	15.4	-5.4	-35.2%
CEN1301	Honda Civic	62	61.6	0.4	0.6%	11	14.5	-3.5	-24.4%
CEN1302	Honda Civic	62	63.0	-1.0	-1.6%	12	16.0	-4.0	-25.2%
CEN1341	Acura RLX	55	56.8	-1.8	-3.2%	10	19.2	-9.2	-48.0%
CEN1405	Honda Pilot	32	48.9	-16.9	-34.6%	—	—	—	—
CEN1237	Hyundai Tucson	59	56.9	2.1	3.8%	7	16.5	-9.5	-57.7%
CEN1310	Hyundai Elantra	62	57.8	4.2	7.2%	10	14.9	-4.9	-33.1%
CEN1317	Kia Soul	45	41.0	4.0	9.6%	16	15.9	0.1	0.6%
CEN1318	Kia Forte	55	48.5	6.5	13.4%	9	14.8	-5.8	-39.1%
CEN1330	Kia Rio	52	48.6	3.4	7.0%	12	14.6	-2.6	-17.8%

Table A.12 (Cont'd) Comparison of EDR and crash test maximum delta-v (small overlap crash test study)

Test ID	Make & Model	Longitudinal Maximum Delta-V (kph)				Lateral Maximum Delta-V (kph)			
		EDR	TEST	ERR	% ERR	EDR	TEST	ERR	% ERR
CEN1220	Mazda Mazda6	45	41.7	3.3	7.9%	14	16.6	-2.6	-15.5%
CEN1306	Mazda CX5	54	53.7	0.3	0.6%	13	13.5	-0.5	-4.0%
CEN1324	Mazda Mazda2	48	42.3	5.7	13.5%	20	16.2	3.8	23.2%
CEN1345	Mazda CX-5	58	58.2	-0.2	-0.3%	12	18.7	-6.7	-35.8%
CEN1346	Mazda Mazda3	55	56.5	-1.5	-2.7%	17	15.5	1.5	9.4%
CEN1408	Mazda CX-9	41	38.9	2.1	5.5%	12	16.7	-4.7	-28.3%
CEN1424	Mazda Mazda5	57	56.4	0.6	1.1%	13	14.5	-1.5	-10.1%
CEN1334	Nissan Versa	49	43.6	5.4	12.4%	17	17.4	-0.4	-2.5%
CEN1407	Nissan Rogue	46	46.3	-0.3	-0.7%	19	19.6	-0.6	-3.1%
CEN1416	Nissan Juke	40	41.5	-1.5	-3.7%	16	16.6	-0.6	-3.7%
CEN1215	Toyota Camry	51.4	50.9	0.5	0.9%	—	—	—	—
CEN1319	Toyota RAV4	49.1	45.7	3.4	7.5%	—	—	—	—
CEN1320	Scion tC	45.8	40.8	5.0	12.1%	—	—	—	—
CEN1328	Toyota Prius C	53.5	51.0	2.5	4.9%	—	—	—	—
CEN1331	Toyota Yaris	56.5	55.0	1.5	2.7%	—	—	—	—
CEN1332	Toyota Corolla	57.6	56.9	0.7	1.2%	—	—	—	—
CEN1347	Toyota Prius	48.3	48.5	-0.2	-0.4%	—	—	—	—
CEN1349	Toyota Camry	53.5	47.3	6.2	13.0%	—	—	—	—
RA5135	Toyota Yaris	49.7	50.4	-0.7	-1.4%	8	16.7	-8.8	-52.7%
RB5137	Toyota Yaris	50.7	51.6	-0.9	-1.7%	19	18.3	0.6	3.1%
CEN1304	Volvo XC60	42	42.3	-0.3	-0.7%	—	—	—	—
CEN1344	Volvo S80	43	43.5	-0.5	-1.1%	—	—	—	—

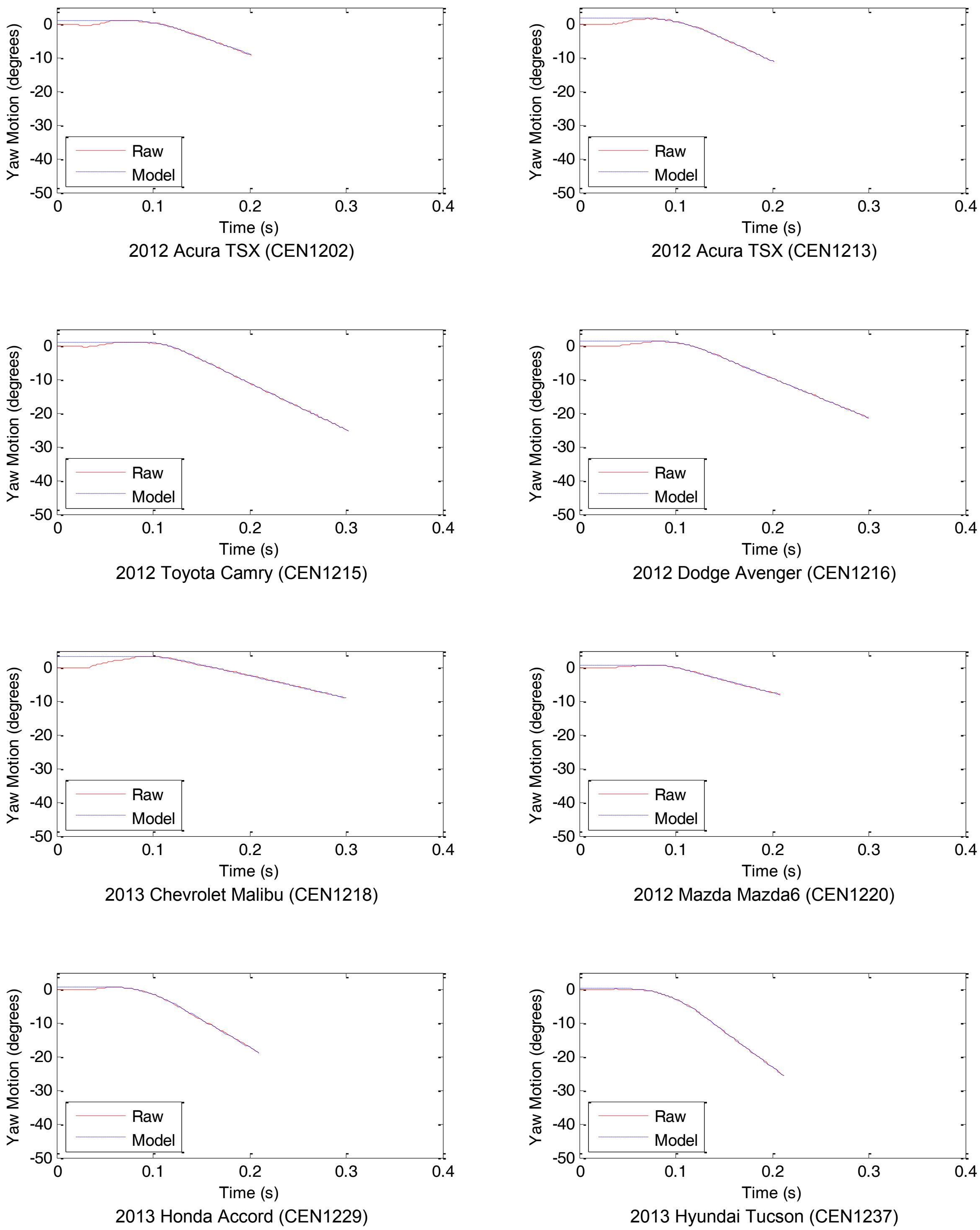
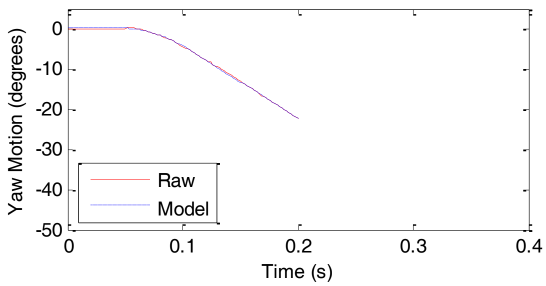
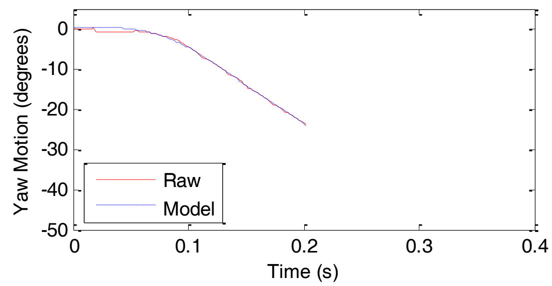


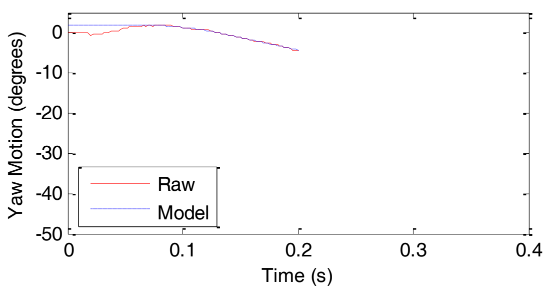
Figure A.5 Comparison of the raw TEMA yaw motion to the simplified rotation model used for the small overlap crash test study



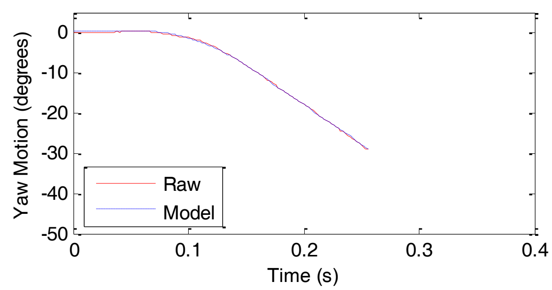
2013 Honda Civic (CEN1301)



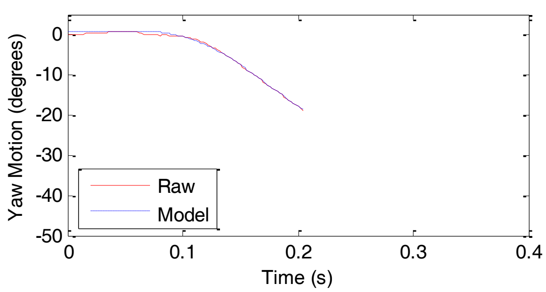
2013 Honda Civic (CEN1302)



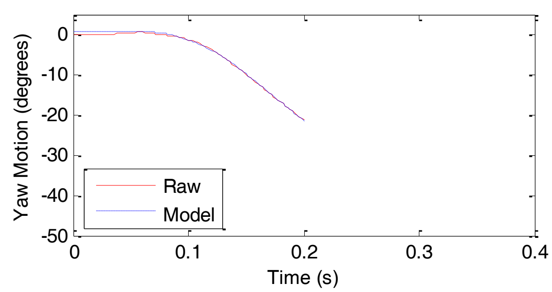
2013 Volvo XC60 (CEN1304)



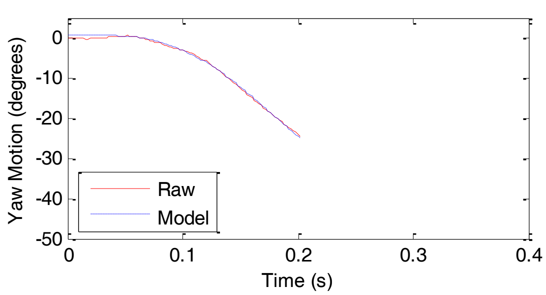
2013 Mazda CX5 (CEN1306)



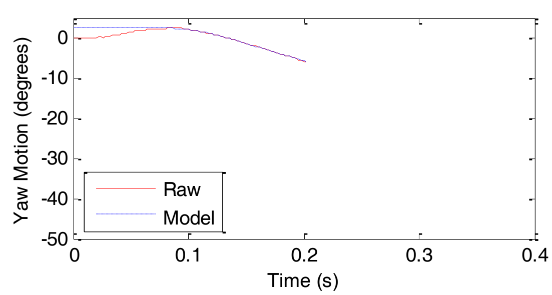
2013 Buick Encore (CEN1308)



2013 Hyundai Elantra (CEN1310)

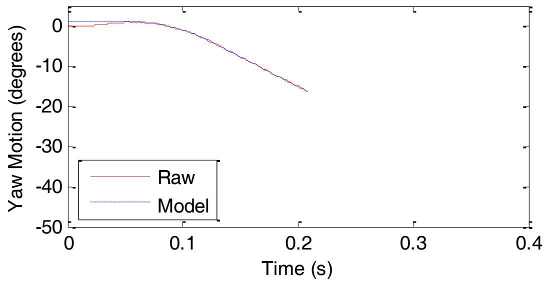


2013 Buick Encore (CEN1311)

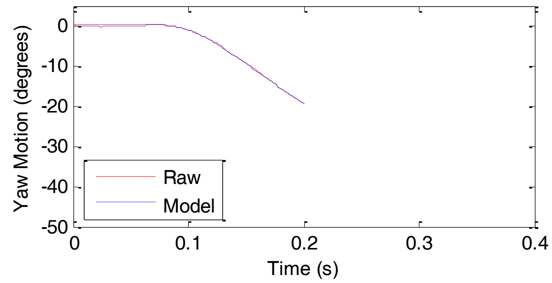


2013 Chevrolet Cruze (CEN1312)

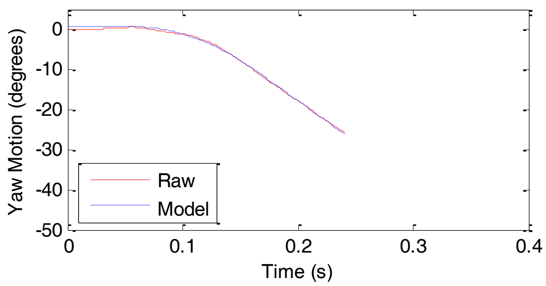
Figure A.5 (Cont'd) Comparison of the raw TEMA yaw motion to the simplified rotation model used for the small overlap crash test study



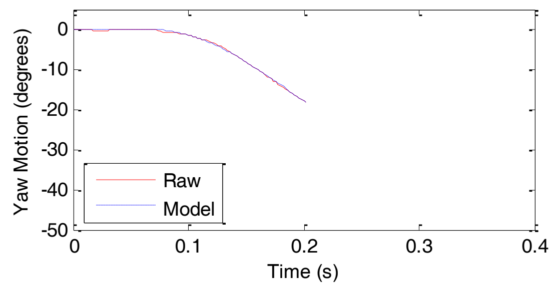
2013 Chevrolet Sonic (CEN1313)



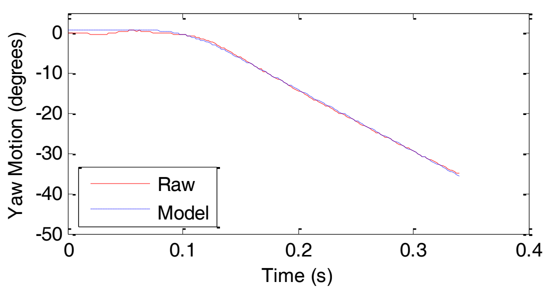
2013 Ford Focus (CEN1314)



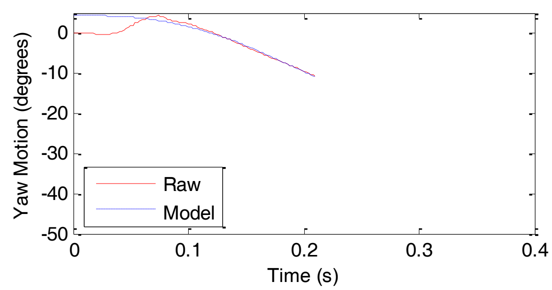
2013 Kia Soul (CEN1317)



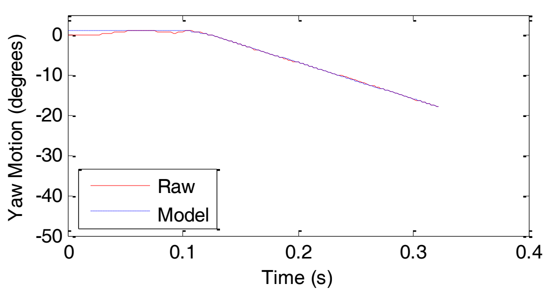
2014 Kia Forte (CEN1318)



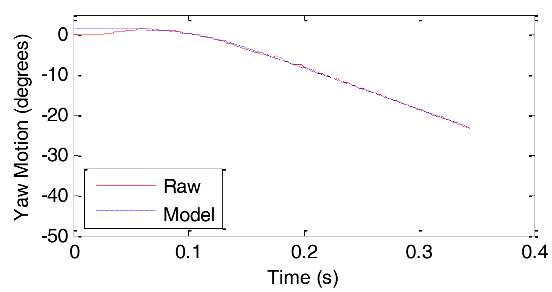
2013 Toyota RAV4 (CEN1319)



2014 Scion tC (CEN1320)



2013 Dodge Dart (CEN1321)



2013 Dodge Dart (CEN1322)

Figure A.5 (Cont'd) Comparison of the raw TEMA yaw motion to the simplified rotation model used for the small overlap crash test study

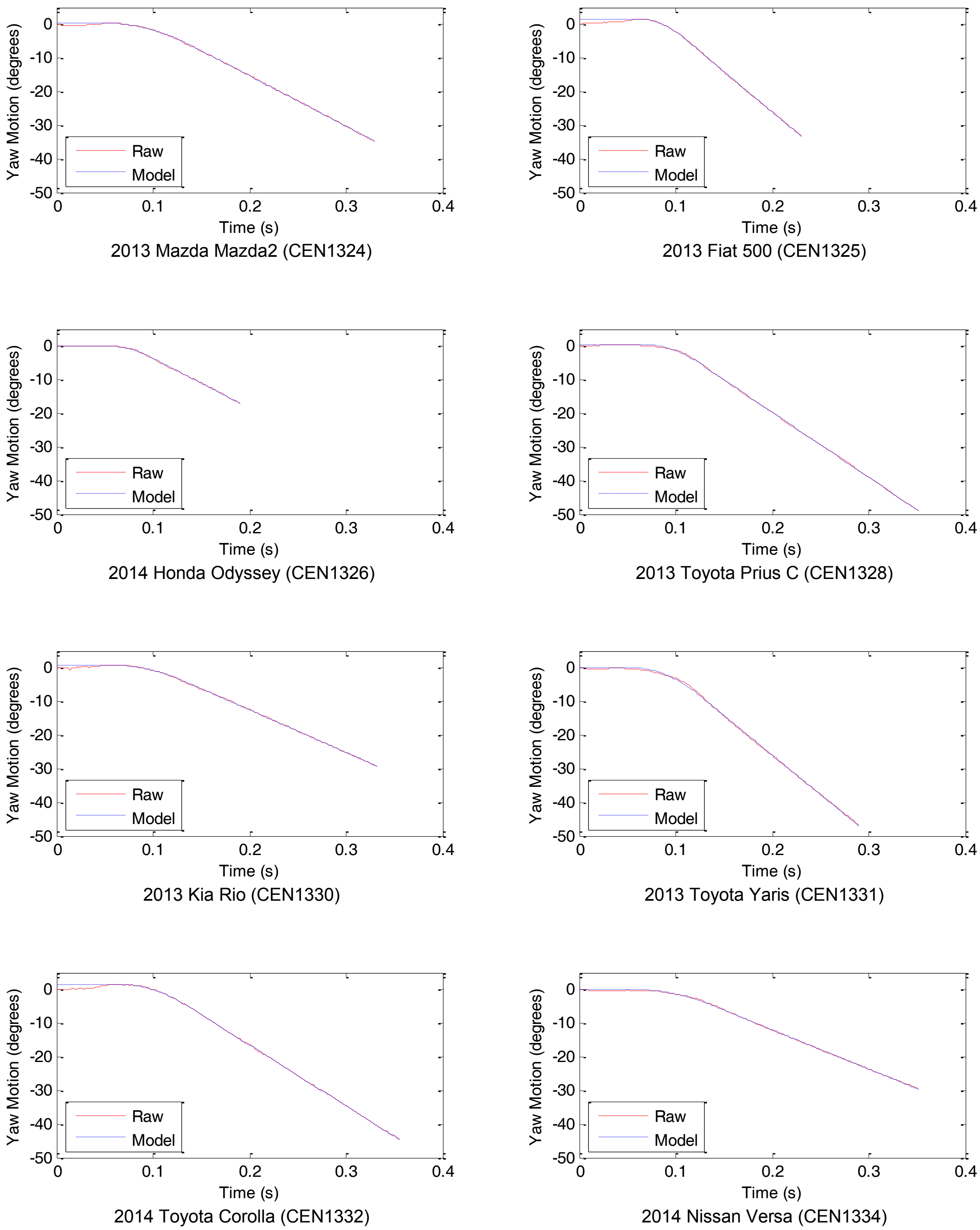
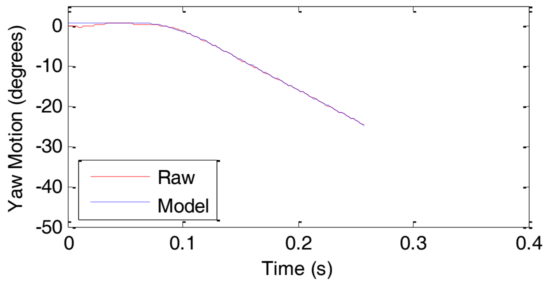
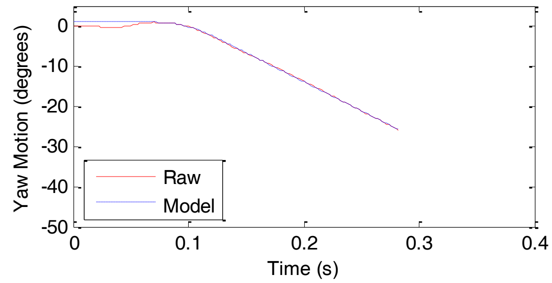


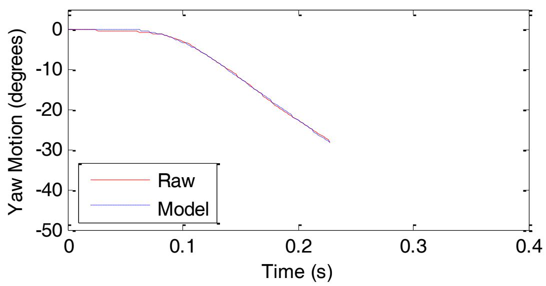
Figure A.5 (Cont'd) Comparison of the raw TEMA yaw motion to the simplified rotation model used for the small overlap crash test study



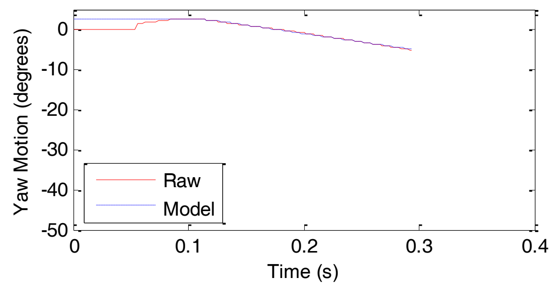
2013 Chevrolet Spark (CEN1335)



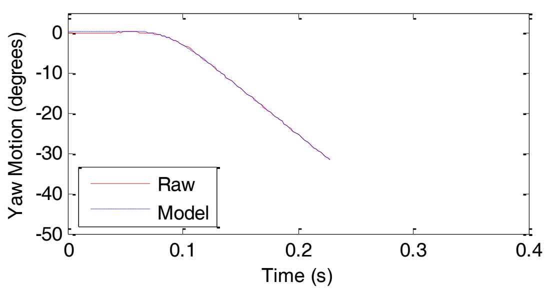
2014 Acura RLX (CEN1341)



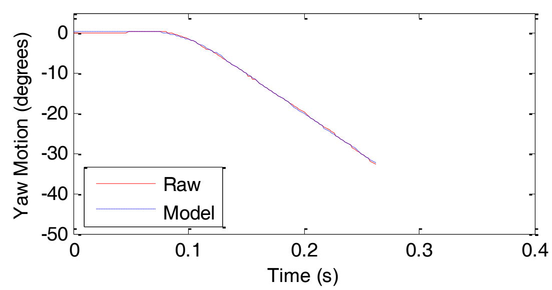
2014 Ford Fiesta (CEN1343)



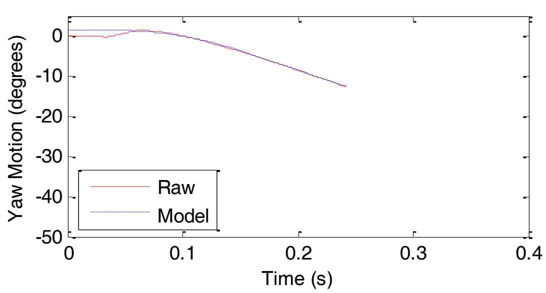
2014 Volvo S80 (CEN1344)



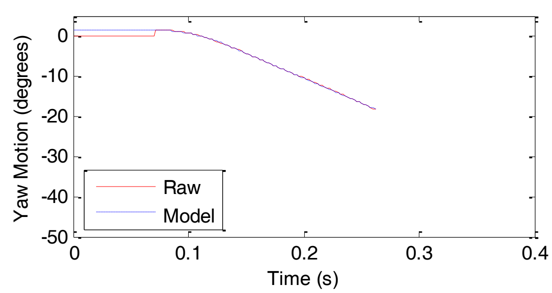
2014 Mazda CX-5 (CEN1345)



2014 Mazda Mazda3 (CEN1346)

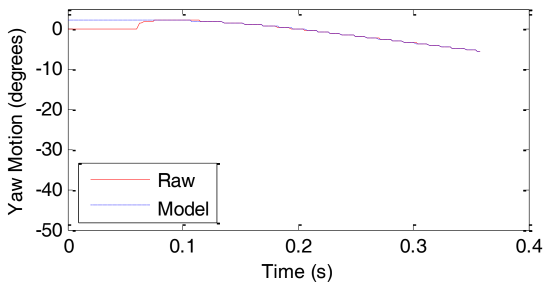


2014 Toyota Prius (CEN1347)

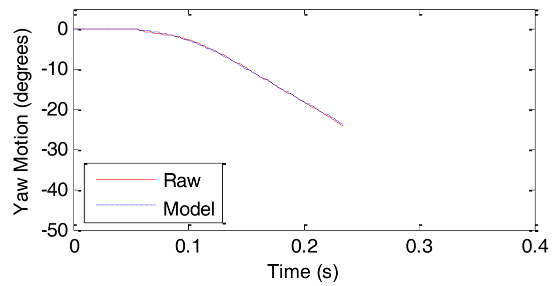


2014 Toyota Camry (CEN1349)

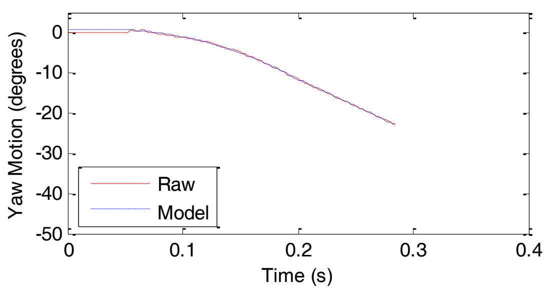
Figure A.5 (Cont'd) Comparison of the raw TEMA yaw motion to the simplified rotation model used for the small overlap crash test study



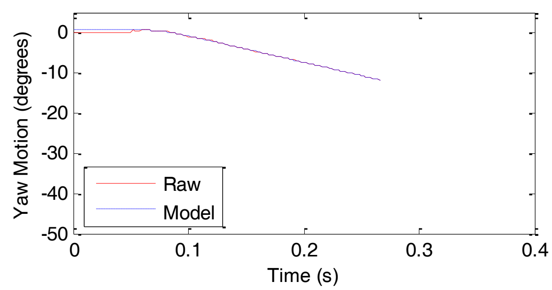
2014 Chevrolet Equinox (CEN1401)



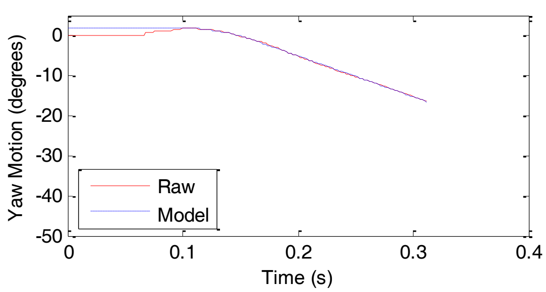
2014 Jeep Grand Cherokee (CEN1404)



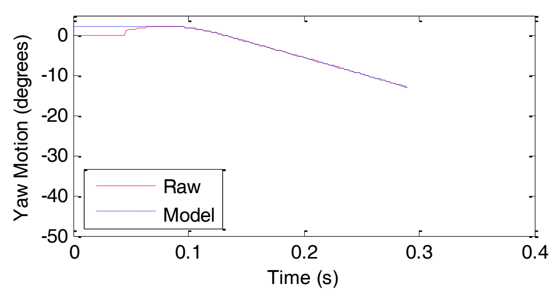
2014 Honda Pilot (CEN1405)



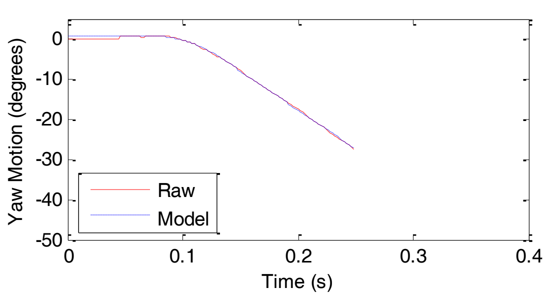
2014 Nissan Rogue (CEN1407)



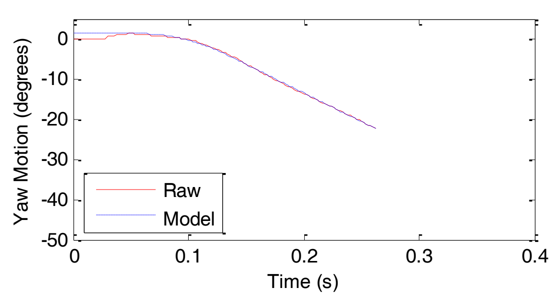
2014 Mazda CX-9 (CEN1408)



2014 Chevrolet Malibu (CEN1412)



2014 Fiat 500L (CEN1414)



2014 Nissan Juke (CEN1416)

Figure A.5 (Cont'd) Comparison of the raw TEMA yaw motion to the simplified rotation model used for the small overlap crash test study

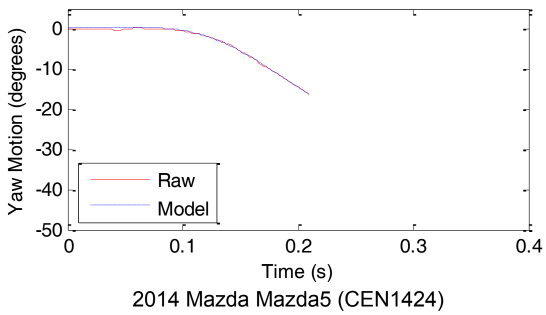
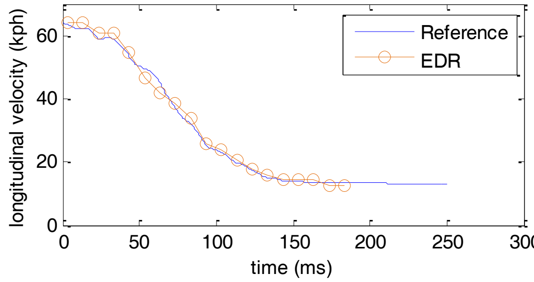
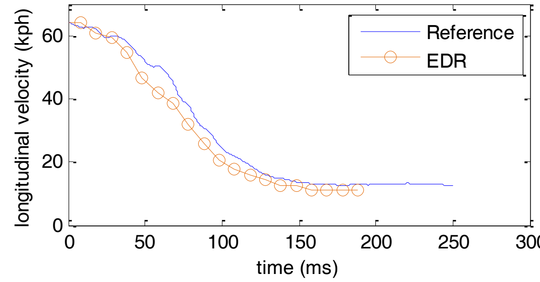


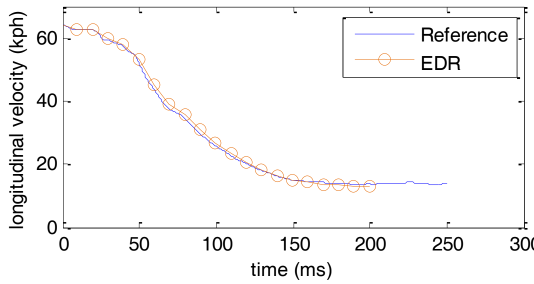
Figure A.5 (Cont'd) Comparison of the raw TEMA yaw motion to the simplified rotation model used for the small overlap crash test study



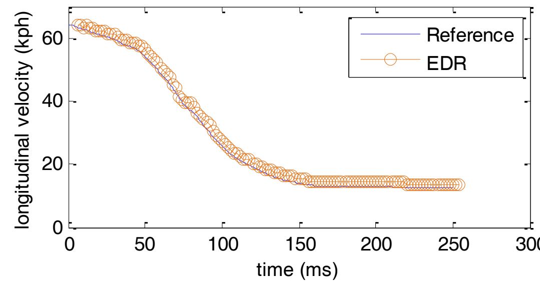
2012 Acura TSX (CEN1202): Rotation corrected reference velocity vs. EDR velocity (time shifted 3.3 ms)



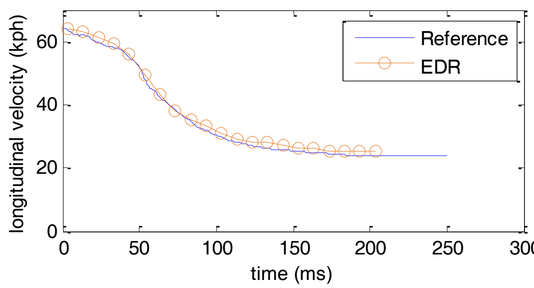
2012 Acura TSX (CEN1213): Rotation corrected reference velocity vs. EDR velocity (time shifted -1.8 ms)



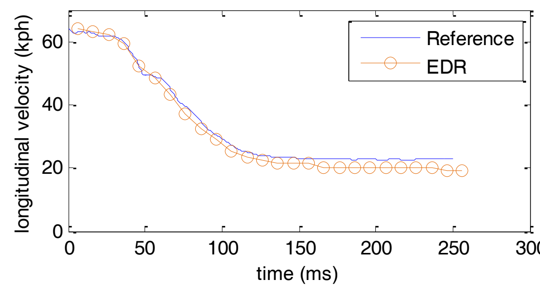
2012 Toyota Camry (CEN1215): Rotation corrected reference velocity vs. EDR velocity (time shifted -0.4 ms)



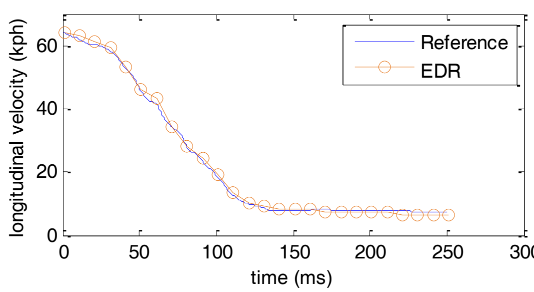
2012 Dodge Avenger (CEN1216): Rotation corrected reference velocity vs. EDR velocity (time shifted 6.0 ms)



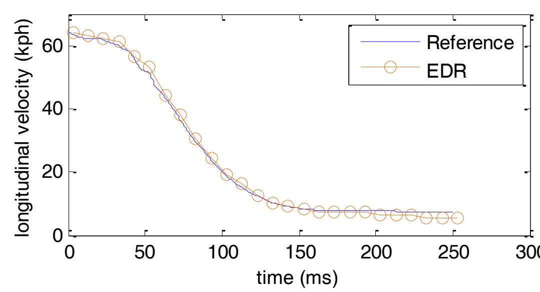
2013 Chevrolet Malibu (CEN1218): Rotation corrected reference velocity vs. EDR velocity (time shifted 3.5 ms)



2012 Mazda Mazda6 (CEN1220): Rotation corrected reference velocity vs. EDR velocity (time shifted 6.3 ms)

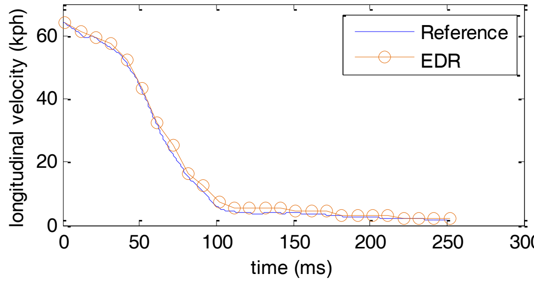


2013 Honda Accord (CEN1229): Rotation corrected reference velocity vs. EDR velocity (time shifted 1.0 ms)

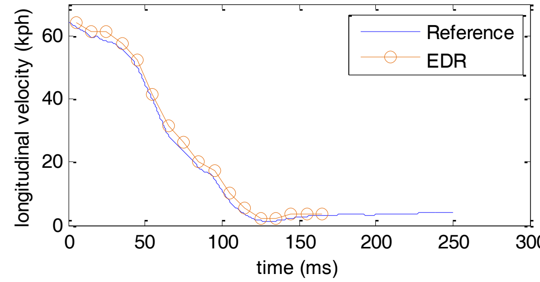


2013 Hyundai Tucson (CEN1237): Rotation corrected reference velocity vs. EDR velocity (time shifted 3.0 ms)

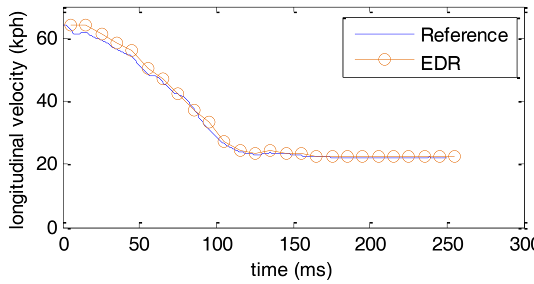
Figure A.6 Overlay of EDR and reference instrumentation longitudinal velocity versus time after optimization in time (small overlap crash test study)



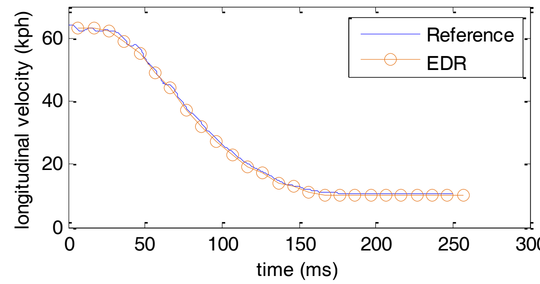
2013 Honda Civic (CEN1301): Rotation corrected reference velocity vs. EDR velocity (time shifted 1.8 ms)



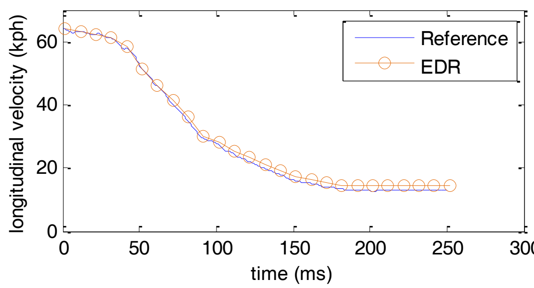
2013 Honda Civic (CEN1302): Rotation corrected reference velocity vs. EDR velocity (time shifted 5.0 ms)



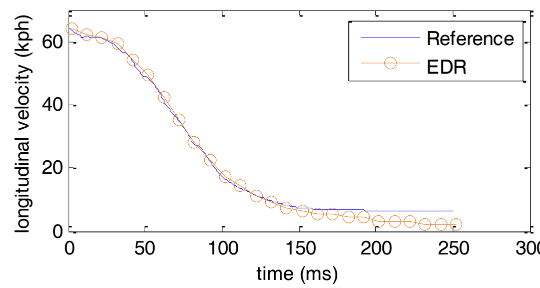
2013 Volvo XC60 (CEN1304): Rotation corrected reference velocity vs. EDR velocity (time shifted 5.3 ms)



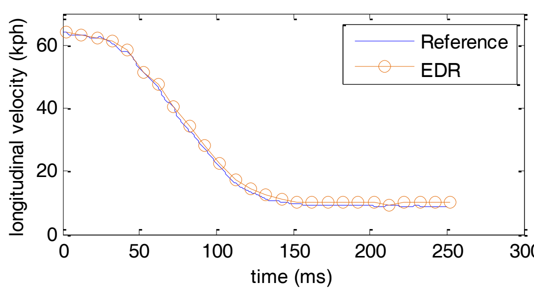
2013 Mazda CX5 (CEN1306): Rotation corrected reference velocity vs. EDR velocity (time shifted 6.7 ms)



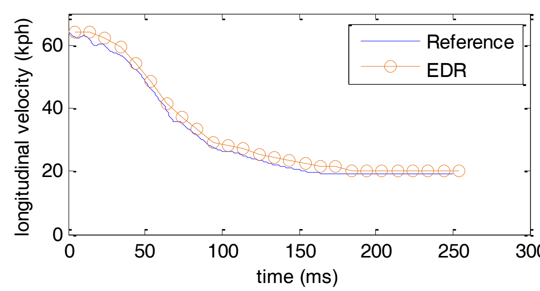
2013 Buick Encore (CEN1308): Rotation corrected reference velocity vs. EDR velocity (time shifted 1.9 ms)



2013 Hyundai Elantra (CEN1310): Rotation corrected reference velocity vs. EDR velocity (time shifted 2.0 ms)

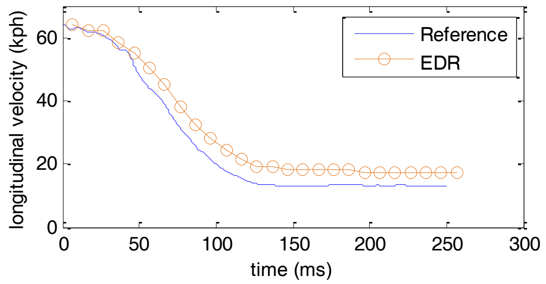


2013 Buick Encore (CEN1311): Rotation corrected reference velocity vs. EDR velocity (time shifted 2.3 ms)

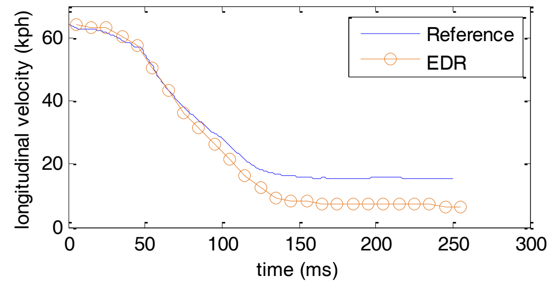


2013 Chevrolet Cruze (CEN1312): Rotation corrected reference velocity vs. EDR velocity (time shifted 0.9 ms)

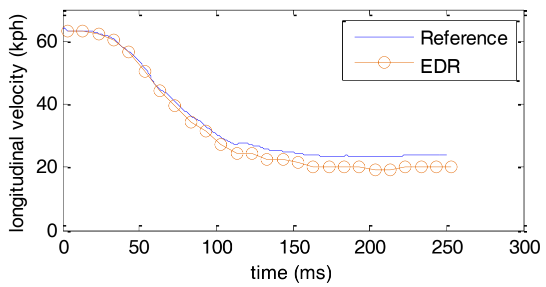
Figure A.6 (Cont'd) Overlay of EDR and reference instrumentation longitudinal velocity versus time after optimization in time (small overlap crash test study)



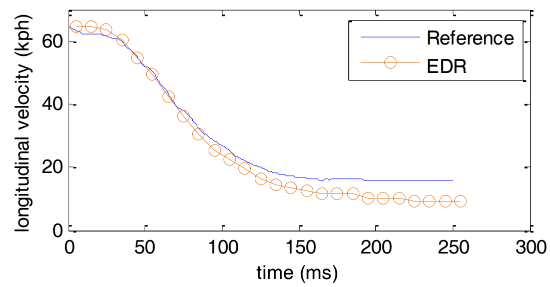
2013 Chevrolet Sonic (CEN1313): Rotation corrected reference velocity vs. EDR velocity (time shifted 1.6 ms)



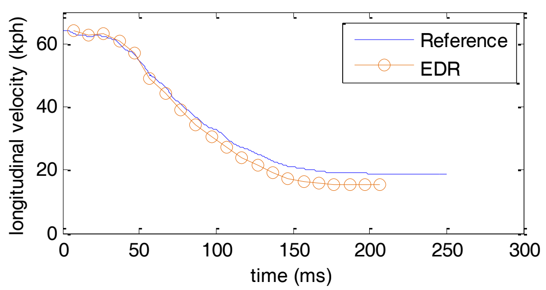
2013 Ford Focus (CEN1314): Rotation corrected reference velocity vs. EDR velocity (time shifted 4.9 ms)



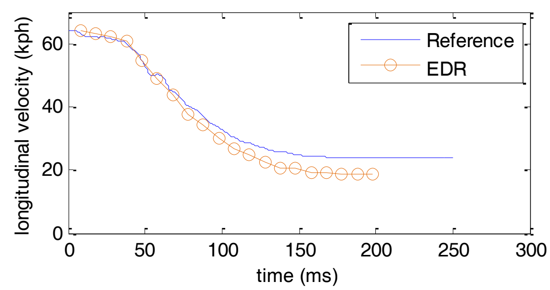
2013 Kia Soul (CEN1317): Rotation corrected reference velocity vs. EDR velocity (time shifted 3.5 ms)



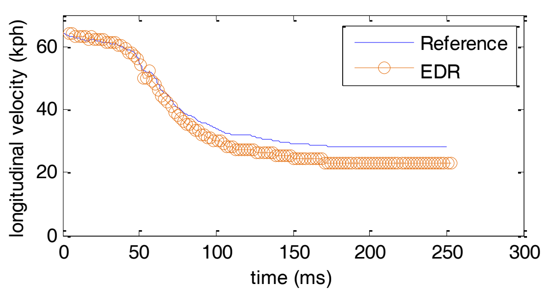
2014 Kia Forte (CEN1318): Rotation corrected reference velocity vs. EDR velocity (time shifted 5.1 ms)



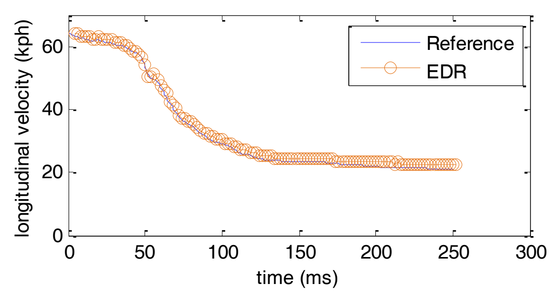
2013 Toyota RAV4 (CEN1319): Rotation corrected reference velocity vs. EDR velocity (time shifted 6.9 ms)



2014 Scion tC (CEN1320): Rotation corrected reference velocity vs. EDR velocity (time shifted 7.9 ms)

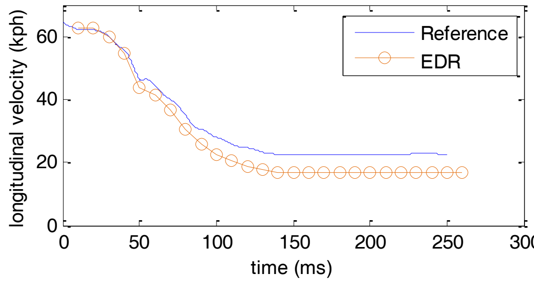


2013 Dodge Dart (CEN1321): Rotation corrected reference velocity vs. EDR velocity (time shifted 4.7 ms)

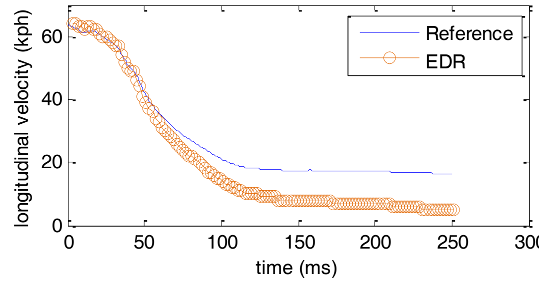


2013 Dodge Dart (CEN1322): Rotation corrected reference velocity vs. EDR velocity (time shifted 4.1 ms)

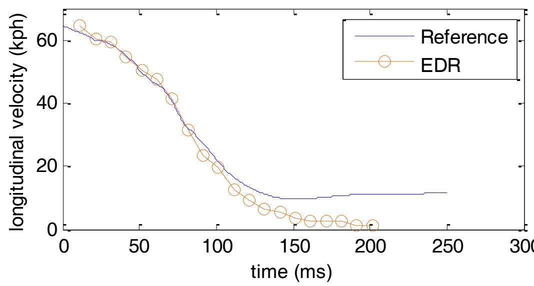
Figure A.6 (Cont'd) Overlay of EDR and reference instrumentation longitudinal velocity versus time after optimization in time (small overlap crash test study)



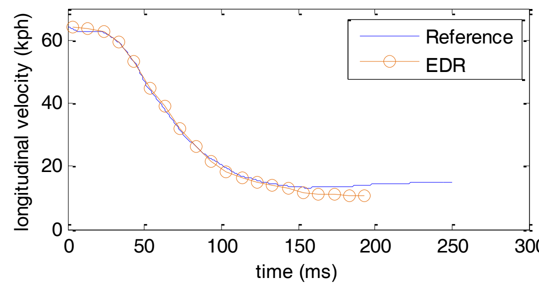
2013 Mazda Mazda2 (CEN1324): Rotation corrected reference velocity vs. EDR velocity (time shifted -0.8 ms)



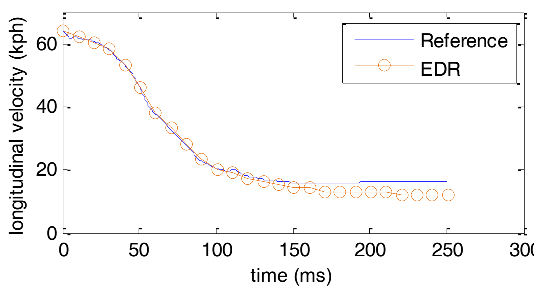
2013 Fiat 500 (CEN1325): Rotation corrected reference velocity vs. EDR velocity (time shifted 3.2 ms)



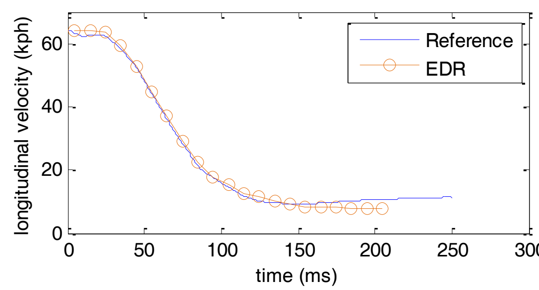
2014 Honda Odyssey (CEN1326): Rotation corrected reference velocity vs. EDR velocity (time shifted 11.6 ms)



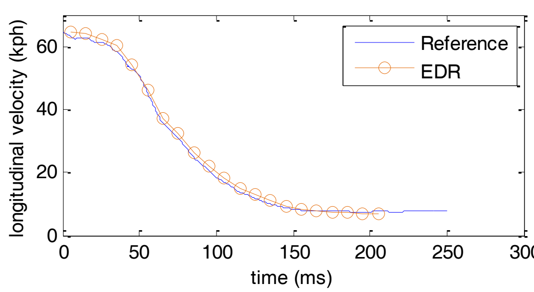
2013 Toyota Prius C (CEN1328): Rotation corrected reference velocity vs. EDR velocity (time shifted 3.4 ms)



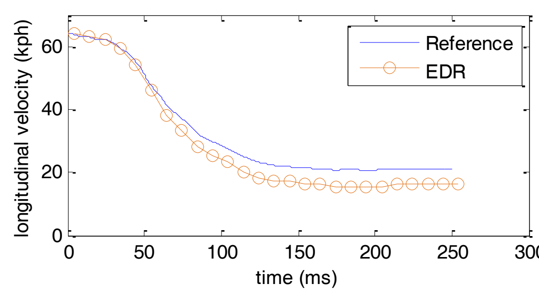
2013 Kia Rio (CEN1330): Rotation corrected reference velocity vs. EDR velocity (time shifted 0.8 ms)



2013 Toyota Yaris (CEN1331): Rotation corrected reference velocity vs. EDR velocity (time shifted 4.7 ms)

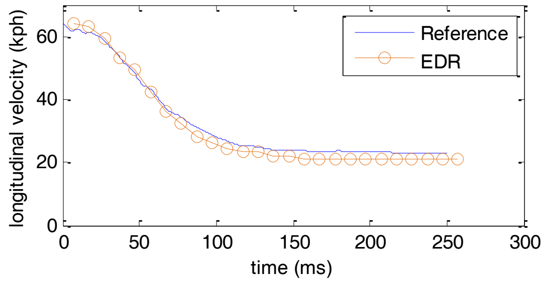


2014 Toyota Corolla (CEN1332): Rotation corrected reference velocity vs. EDR velocity (time shifted 5.4 ms)

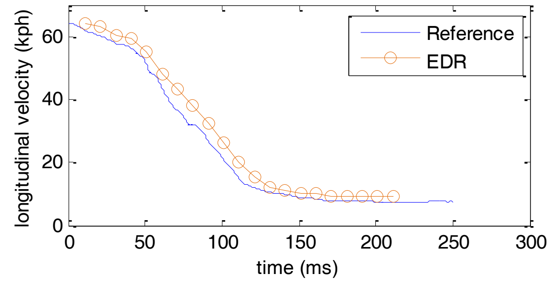


2014 Nissan Versa (CEN1334): Rotation corrected reference velocity vs. EDR velocity (time shifted 4.2 ms)

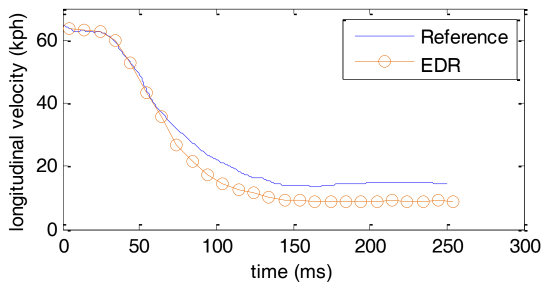
Figure A.6 (Cont'd) Overlay of EDR and reference instrumentation longitudinal velocity versus time after optimization in time (small overlap crash test study)



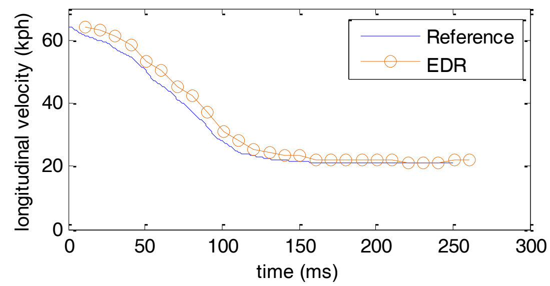
2013 Chevrolet Spark (CEN1335): Rotation corrected reference velocity vs. EDR velocity (time shifted 7.2 ms)



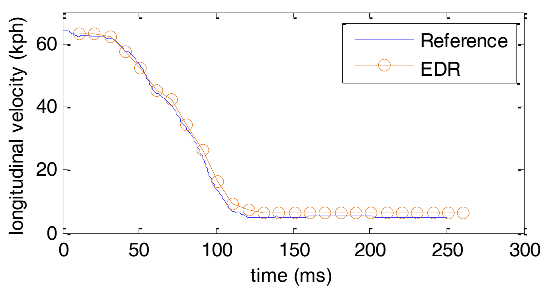
2014 Acura RLX (CEN1341): Rotation corrected reference velocity vs. EDR velocity (time shifted 11.1 ms)



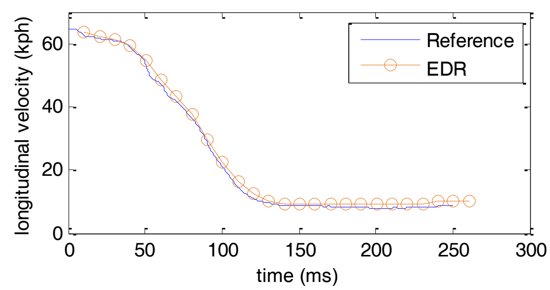
2014 Ford Fiesta (CEN1343): Rotation corrected reference velocity vs. EDR velocity (time shifted 4.2 ms)



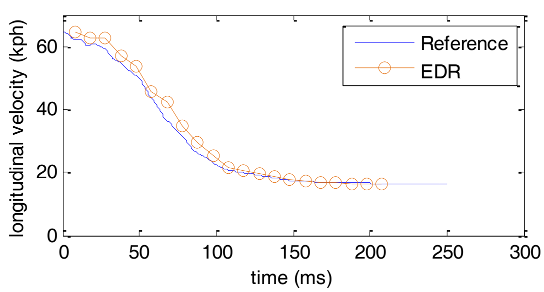
2014 Volvo S80 (CEN1344): Rotation corrected reference velocity vs. EDR velocity (time shifted 10.9 ms)



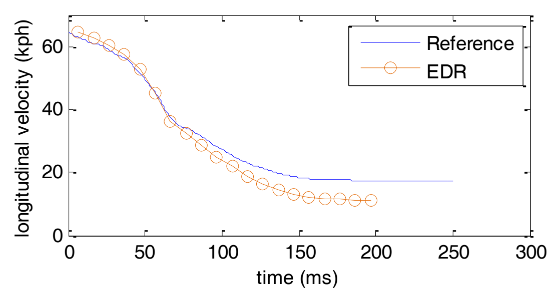
2014 Mazda CX-5 (CEN1345): Rotation corrected reference velocity vs. EDR velocity (time shifted 11.0 ms)



2014 Mazda Mazda3 (CEN1346): Rotation corrected reference velocity vs. EDR velocity (time shifted 10.5 ms)

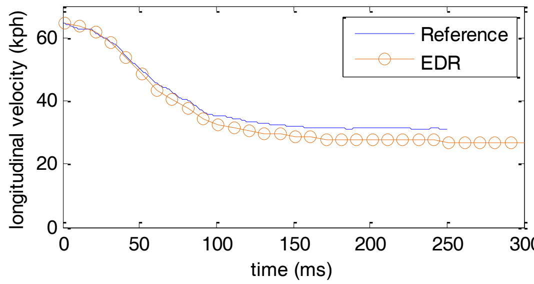


2014 Toyota Prius (CEN1347): Rotation corrected reference velocity vs. EDR velocity (time shifted 7.9 ms)

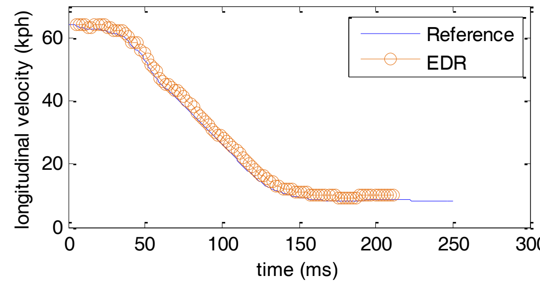


2014 Toyota Camry (CEN1349): Rotation corrected reference velocity vs. EDR velocity (time shifted 6.7 ms)

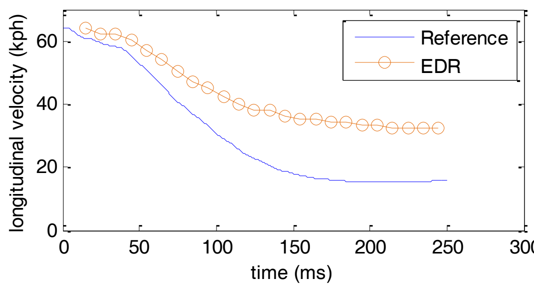
Figure A.6 (Cont'd) Overlay of EDR and reference instrumentation longitudinal velocity versus time after optimization in time (small overlap crash test study)



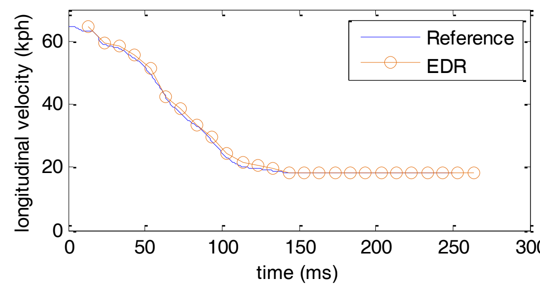
2014 Chevrolet Equinox (CEN1401): Rotation corrected reference velocity vs. EDR velocity (time shifted 1.4 ms)



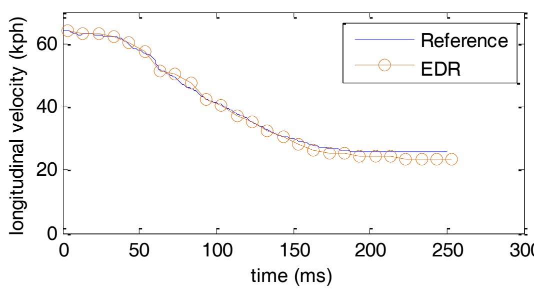
2014 Jeep Grand Cherokee (CEN1404): Rotation corrected reference velocity vs. EDR velocity (time shifted 5.4 ms)



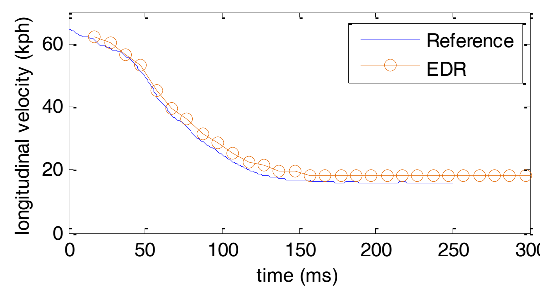
2014 Honda Pilot (CEN1405): Rotation corrected reference velocity vs. EDR velocity (time shifted 14.7 ms)



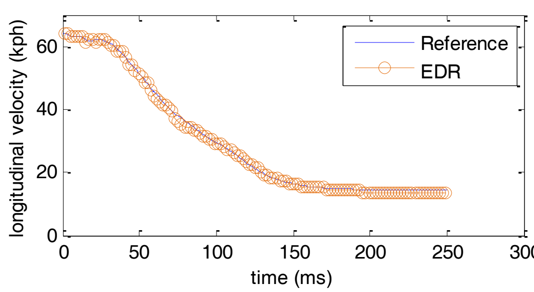
2014 Nissan Rogue (CEN1407): Rotation corrected reference velocity vs. EDR velocity (time shifted 13.5 ms)



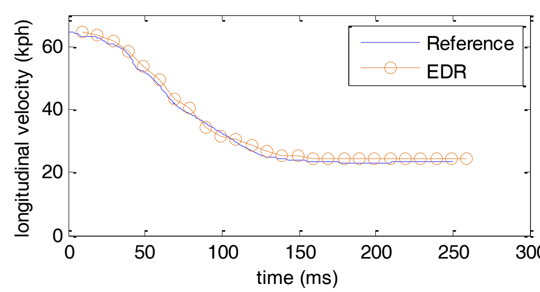
2014 Mazda CX-9 (CEN1408): Rotation corrected reference velocity vs. EDR velocity (time shifted 3.5 ms)



2014 Chevrolet Malibu (CEN1412): Rotation corrected reference velocity vs. EDR velocity (time shifted 7.1 ms)

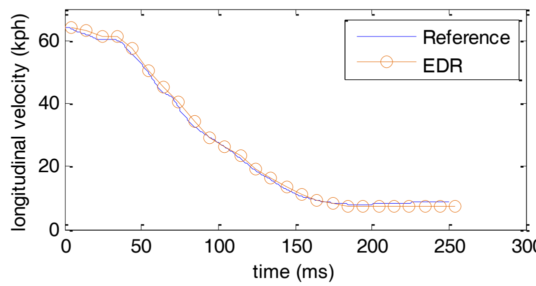


2014 Fiat 500L (CEN1414): Rotation corrected reference velocity vs. EDR velocity (time shifted 1.4 ms)

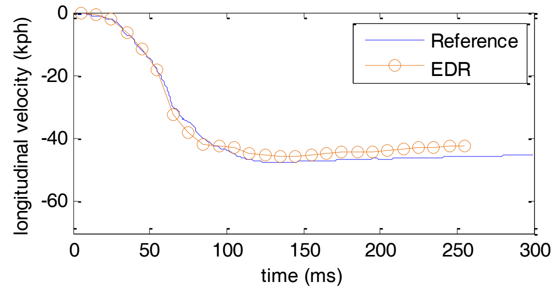


2014 Nissan Juke (CEN1416): Rotation corrected reference velocity vs. EDR velocity (time shifted 9.3 ms)

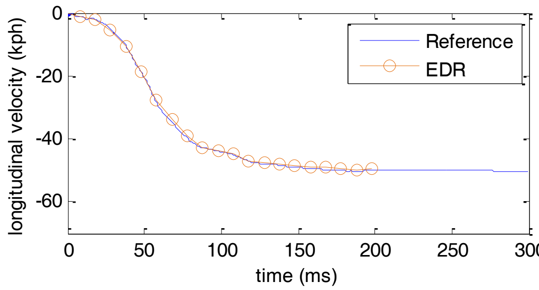
Figure A.6 (Cont'd) Overlay of EDR and reference instrumentation longitudinal velocity versus time after optimization in time (small overlap crash test study)



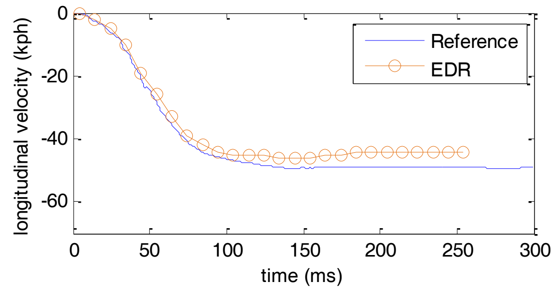
2014 Mazda Mazda5 (CEN1424): Rotation corrected reference velocity vs. EDR velocity (time shifted 4.4 ms)



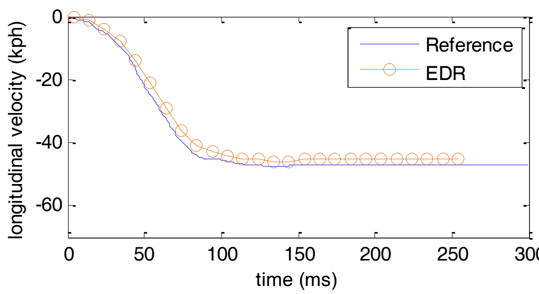
2010 Ford Fusion (RA0220): Rotation corrected reference velocity vs. EDR velocity (time shifted 5.1 ms)



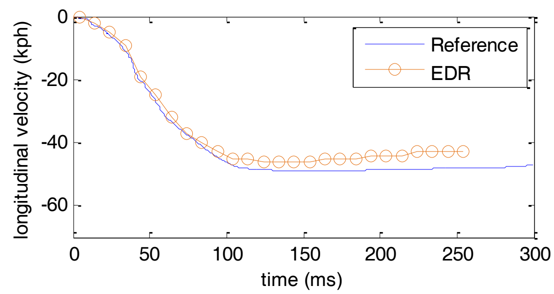
2010 Toyota Yaris (RA5135): Rotation corrected reference velocity vs. EDR velocity (time shifted -2.2 ms)



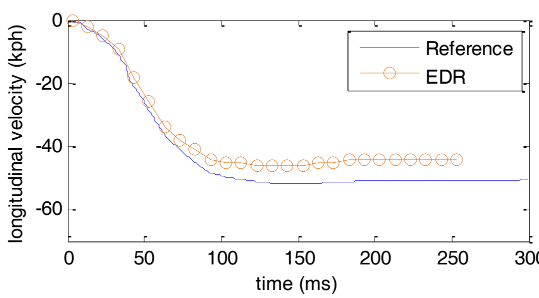
2011 Chevrolet Cruze (RB0178): Rotation corrected reference velocity vs. EDR velocity (time shifted 34.4 ms)



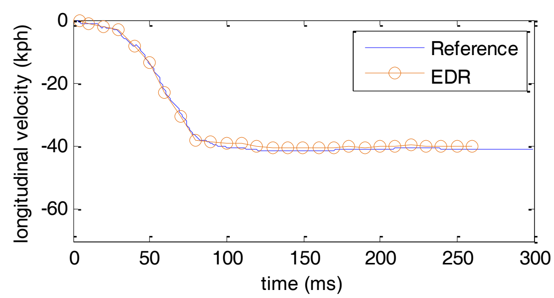
2011 Buick Lacrosse (RB0180): Rotation corrected reference velocity vs. EDR velocity (time shifted 34.1 ms)



2011 Chevrolet Cruze (RB0182): Rotation corrected reference velocity vs. EDR velocity (time shifted 33.9 ms)

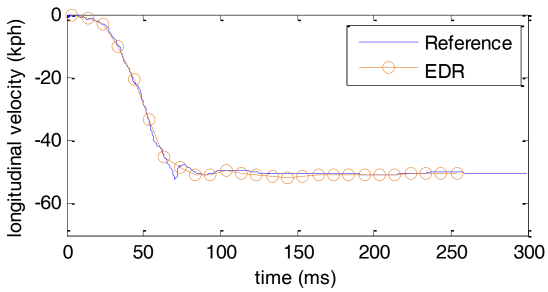


2011 Chevrolet Cruze (RB0183): Rotation corrected reference velocity vs. EDR velocity (time shifted 33.1 ms)

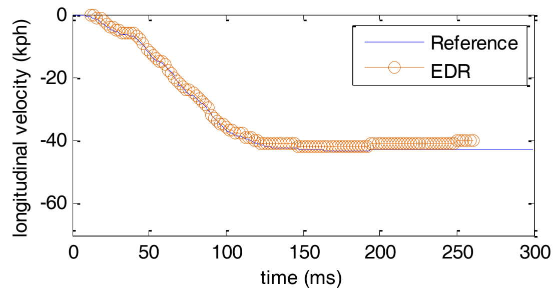


2011 Ford Explorer (RB0222): Rotation corrected reference velocity vs. EDR velocity (time shifted 4.4 ms)

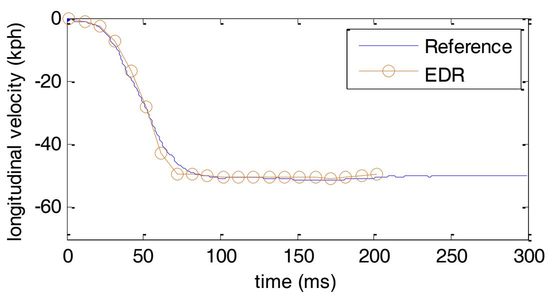
Figure A.6 (Cont'd) Overlay of EDR and reference instrumentation longitudinal velocity versus time after optimization in time (small overlap crash test study)



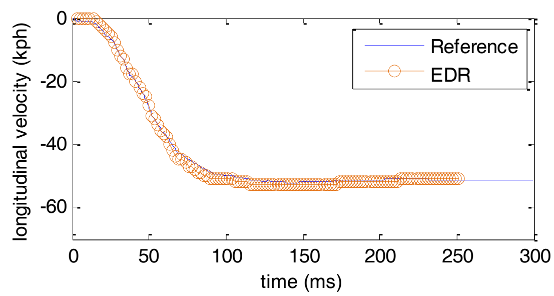
2011 Ford Fiesta (RB0224): Rotation corrected reference velocity vs. EDR velocity (time shifted 3.0 ms)



2011 Dodge Ram1500 (RB0330): Rotation corrected reference velocity vs. EDR velocity (time shifted 12.4 ms)

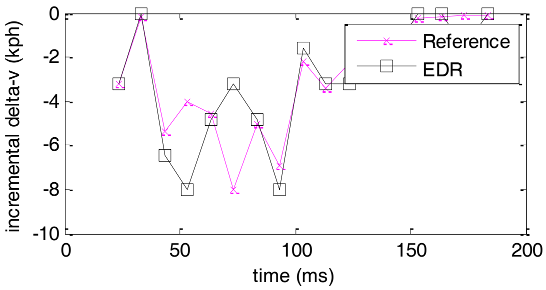


2010 Toyota Yaris (RB5137): Rotation corrected reference velocity vs. EDR velocity (time shifted 1.8 ms)

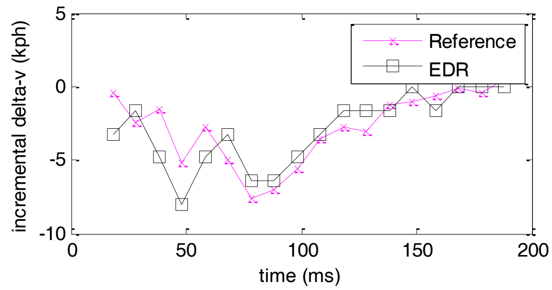


2012 Fiat 500 (RC0528): Rotation corrected reference velocity vs. EDR velocity (time shifted 3.5 ms)

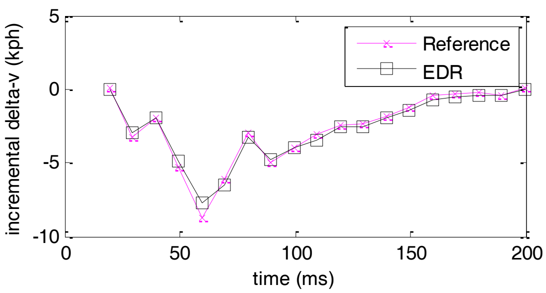
Figure A.6 (Cont'd) Overlay of EDR and reference instrumentation longitudinal velocity versus time after optimization in time (small overlap crash test study)



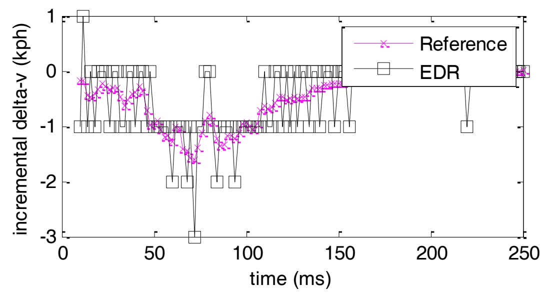
2012 Acura TSX (CEN1202): time shifted 3.3 ms



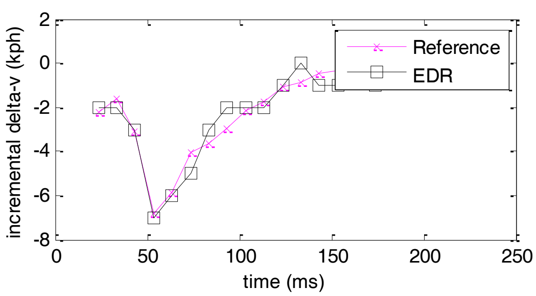
2012 Acura TSX (CEN1213): time shifted -1.8 ms)



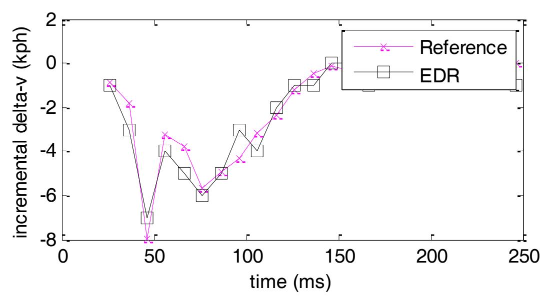
2012 Toyota Camry (CEN1215): time shifted -0.4 ms



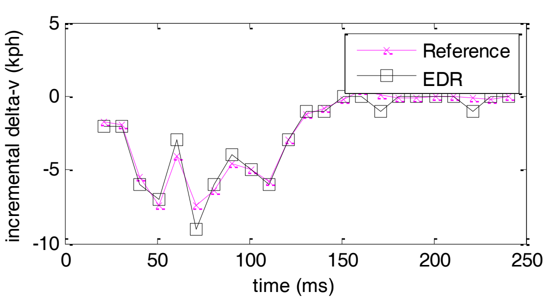
2012 Dodge Avenger (CEN1216): time shifted 6.0 ms



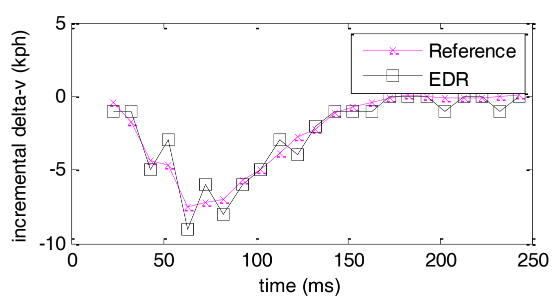
2013 Chevrolet Malibu (CEN1218): time shifted 3.5 ms



2012 Mazda Mazda6 (CEN1220): time shifted 6.3 ms

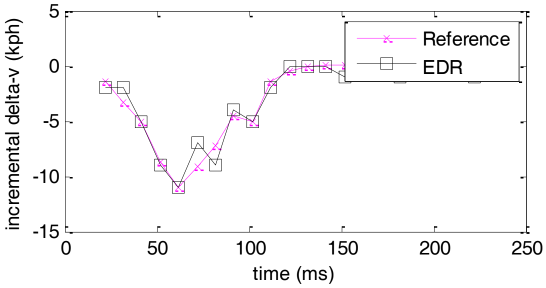


2013 Honda Accord (CEN1229): time shifted 1 ms

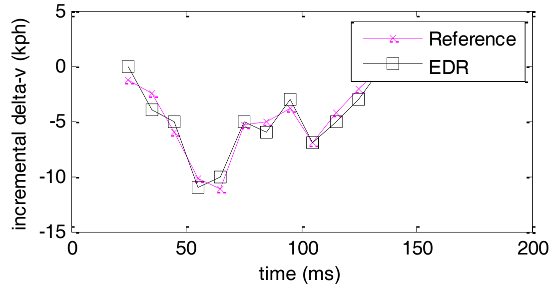


2013 Hyundai Tucson (CEN1237): time shifted 3.0 ms

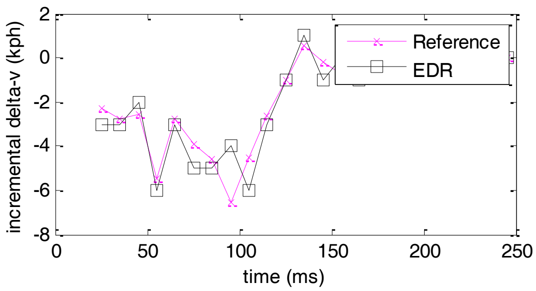
Figure A.7 Overlay of EDR and reference instrumentation longitudinal incremental delta-v versus time after optimization in time (small overlap crash test study)



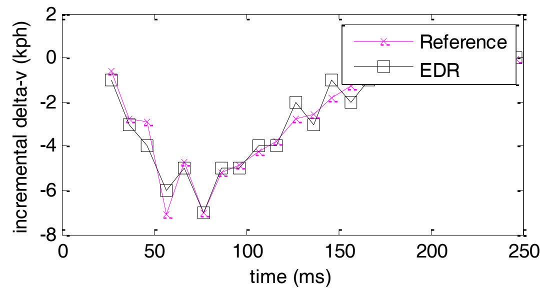
2013 Honda Civic (CEN1301): time shifted 1.8 ms



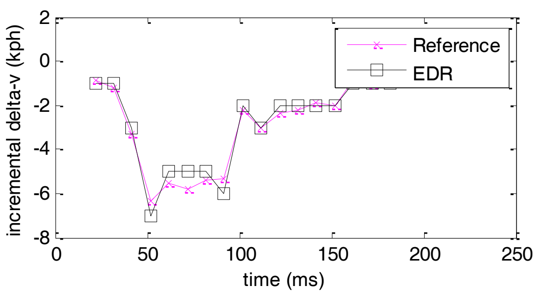
2013 Honda Civic (CEN1302): time shifted 5.0 ms



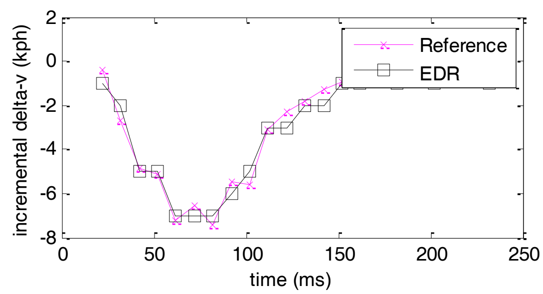
2013 Volvo XC60 (CEN1304): time shifted 5.3 ms



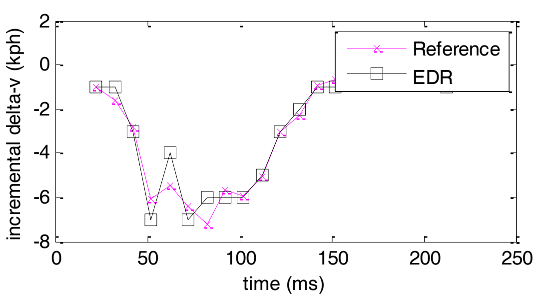
2013 Mazda CX5 (CEN1306): time shifted 6.7 ms



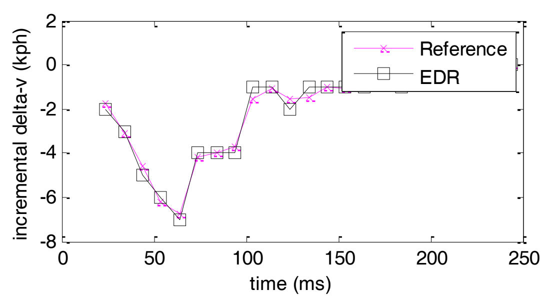
2013 Buick Encore (CEN1308): time shifted 1.9 ms



2013 Hyundai Elantra (CEN1310): time shifted 2.0 ms

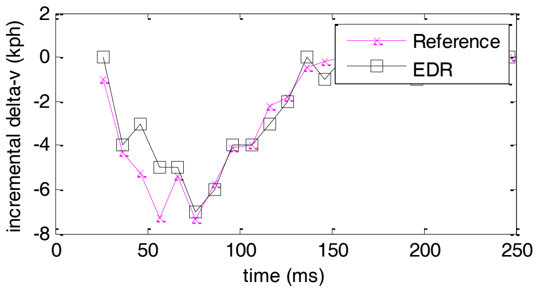


2013 Buick Encore (CEN1311): time shifted 2.3 ms

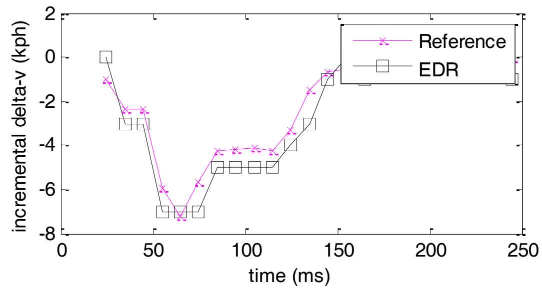


2013 Chevrolet Cruze (CEN1312): time shifted 0.9 ms

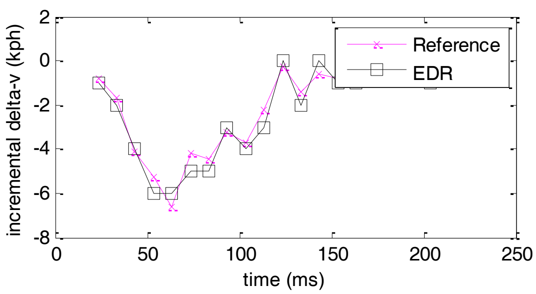
Figure A.7 (Cont'd) Overlay of EDR and reference instrumentation longitudinal incremental delta-v versus time after optimization in time (small overlap crash test study)



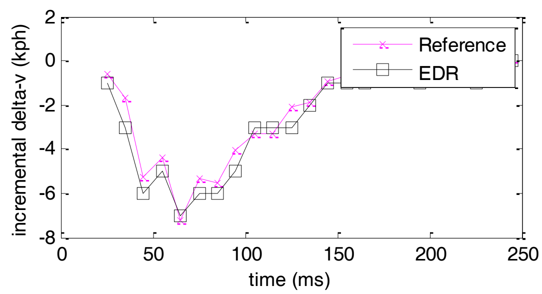
2013 Chevrolet Sonic (CEN1313): time shifted 1.6 ms



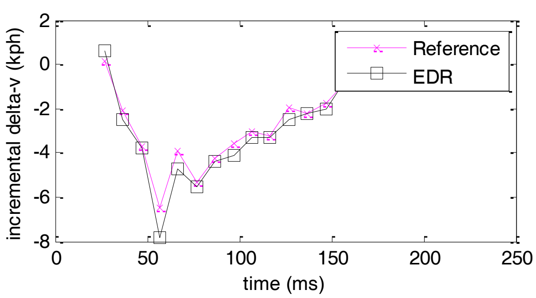
2013 Ford Focus (CEN1314): time shifted 4.9 ms



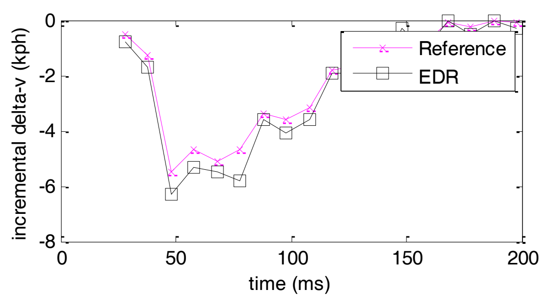
2013 Kia Soul (CEN1317): time shifted 3.5 ms



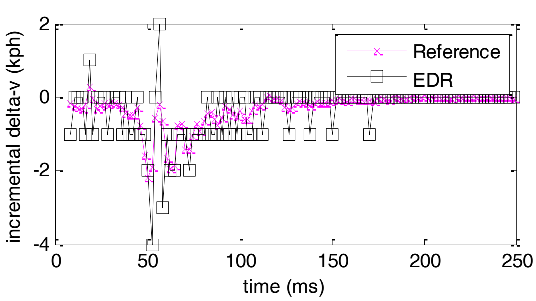
2014 Kia Forte (CEN1318): time shifted 5.1 ms



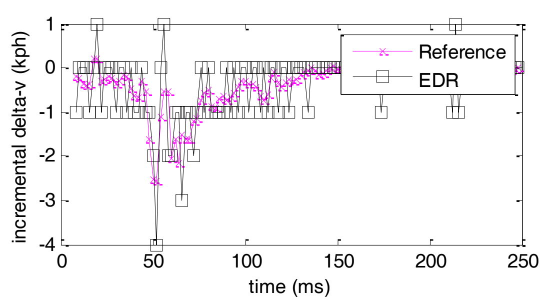
2013 Toyota RAV4 (CEN1319): time shifted 6.9 ms



2014 Scion tC (CEN1320): time shifted 7.9 ms

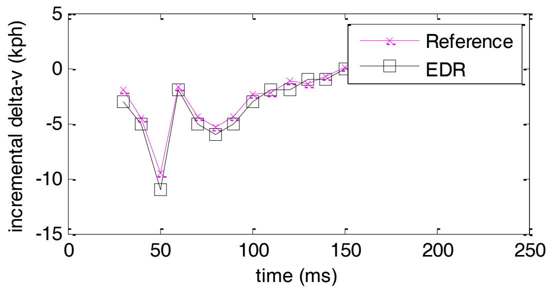


2013 Dodge Dart (CEN1321): time shifted 4.7 ms

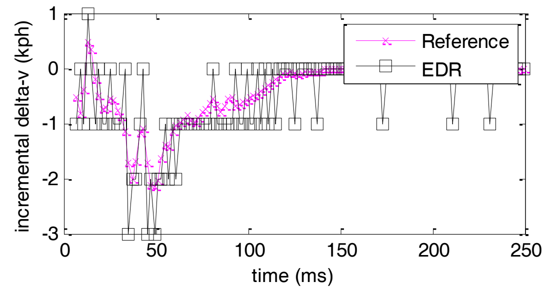


2013 Dodge Dart (CEN1322): time shifted 4.1 ms

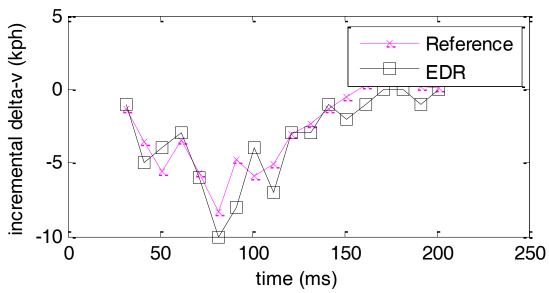
Figure A.7 (Cont'd) Overlay of EDR and reference instrumentation longitudinal incremental delta-v versus time after optimization in time (small overlap crash test study)



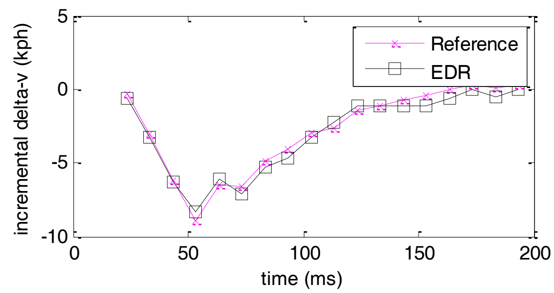
2013 Mazda Mazda2 (CEN1324): time shifted -0.8 ms



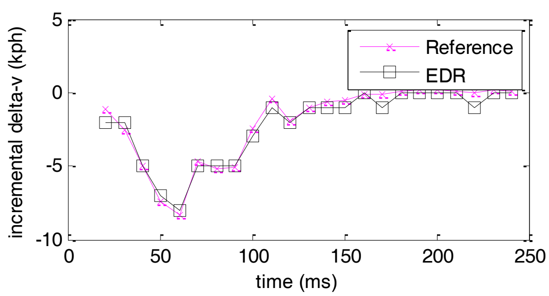
2013 Fiat 500 (CEN1325): time shifted 3.2 ms



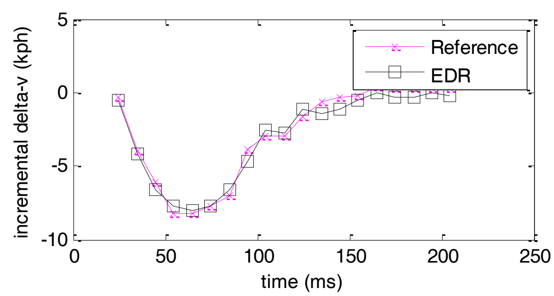
2014 Honda Odyssey (CEN1326): time shifted 11.6 ms



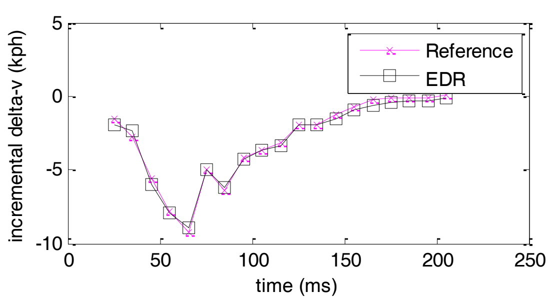
2013 Toyota Prius C (CEN1328): time shifted 3.4 ms



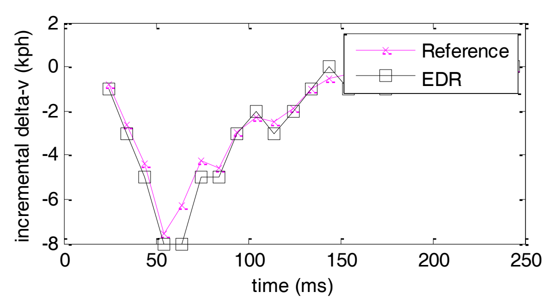
2013 Kia Rio (CEN1330): time shifted 0.8 ms



2013 Toyota Yaris (CEN1331): time shifted 4.7 ms



2014 Toyota Corolla (CEN1332): time shifted 5.4 ms



2014 Nissan Versa (CEN1334): time shifted 4.2 ms

Figure A.7 (Cont'd) Overlay of EDR and reference instrumentation longitudinal incremental delta-v versus time after optimization in time (small overlap crash test study)

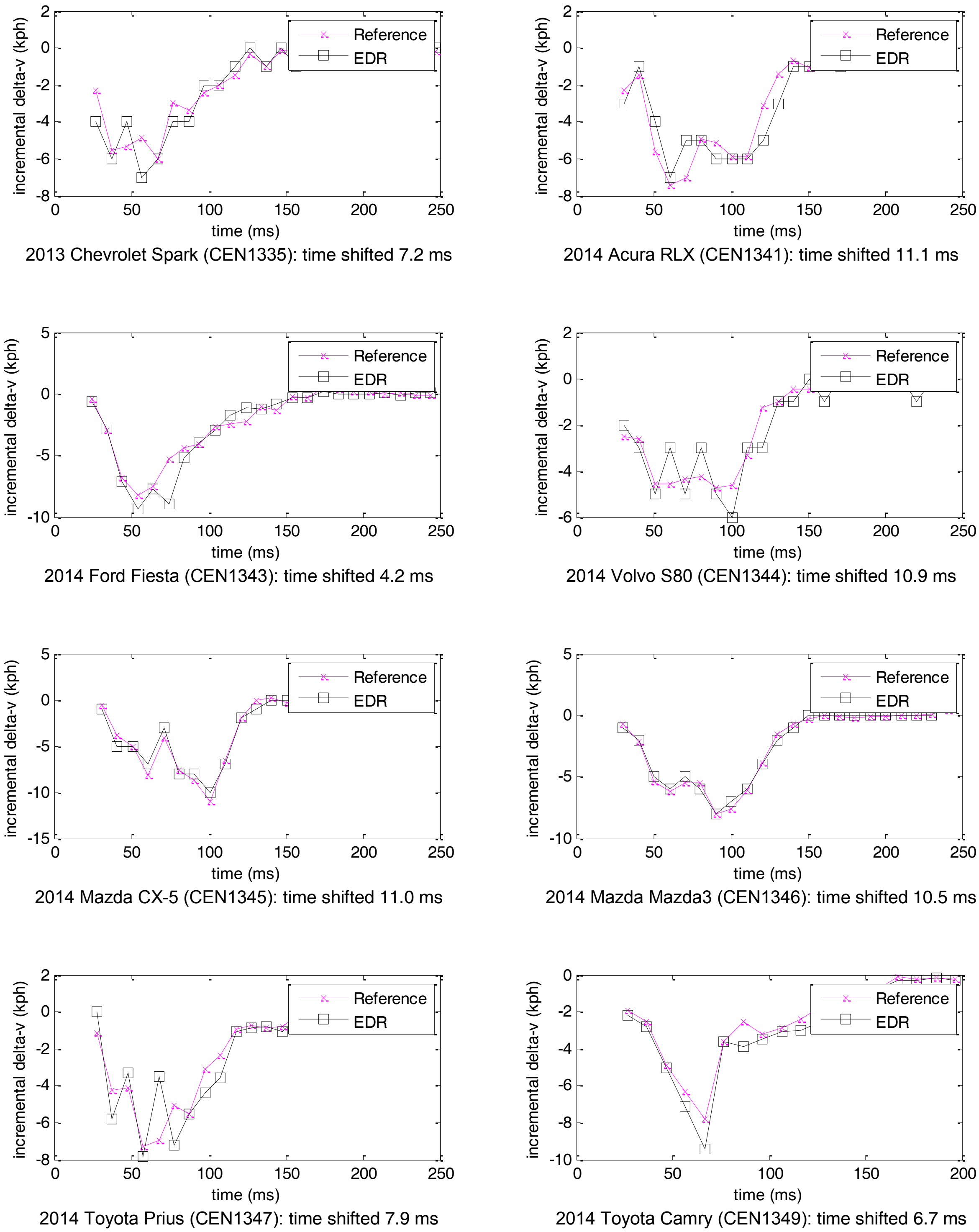
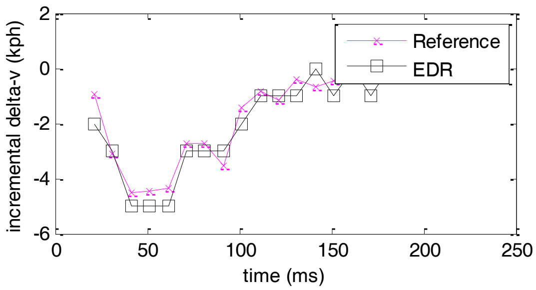
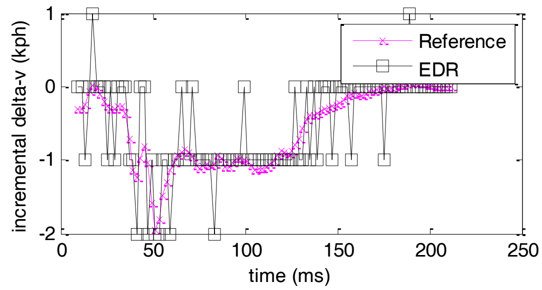


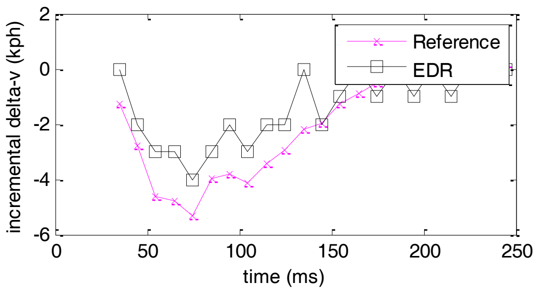
Figure A.7 (Cont'd) Overlay of EDR and reference instrumentation longitudinal incremental delta-v versus time after optimization in time (small overlap crash test study)



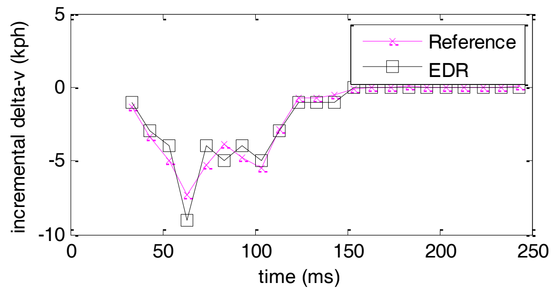
2014 Chevrolet Equinox (CEN1401): time shifted 1.4 ms



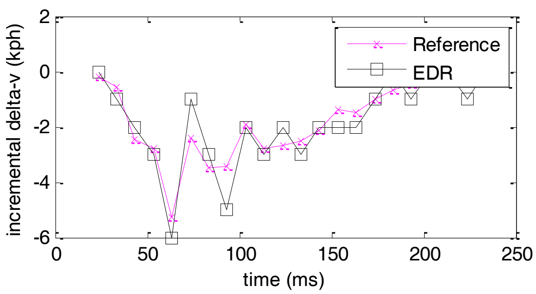
2014 Jeep Grand Cherokee (CEN1404): time shifted 5.4 ms



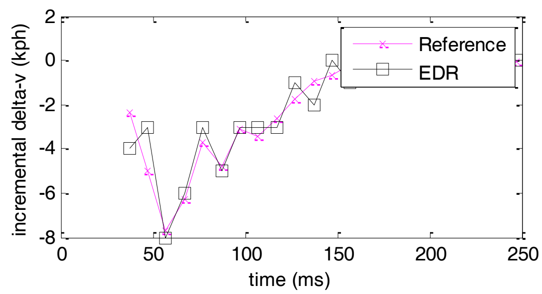
2014 Honda Pilot (CEN1405): time shifted 14.7 ms



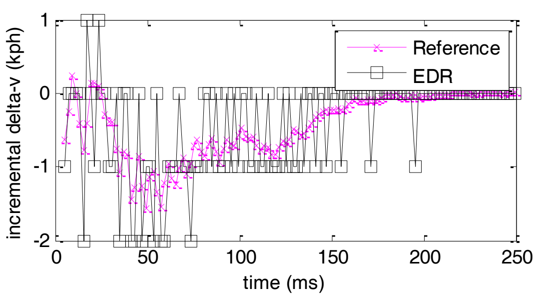
2014 Nissan Rogue (CEN1407): time shifted 13.5 ms



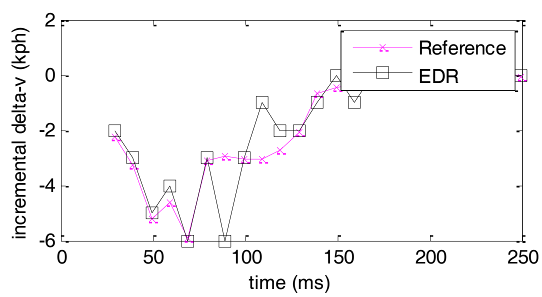
2014 Mazda CX-9 (CEN1408): time shifted 3.5 ms



2014 Chevrolet Malibu (CEN1412): time shifted 7.1 ms



2014 Fiat 500L (CEN1414): time shifted 1.4 ms



2014 Nissan Juke (CEN1416): time shifted 9.3 ms

Figure A.7 (Cont'd) Overlay of EDR and reference instrumentation longitudinal incremental delta-v versus time after optimization in time (small overlap crash test study)

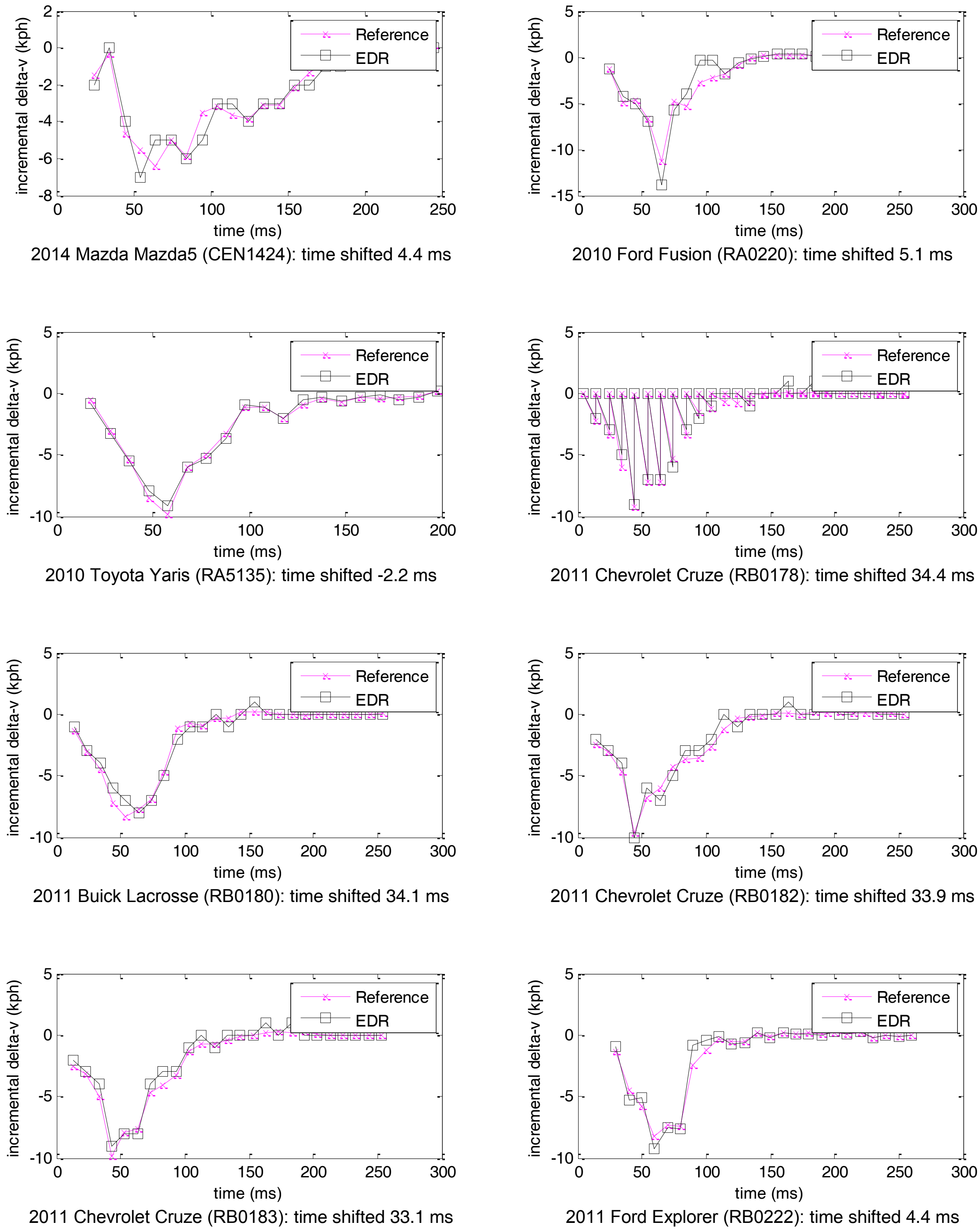
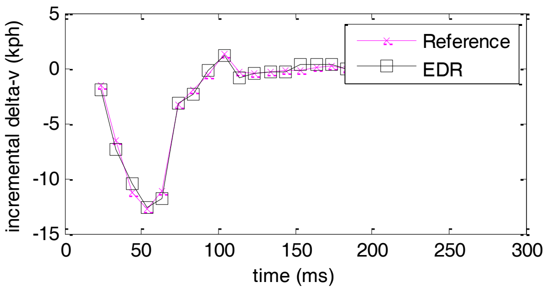
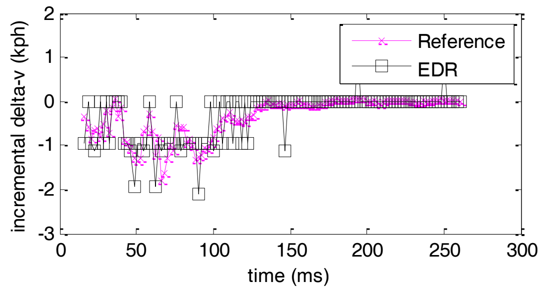


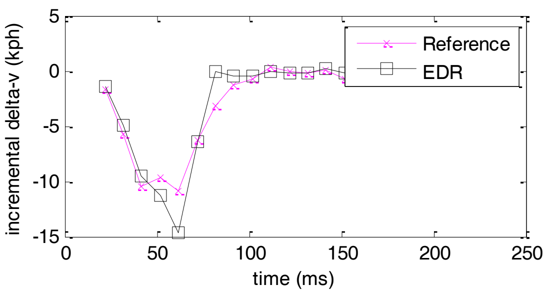
Figure A.7 (Cont'd) Overlay of EDR and reference instrumentation longitudinal incremental delta-v versus time after optimization in time (small overlap crash test study)



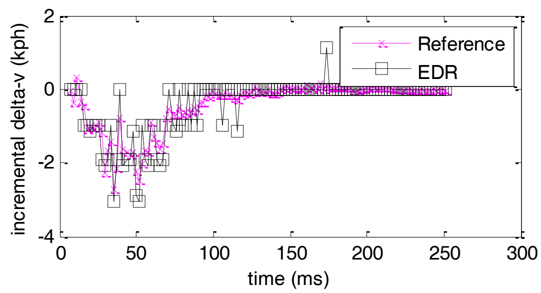
2011 Ford Fiesta (RB0224): time shifted 3.0 ms



2011 Dodge Ram1500 (RB0330): time shifted 12.4 ms

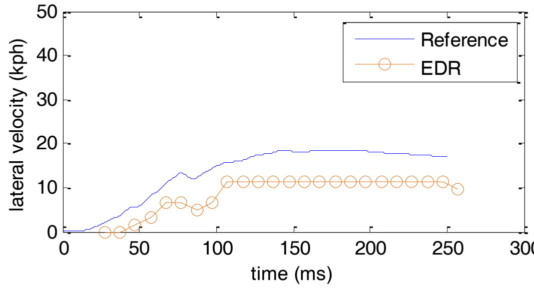


2010 Toyota Yaris (RB5137): time shifted 1.8 ms

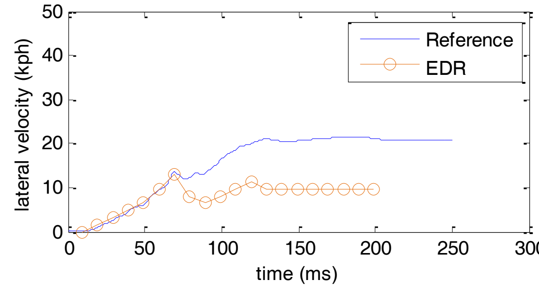


2012 Fiat 500 (RC0528): time shifted 3.5 ms

Figure A.7 (Cont'd) Overlay of EDR and reference instrumentation longitudinal incremental delta-v versus time after optimization in time (small overlap crash test study)

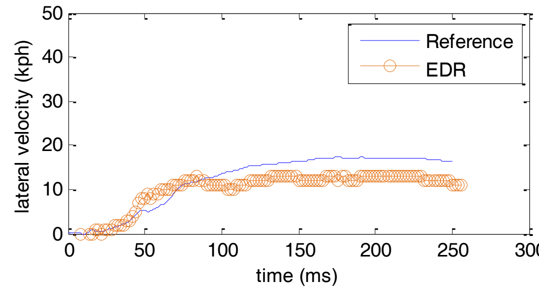


2012 Acura TSX (CEN1202): Rotation corrected reference velocity vs. EDR velocity (time shifted 27.3 ms)

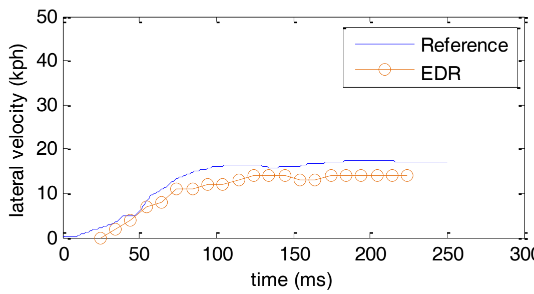


2012 Acura TSX (CEN1213): Rotation corrected reference velocity vs. EDR velocity (time shifted 9.2 ms)

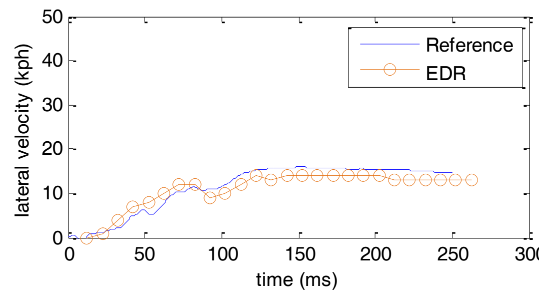
2012 Toyota Camry (CEN1215): Lateral delta-v not available



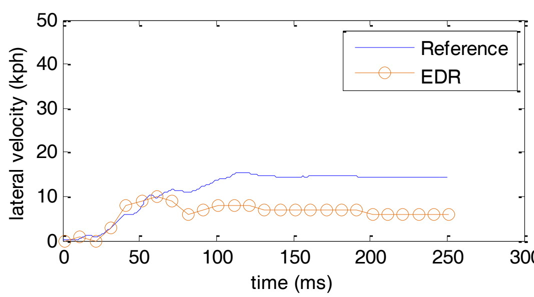
2012 Dodge Avenger (CEN1216): Rotation corrected reference velocity vs. EDR velocity (time shifted 8.1 ms)



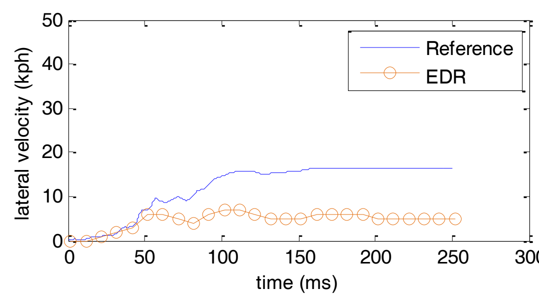
2013 Chevrolet Malibu (CEN1218): Rotation corrected reference velocity vs. EDR velocity (time shifted 24.3 ms)



2012 Mazda Mazda6 (CEN1220): Rotation corrected reference velocity vs. EDR velocity (time shifted 12.3 ms)

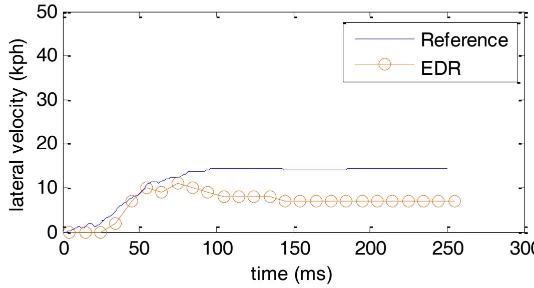


2013 Honda Accord (CEN1229): Rotation corrected reference velocity vs. EDR velocity (time shifted 1.6 ms)

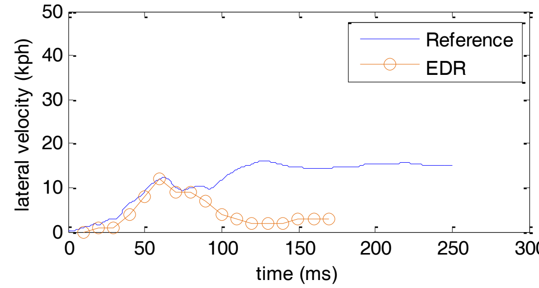


2013 Hyundai Tucson (CEN1237): Rotation corrected reference velocity vs. EDR velocity (time shifted 1.7 ms)

Figure A.8 Overlay of EDR and reference instrumentation lateral velocity versus time after optimization in time (small overlap crash test study)

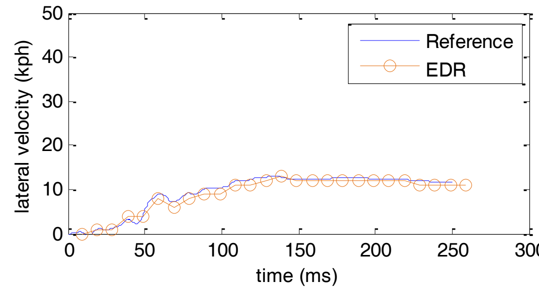


2013 Honda Civic (CEN1301): Rotation corrected reference velocity vs. EDR velocity (time shifted 4.7 ms)

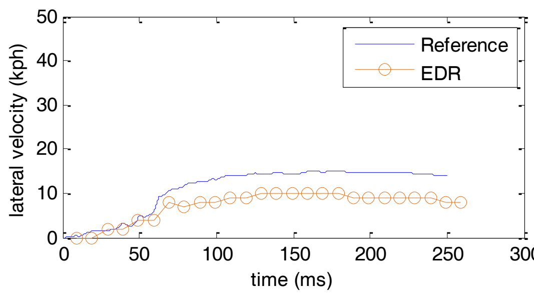


2013 Honda Civic (CEN1302): Rotation corrected reference velocity vs. EDR velocity (time shifted 9.9 ms)

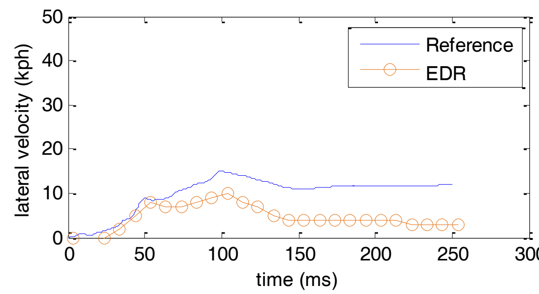
2013 Volvo XC60 (CEN1304): Lateral delta-v not available



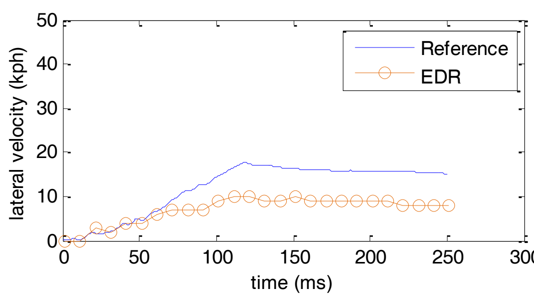
2013 Mazda CX5 (CEN1306): Rotation corrected reference velocity vs. EDR velocity (time shifted 8.8 ms)



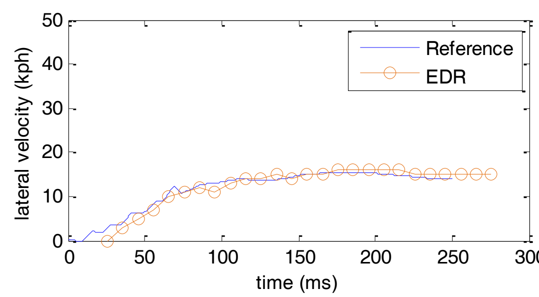
2013 Buick Encore (CEN1308): Rotation corrected reference velocity vs. EDR velocity (time shifted 9.2 ms)



2013 Hyundai Elantra (CEN1310): Rotation corrected reference velocity vs. EDR velocity (time shifted 3.6 ms)

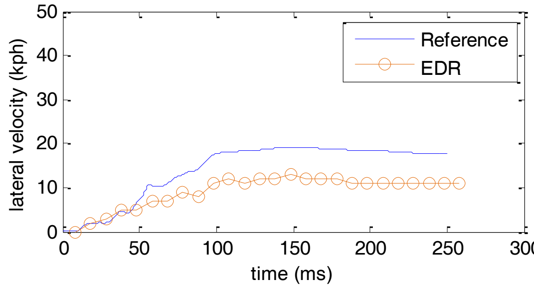


2013 Buick Encore (CEN1311): Rotation corrected reference velocity vs. EDR velocity (time shifted 1.6 ms)

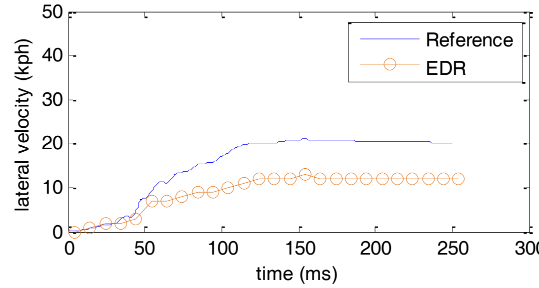


2013 Chevrolet Cruze (CEN1312): Rotation corrected reference velocity vs. EDR velocity (time shifted 22.7 ms)

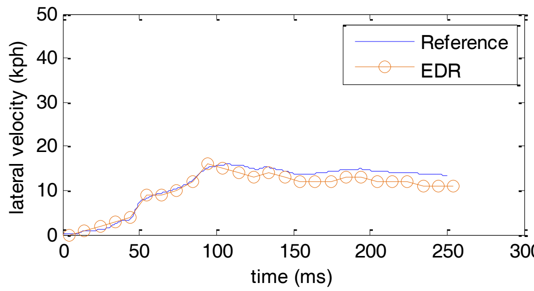
Figure A.8 (Cont'd) Overlay of EDR and reference instrumentation lateral velocity versus time after optimization in time (small overlap crash test study)



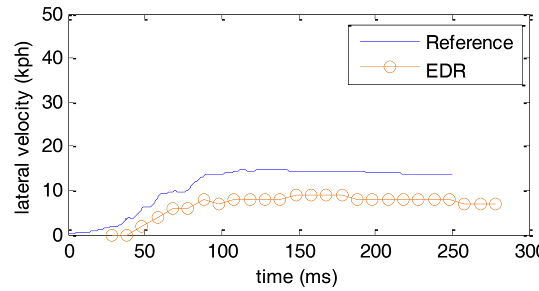
2013 Chevrolet Sonic (CEN1313): Rotation corrected reference velocity vs. EDR velocity (time shifted 3.3 ms)



2013 Ford Focus (CEN1314): Rotation corrected reference velocity vs. EDR velocity (time shifted 4.3 ms)



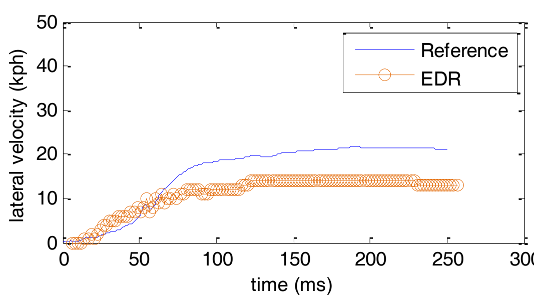
2013 Kia Soul (CEN1317): Rotation corrected reference velocity vs. EDR velocity (time shifted 4.4 ms)



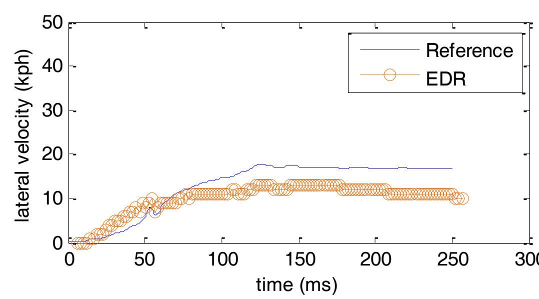
2014 Kia Forte (CEN1318): Rotation corrected reference velocity vs. EDR velocity (time shifted 28.3 ms)

2013 Toyota RAV4 (CEN1319): Lateral delta-v not available

2014 Scion tC (CEN1320): Lateral delta-v not available

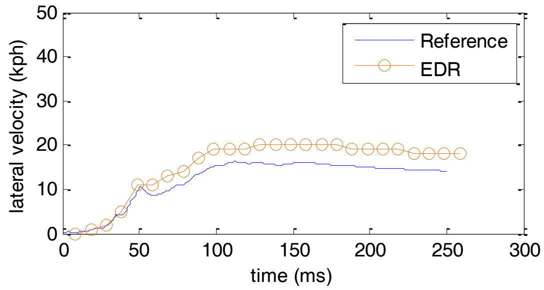


2013 Dodge Dart (CEN1321): Rotation corrected reference velocity vs. EDR velocity (time shifted 6.5 ms)

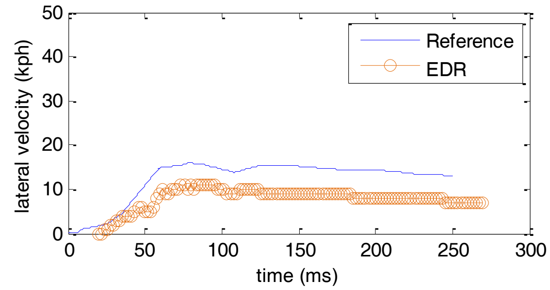


2013 Dodge Dart (CEN1322): Rotation corrected reference velocity vs. EDR velocity (time shifted 6.5 ms)

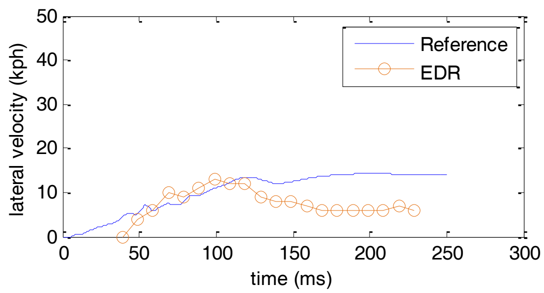
Figure A.8 (Cont'd) Overlay of EDR and reference instrumentation lateral velocity versus time after optimization in time (small overlap crash test study)



2013 Mazda Mazda2 (CEN1324): Rotation corrected reference velocity vs. EDR velocity (time shifted -2.3 ms)

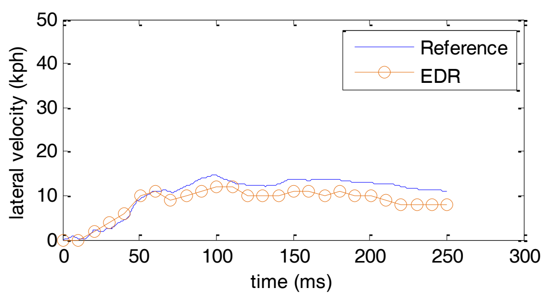


2013 Fiat 500 (CEN1325): Rotation corrected reference velocity vs. EDR velocity (time shifted 19.5 ms)



2014 Honda Odyssey (CEN1326): Rotation corrected reference velocity vs. EDR velocity (time shifted 38.8 ms)

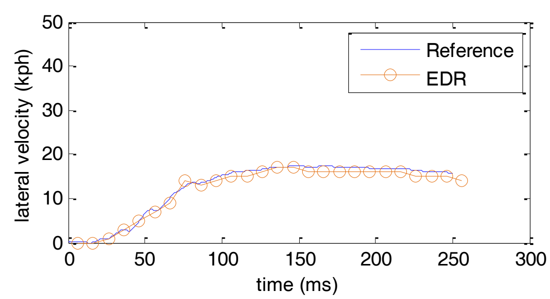
2013 Toyota Prius C (CEN1328):
Lateral delta-v not available



2013 Kia Rio (CEN1330): Rotation corrected reference velocity vs. EDR velocity (time shifted 0.4 ms)

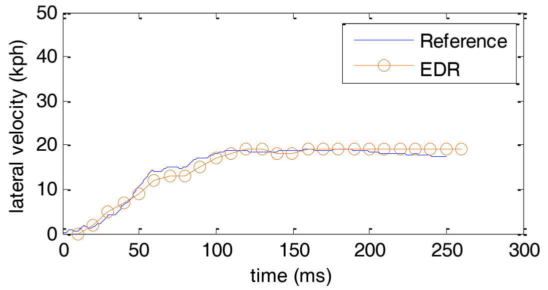
2013 Toyota Yaris (CEN1331):
Lateral delta-v not available

2014 Toyota Corolla (CEN1332):
Lateral delta-v not available

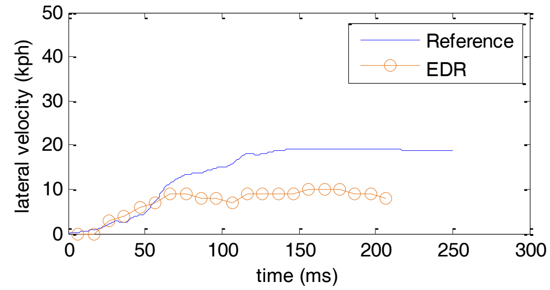


2014 Nissan Versa (CEN1334): Rotation corrected reference velocity vs. EDR velocity (time shifted 6.3 ms)

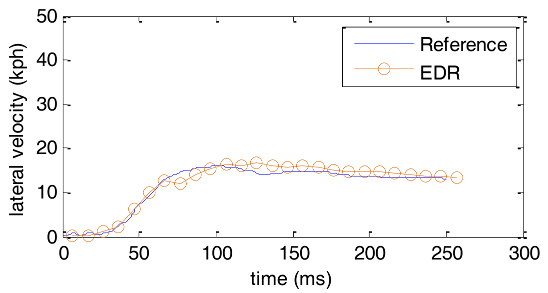
Figure A.8 (Cont'd) Overlay of EDR and reference instrumentation lateral velocity versus time after optimization in time (small overlap crash test study)



2013 Chevrolet Spark (CEN1335): Rotation corrected reference velocity vs. EDR velocity (time shifted 9.8 ms)

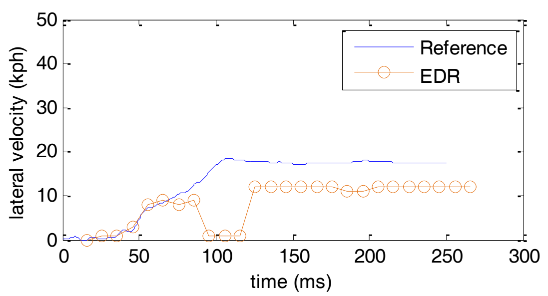


2014 Acura RLX (CEN1341): Rotation corrected reference velocity vs. EDR velocity (time shifted 6.7 ms)

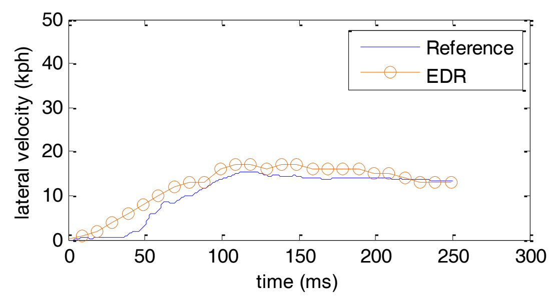


2014 Ford Fiesta (CEN1343): Rotation corrected reference velocity vs. EDR velocity (time shifted 6.5 ms)

2014 Volvo S80 (CEN1344): Lateral delta-v not available



2014 Mazda CX-5 (CEN1345): Rotation corrected reference velocity vs. EDR velocity (time shifted 15.8 ms)

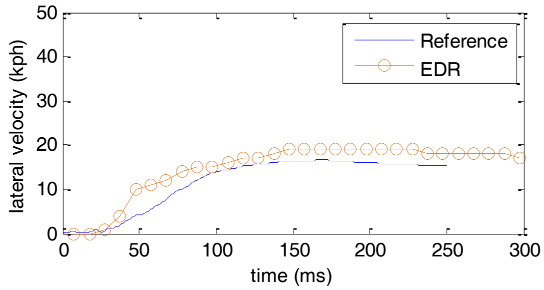


2014 Mazda Mazda3 (CEN1346): Rotation corrected reference velocity vs. EDR velocity (time shifted -1.1 ms)

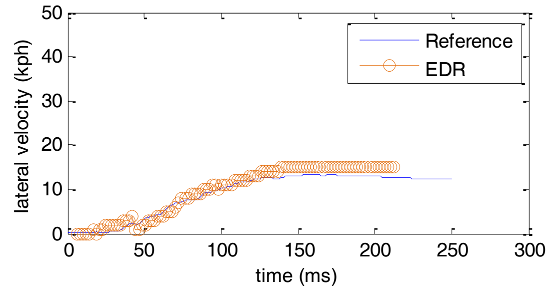
2014 Toyota Prius (CEN1347): Lateral delta-v not available

2014 Toyota Camry (CEN1349): Lateral delta-v not available

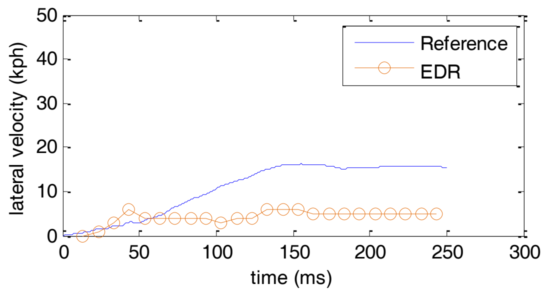
Figure A.8 (Cont'd) Overlay of EDR and reference instrumentation lateral velocity versus time after optimization in time (small overlap crash test study)



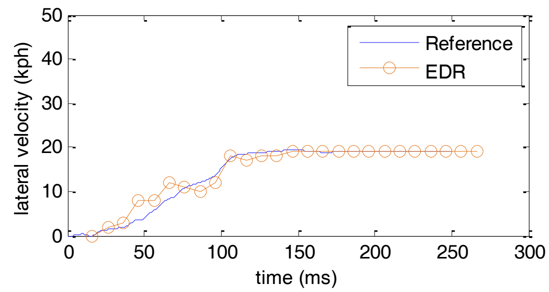
2014 Chevrolet Equinox (CEN1401): Rotation corrected reference velocity vs. EDR velocity (time shifted 7.5 ms)



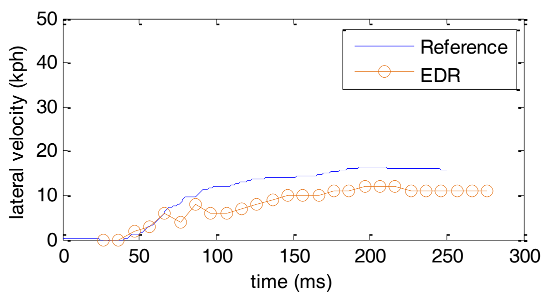
2014 Jeep Grand Cherokee (CEN1404): Rotation corrected reference velocity vs. EDR velocity (time shifted 6.5 ms)



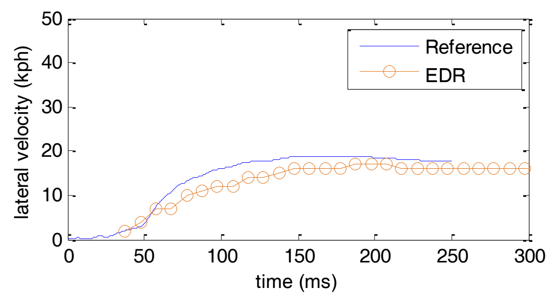
2014 Honda Pilot (CEN1405): Rotation corrected reference velocity vs. EDR velocity (time shifted 13.3 ms)



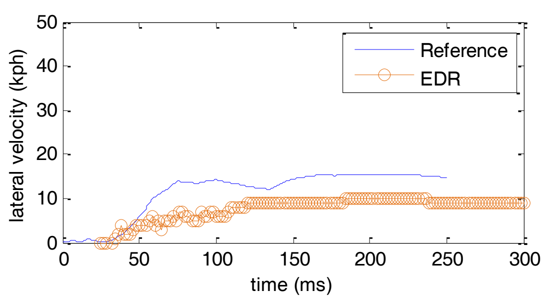
2014 Nissan Rogue (CEN1407): Rotation corrected reference velocity vs. EDR velocity (time shifted 16.2 ms)



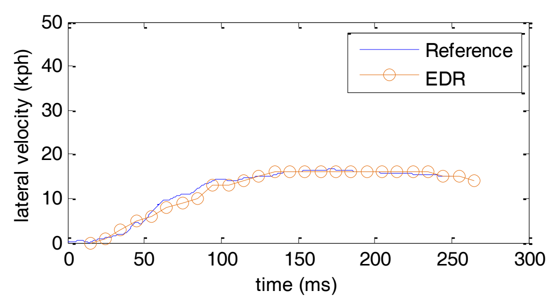
2014 Mazda CX-9 (CEN1408): Rotation corrected reference velocity vs. EDR velocity (time shifted 26.5 ms)



2014 Chevrolet Malibu (CEN1412): Rotation corrected reference velocity vs. EDR velocity (time shifted 27.7 ms)

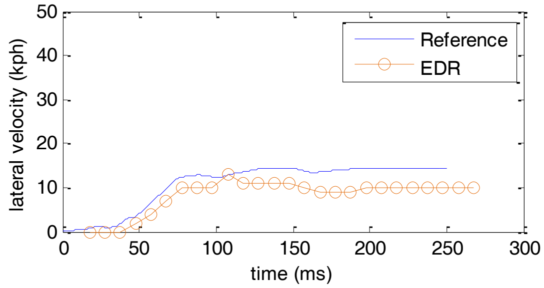


2014 Fiat 500L (CEN1414): Rotation corrected reference velocity vs. EDR velocity (time shifted 24.2 ms)

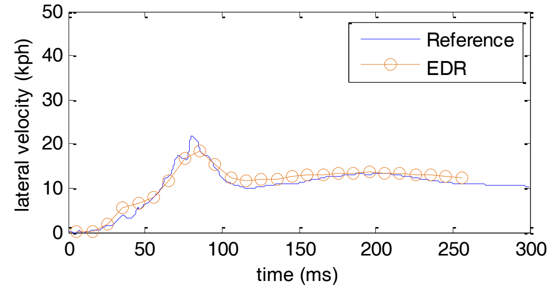


2014 Nissan Juke (CEN1416): Rotation corrected reference velocity vs. EDR velocity (time shifted 14.7 ms)

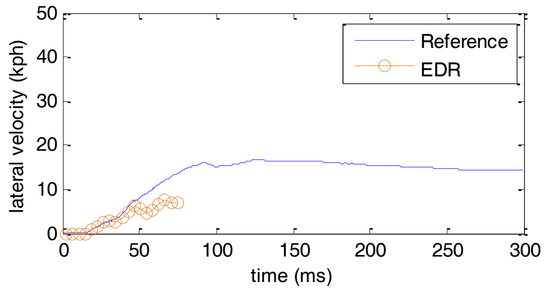
Figure A.8 (Cont'd) Overlay of EDR and reference instrumentation lateral velocity versus time after optimization in time (small overlap crash test study)



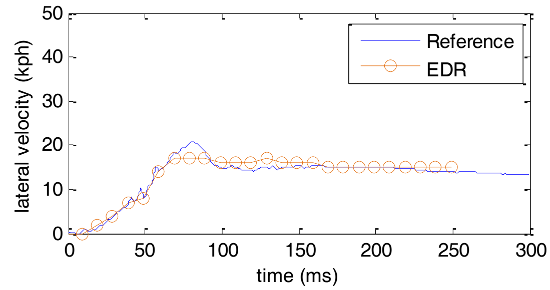
2014 Mazda Mazda5 (CEN1424): Rotation corrected reference velocity vs. EDR velocity (time shifted 17.5 ms)



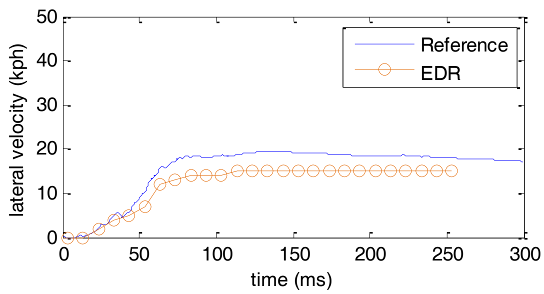
2010 Ford Fusion (RA0220): Rotation corrected reference velocity vs. EDR velocity (time shifted 5.7 ms)



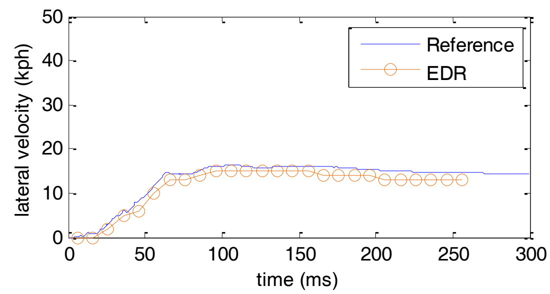
2010 Toyota Yaris (RA5135): Rotation corrected reference velocity vs. EDR velocity (time shifted 4.7 ms)



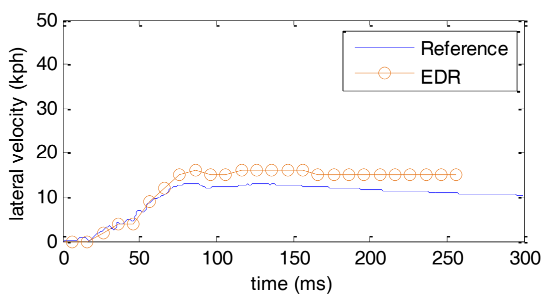
2011 Chevrolet Cruze (RB0178): Rotation corrected reference velocity vs. EDR velocity (time shifted 29.0 ms)



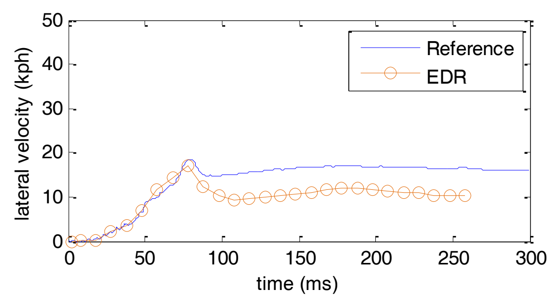
2011 Buick Lacrosse (RB0180): Rotation corrected reference velocity vs. EDR velocity (time shifted 33.3 ms)



2011 Chevrolet Cruze (RB0182): Rotation corrected reference velocity vs. EDR velocity (time shifted 36.1 ms)

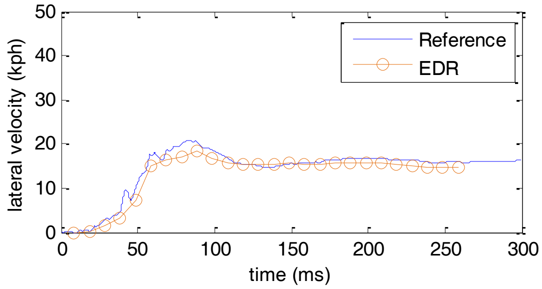


2011 Chevrolet Cruze (RB0183): Rotation corrected reference velocity vs. EDR velocity (time shifted 36.3 ms)

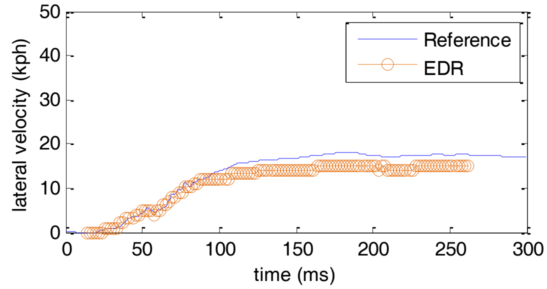


2011 Ford Explorer (RB0222): Rotation corrected reference velocity vs. EDR velocity (time shifted 2.3 ms)

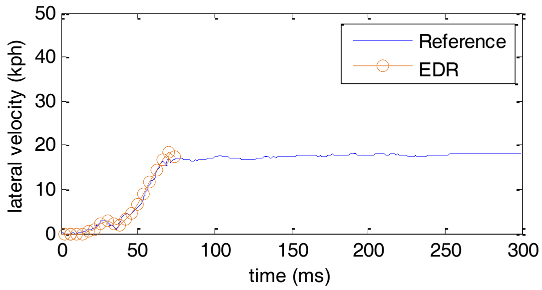
Figure A.8 (Cont'd) Overlay of EDR and reference instrumentation lateral velocity versus time after optimization in time (small overlap crash test study)



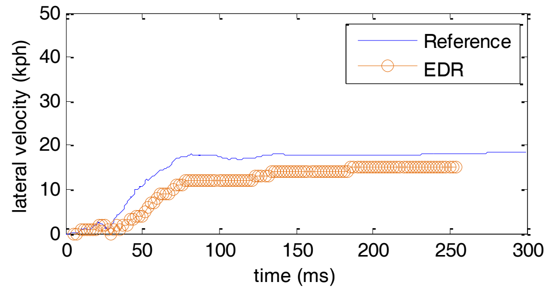
2011 Ford Fiesta (RB0224): Rotation corrected reference velocity vs. EDR velocity (time shifted 8.2 ms)



2011 Dodge Ram1500 (RB0330): Rotation corrected reference velocity vs. EDR velocity (time shifted 13.5 ms)

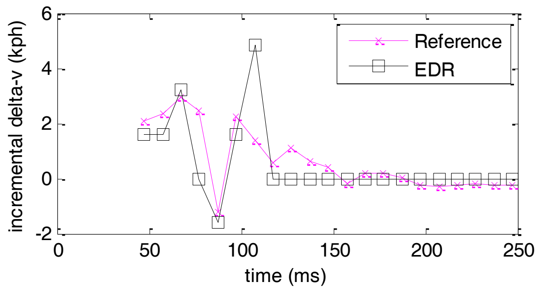


2010 Toyota Yaris (RB5137): Rotation corrected reference velocity vs. EDR velocity (time shifted 6.0 ms)

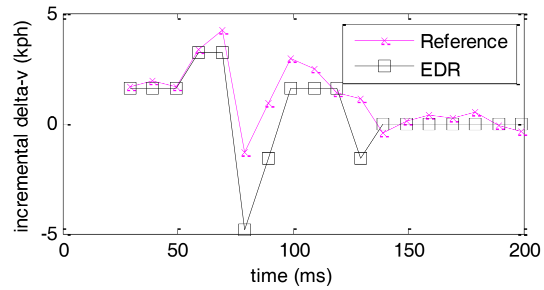


2012 Fiat 500 (RC0528): Rotation corrected reference velocity vs. EDR velocity (time shifted 5.7 ms)

Figure A.8 (Cont'd) Overlay of EDR and reference instrumentation lateral velocity versus time after optimization in time (small overlap crash test study)

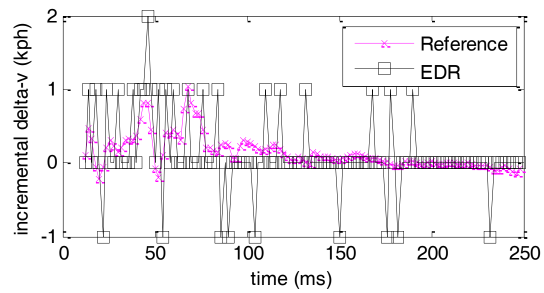


2012 Acura TSX (CEN1202): time shifted 27.3 ms

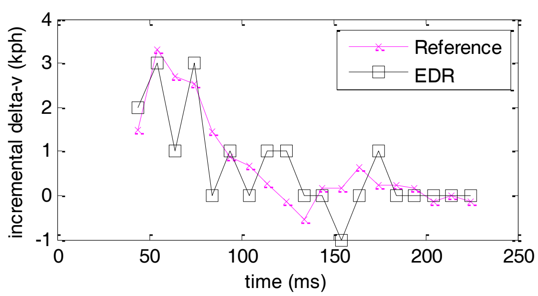


2012 Acura TSX (CEN1213): time shifted9.2 ms

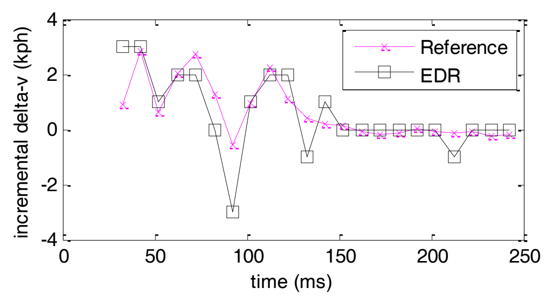
2012 Toyota Camry (CEN1215):
Lateral delta-v not available



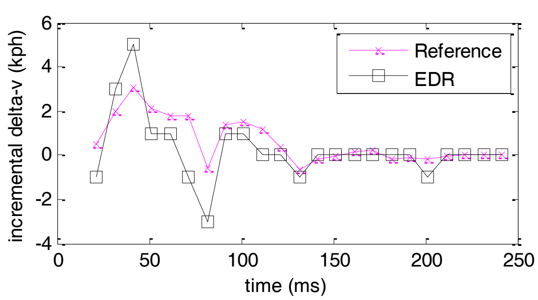
2012 Dodge Avenger (CEN1216): time shifted 8.1 ms



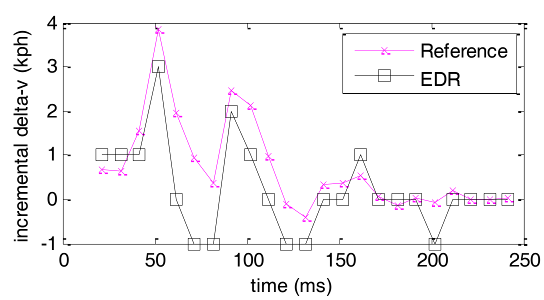
2013 Chevrolet Malibu (CEN1218): time shifted 24.3 ms



2012 Mazda Mazda6 (CEN1220): time shifted 12.3 ms

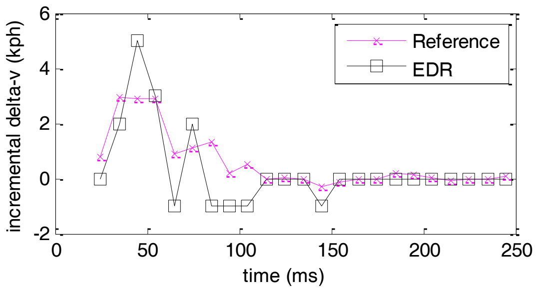


2013 Honda Accord (CEN1229): time shifted 1.6 ms

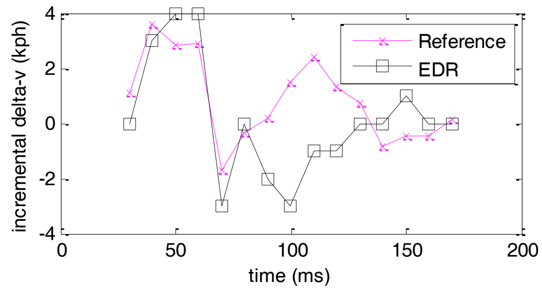


2013 Hyundai Tucson (CEN1237): time shifted 1.7 ms

Figure A.9 Overlay of EDR and reference instrumentation lateral incremental delta-v versus time after optimization in time (small overlap crash test study)

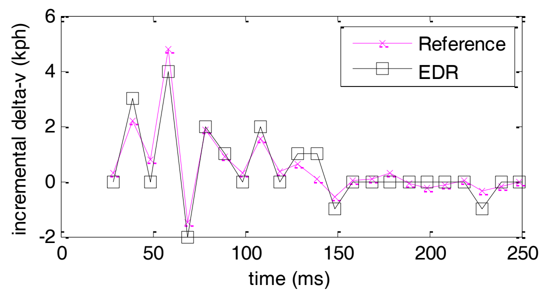


2013 Honda Civic (CEN1301): time shifted 4.7 ms

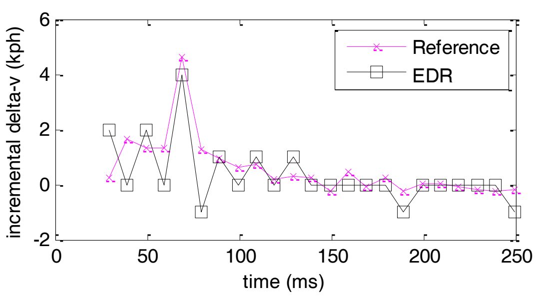


2013 Honda Civic (CEN1302): time shifted 9.9 ms

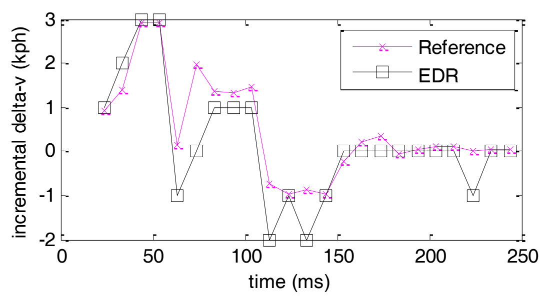
2013 Volvo XC60 (CEN1304):
Lateral delta-v not available



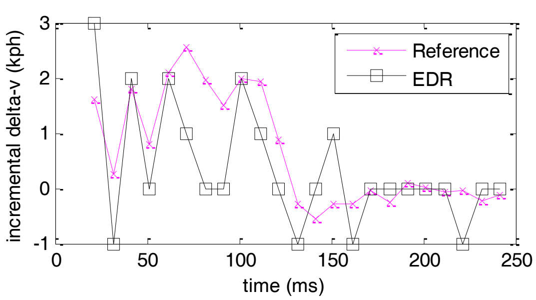
2013 Mazda CX5 (CEN1306): time shifted 8.8 ms



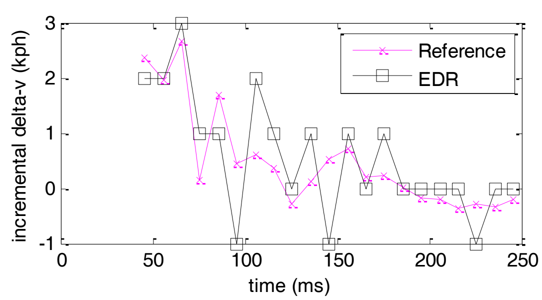
2013 Buick Encore (CEN1308): time shifted 9.2 ms



2013 Hyundai Elantra (CEN1310): time shifted 3.6 ms

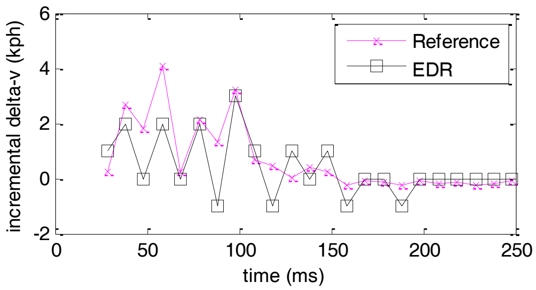


2013 Buick Encore (CEN1311): time shifted 1.6 ms

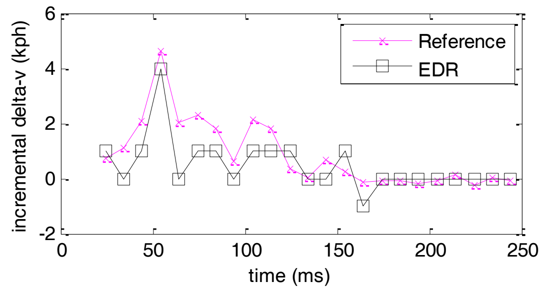


2013 Chevrolet Cruze (CEN1312): time shifted 22.7 ms

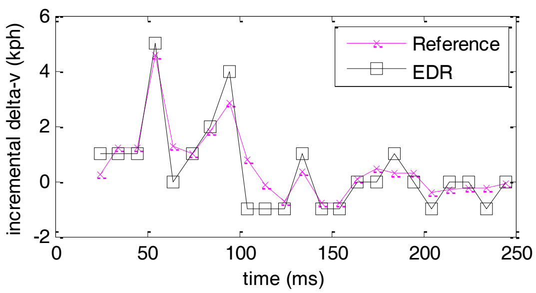
Figure A.9 (Cont'd) Overlay of EDR and reference instrumentation lateral incremental delta-v versus time after optimization in time (small overlap crash test study)



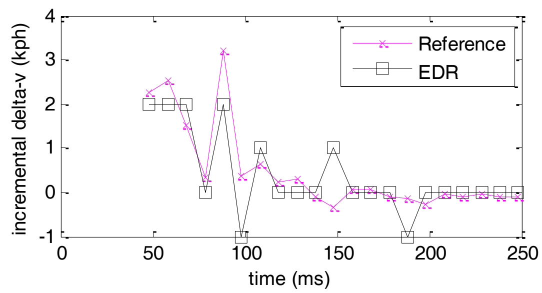
2013 Chevrolet Sonic (CEN1313): time shifted 3.3 ms



2013 Ford Focus (CEN1314): time shifted 4.3 ms



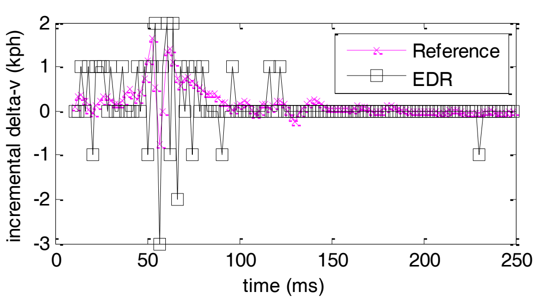
2013 Kia Soul (CEN1317): time shifted 4.4 ms



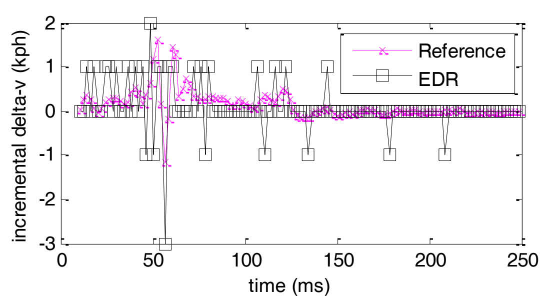
2014 Kia Forte (CEN1318): time shifted 28.3 ms

2013 Toyota RAV4 (CEN1319):
Lateral delta-v not available

2014 Scion tC (CEN1320):
Lateral delta-v not available

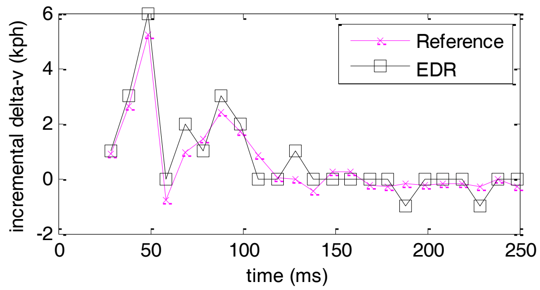


2013 Dodge Dart (CEN1321): time shifted 6.5 ms

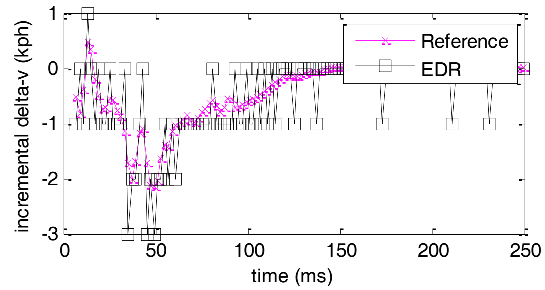


2013 Dodge Dart (CEN1322): time shifted 6.5 ms

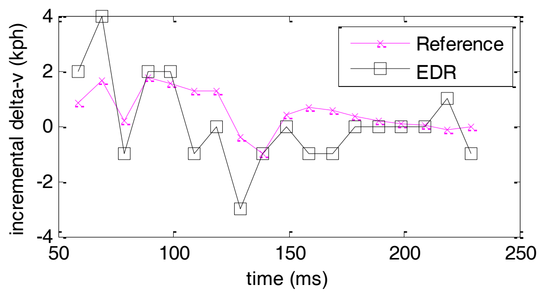
Figure A.9 (Cont'd) Overlay of EDR and reference instrumentation lateral incremental delta-v versus time after optimization in time (small overlap crash test study)



2013 Mazda Mazda2 (CEN1324): time shifted -2.3 ms

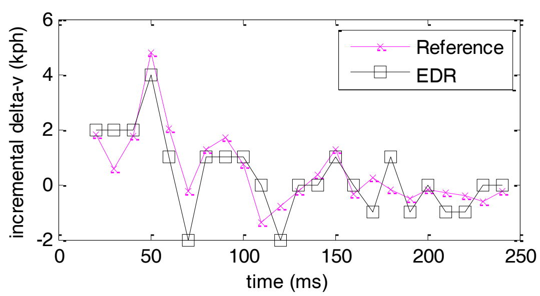


2013 Fiat 500 (CEN1325): time shifted 19.5 ms



2014 Honda Odyssey (CEN1326): time shifted 38.8 ms

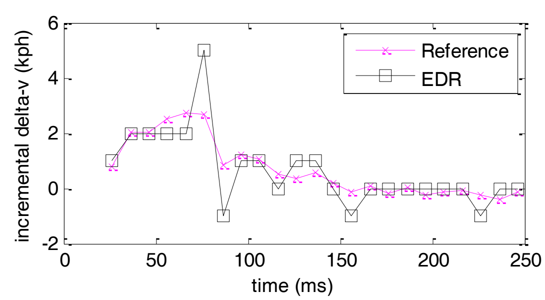
2013 Toyota Prius C (CEN1328):
Lateral delta-v not available



2013 Kia Rio (CEN1330): time shifted 0.4 ms

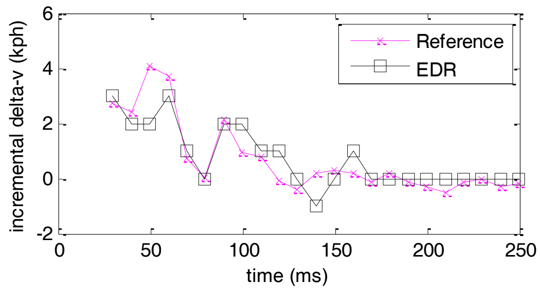
2013 Toyota Yaris (CEN1331):
Lateral delta-v not available

2014 Toyota Corolla (CEN1332):
Lateral delta-v not available

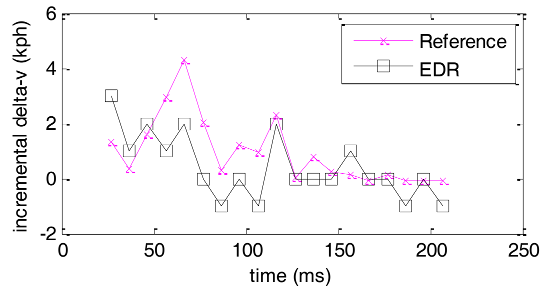


2014 Nissan Versa (CEN1334): time shifted 6.3 ms

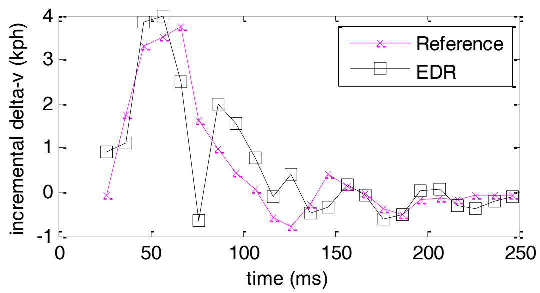
Figure A.9 (Cont'd) Overlay of EDR and reference instrumentation lateral incremental delta-v versus time after optimization in time (small overlap crash test study)



2013 Chevrolet Spark (CEN1335): time shifted 9.8 ms

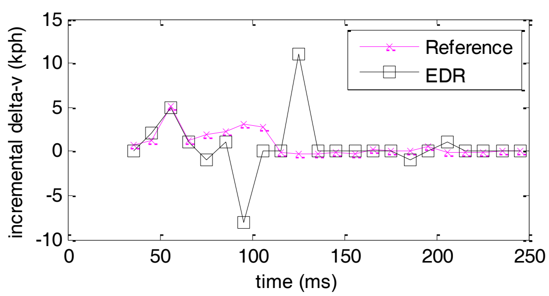


2014 Acura RLX (CEN1341): time shifted 6.7 ms

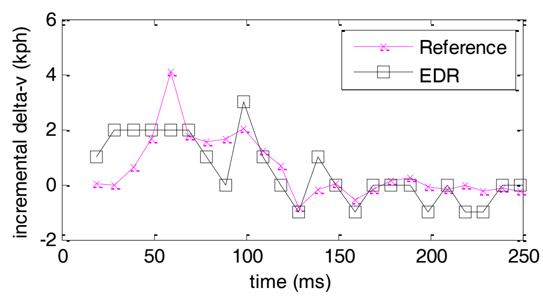


2014 Ford Fiesta (CEN1343): time shifted 6.5 ms

2014 Volvo S80 (CEN1344):
Lateral delta-v not available



2014 Mazda CX-5 (CEN1345): time shifted 15.8 ms

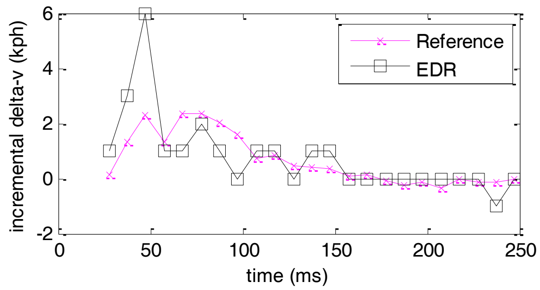


2014 Mazda Mazda3 (CEN1346): time shifted -1.1 ms

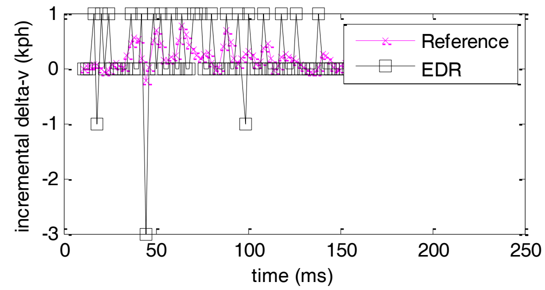
2014 Toyota Prius (CEN1347):
Lateral delta-v not available

2014 Toyota Camry (CEN1349):
Lateral delta-v not available

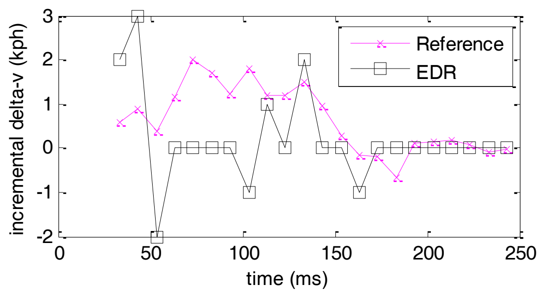
Figure A.9 (Cont'd) Overlay of EDR and reference instrumentation lateral incremental delta-v versus time after optimization in time (small overlap crash test study)



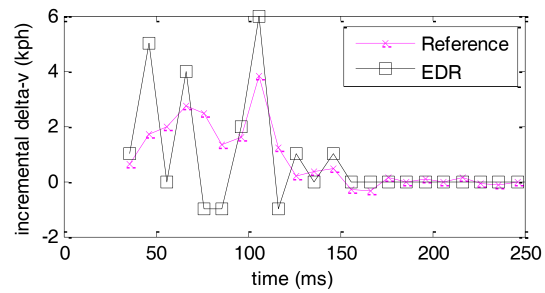
2014 Chevrolet Equinox (CEN1401): time shifted 7.5 ms



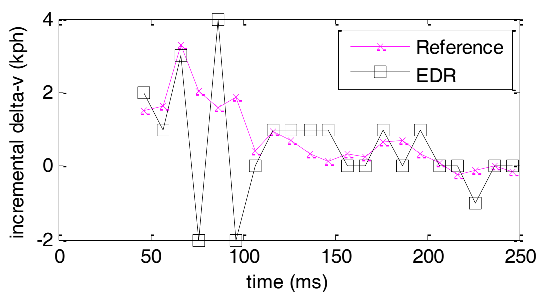
2014 Jeep Grand Cherokee (CEN1404): time shifted 6.5 ms



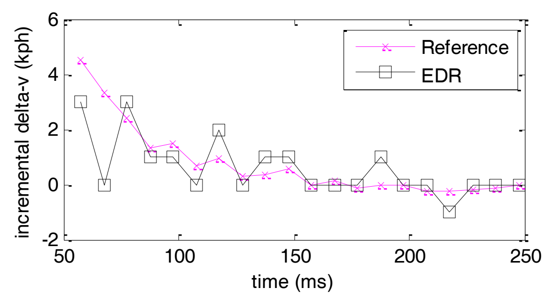
2014 Honda Pilot (CEN1405): time shifted 13.3 ms



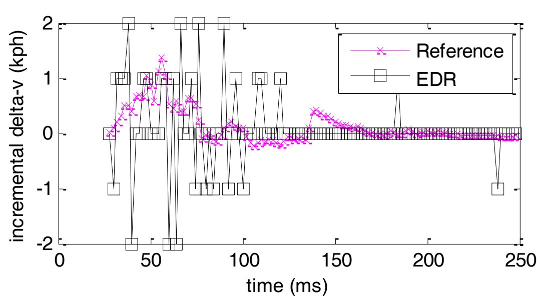
2014 Nissan Rogue (CEN1407): time shifted 16.2 ms



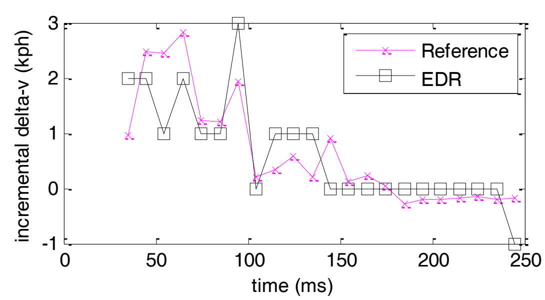
2014 Mazda CX-9 (CEN1408): time shifted 26.5 ms



2014 Chevrolet Malibu (CEN1412): time shifted 27.7 ms

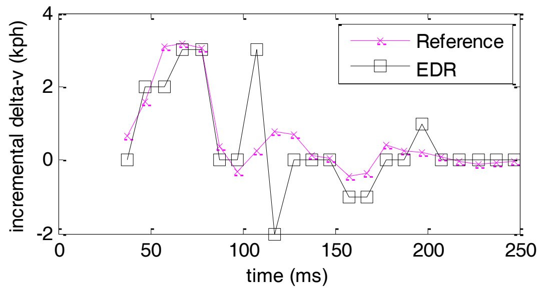


2014 Fiat 500L (CEN1414): time shifted 24.2 ms

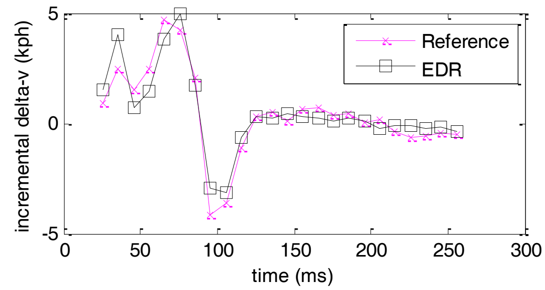


2014 Nissan Juke (CEN1416): time shifted 14.7 ms

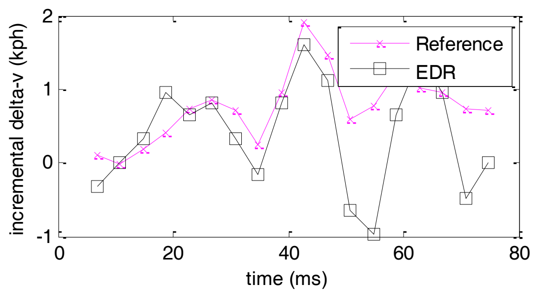
Figure A.9 (Cont'd) Overlay of EDR and reference instrumentation lateral incremental delta-v versus time after optimization in time (small overlap crash test study)



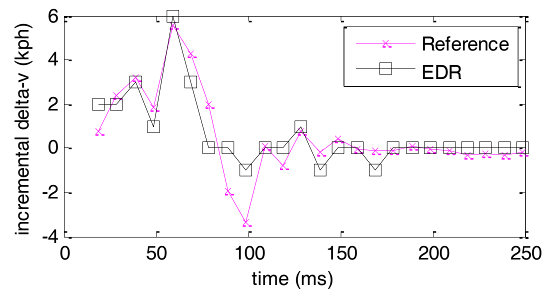
2014 Mazda Mazda5 (CEN1424): time shifted 17.5 ms



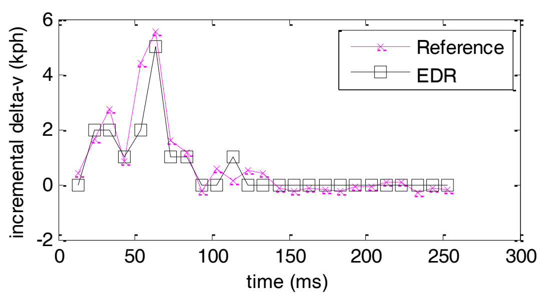
2010 Ford Fusion (RA0220): time shifted 5.7 ms



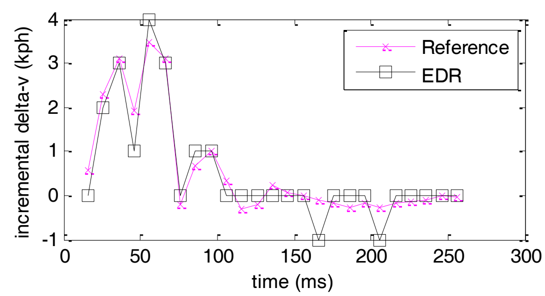
2010 Toyota Yaris (RA5135): time shifted 4.7 ms



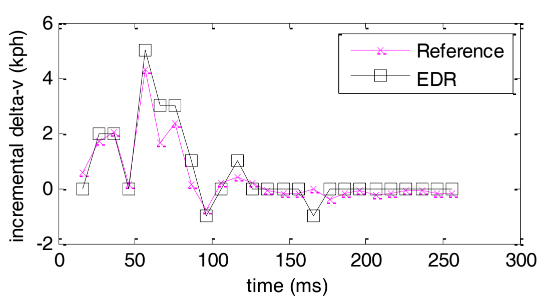
2011 Chevrolet Cruze (RB0178): time shifted 29.0 ms



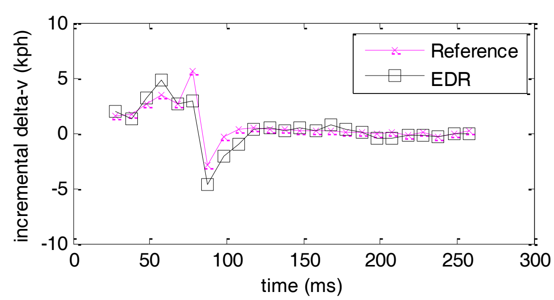
2011 Buick Lacrosse (RB0180): time shifted 33.3 ms



2011 Chevrolet Cruze (RB0182): time shifted 36.1 ms

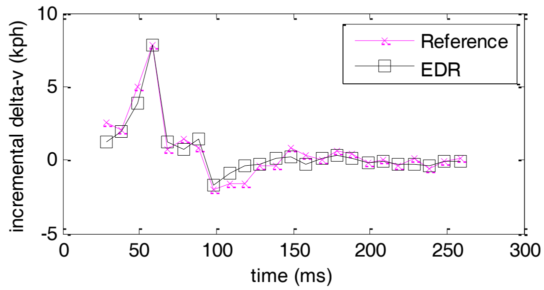


2011 Chevrolet Cruze (RB0183): time shifted 36.3 ms

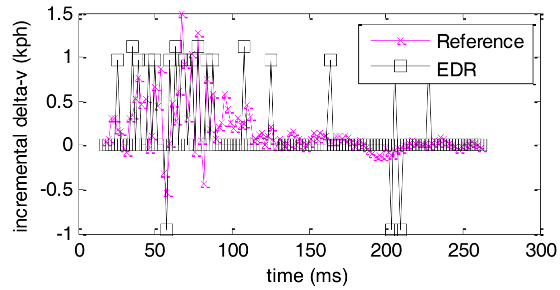


2011 Ford Explorer (RB0222): time shifted 2.3 ms

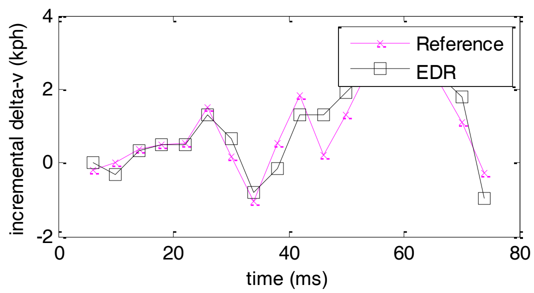
Figure A.9 (Cont'd) Overlay of EDR and reference instrumentation lateral incremental delta-v versus time after optimization in time (small overlap crash test study)



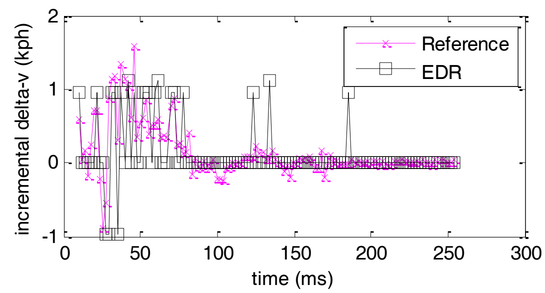
2011 Ford Fiesta (RB0224): time shifted 8.2 ms



2011 Dodge Ram1500 (RB0330): time shifted 13.5 ms



2010 Toyota Yaris (RB5137): time shifted 6.0 ms



2012 Fiat 500 (RC0528): time shifted 5.7 ms

Figure A.9 (Cont'd) Overlay of EDR and reference instrumentation lateral incremental delta-v versus time after optimization in time (small overlap crash test study)

Table A.13 Seatbelt study dataset composition

	Unweighted		Weighted	
Total	1,086		404,904	
Driver Weight (kg)				
Unknown	159	(15%)	69,886	(17%)
00 - 49	19	(02%)	7,038	(02%)
50 - 99	733	(67%)	279,342	(69%)
100 - 149	165	(15%)	48,247	(12%)
150+	10	(01%)	391	(00%)
EDR Belt Use				
Unbuckled	302	(28%)	136,996	(34%)
Buckled	784	(72%)	267,908	(66%)
NASS Belt Use (ManUse)				
None Used/Available	271	(25%)	86,887	(21%)
Lap and Shoulder	815	(75%)	318,017	(79%)
NASS Belt Source (BeltSou)				
Not Equipped/Available	2	(00%)	1,025	(00%)
Vehicle Inspection	1,072	(99%)	396,940	(98%)
Off Injury Data	2	(00%)	984	(00%)
Driver/Occupant Interview	8	(01%)	4,443	(01%)
Other	2	(00%)	1,513	(00%)
Police Belt Use (ParUse)				
None Used	73	(07%)	12,227	(03%)
Shoulder Belt	10	(01%)	4,902	(01%)
Lap Belt	8	(01%)	33,908	(08%)
Lap/Shoulder	929	(86%)	297,642	(74%)
Belt Used-Type Unknown	66	(06%)	56,225	(14%)
Pretensioners				
Not equipped	219	(20%)	98,363	(24%)
Equipped	867	(80%)	306,541	(76%)
Number of Events				
1	654	(60%)	294,517	(73%)
5	273	(25%)	77,490	(19%)
3	105	(10%)	23,771	(06%)
4	21	(02%)	3,432	(01%)
5	16	(01%)	3,584	(01%)
6	8	(01%)	1,172	(00%)
7	5	(00%)	406	(00%)
8	2	(00%)	212	(00%)
9	1	(00%)	258	(00%)
14	1	(00%)	63	(00%)
Total Delta-V (mph)				
Unknown	266	(24%)	125,161	(31%)
0-19	611	(56%)	231,022	(57%)
20-39	193	(18%)	47,141	(12%)
40-59	15	(01%)	1,495	(00%)
60-79	1	(00%)	87	(00%)

Table A.13 (Cont'd) Seatbelt study dataset composition

	Unweighted		Weighted	
Total	1,086		404,904	
General Area of Damage (GAD1)				
Unknown	6	(01%)	3,637	(01%)
Back	8	(01%)	1,055	(00%)
Front	920	(85%)	333,294	(82%)
Left Side	73	(07%)	15,602	(04%)
Right Side	52	(05%)	43,144	(11%)
Top	22	(02%)	7,835	(02%)
Undercarriage	5	(00%)	337	(00%)
Vehicle Body Type				
Passenger Cars	616	(57%)	225,493	(56%)
Light Trucks	192	(18%)	59,271	(15%)
Sports Utility Vehicles	234	(22%)	107,561	(27%)
Vans	38	(03%)	11,593	(03%)
Vehicle Manufacturer				
Chrysler	11	(01%)	3,979	(01%)
Ford	67	(06%)	18,051	(04%)
GM	829	(76%)	314,074	(78%)
Toyota	179	(16%)	68,800	(17%)
Injury Severity (MAIS)				
Unknown	23	(02%)	10,271	(03%)
0 - Not Injured	265	(24%)	147,857	(37%)
1 - Minor Injury	508	(47%)	198,760	(49%)
2 - Moderate Injury	132	(12%)	24,280	(06%)
3 - Serious Injury	77	(07%)	8,894	(02%)
4 - Severe Injury	27	(02%)	2,209	(01%)
5 - Critical Injury	7	(01%)	548	(00%)
6 - Maximum Injury	5	(00%)	320	(00%)
Injured, Severity Unknown	42	(04%)	11,767	(03%)
Case Years				
2001	1	(00%)	46	(00%)
2002	1	(00%)	2,233	(01%)
2003	16	(01%)	7,551	(02%)
2004	29	(03%)	3,062	(01%)
2005	35	(03%)	48,081	(12%)
2006	60	(06%)	17,621	(04%)
2007	44	(04%)	16,304	(04%)
2008	56	(05%)	11,491	(03%)
2012	87	(08%)	19,115	(05%)
2010	79	(07%)	22,067	(05%)
2011	195	(18%)	60,996	(15%)
2012	237	(22%)	76,600	(19%)
2013	246	(23%)	119,738	(30%)

Table A.13 (Cont'd) Seatbelt study dataset composition

	Unweighted		Weighted	
Total	1,086		404,904	
Rollover				
No Rollover	1,015	(93%)	387,529	(96%)
Rollover	68	(06%)	17,179	(04%)
End-Over-End	3	(00%)	259	(00%)
Bosch CDR Module Name				
CHRY0305	4	(00%)	2,274	(01%)
CHRY0403	1	(00%)	110	(00%)
CHRY4005	6	(01%)	1,595	(00%)
Epsilon2005	35	(03%)	11,184	(03%)
Epsilon2006	192	(18%)	101,513	(25%)
FordAB10	5	(00%)	1,163	(00%)
FordRC62011CGEAB	2	(00%)	63	(00%)
FordRC62011CGEAD	9	(01%)	1,342	(00%)
FordRC6_2010	22	(02%)	4,941	(01%)
FordRC6_2011	29	(03%)	10,543	(03%)
SDM10	48	(04%)	16,291	(04%)
SDM10P	6	(01%)	1,216	(00%)
SDM11_AUTOLIVNEW	6	(01%)	393	(00%)
SDMC2006	101	(09%)	25,579	(06%)
SDMC2008V	25	(02%)	5,677	(01%)
SDMD2002	20	(02%)	9,718	(02%)
SDMDG2002	13	(01%)	4,539	(01%)
SDMDS2005	14	(01%)	2,044	(01%)
SDMDW2003	136	(13%)	38,651	(10%)
SDMGF2002	214	(20%)	53,063	(13%)
SDMGT2002	19	(02%)	44,205	(11%)
TOYOTA001	179	(16%)	68,800	(17%)

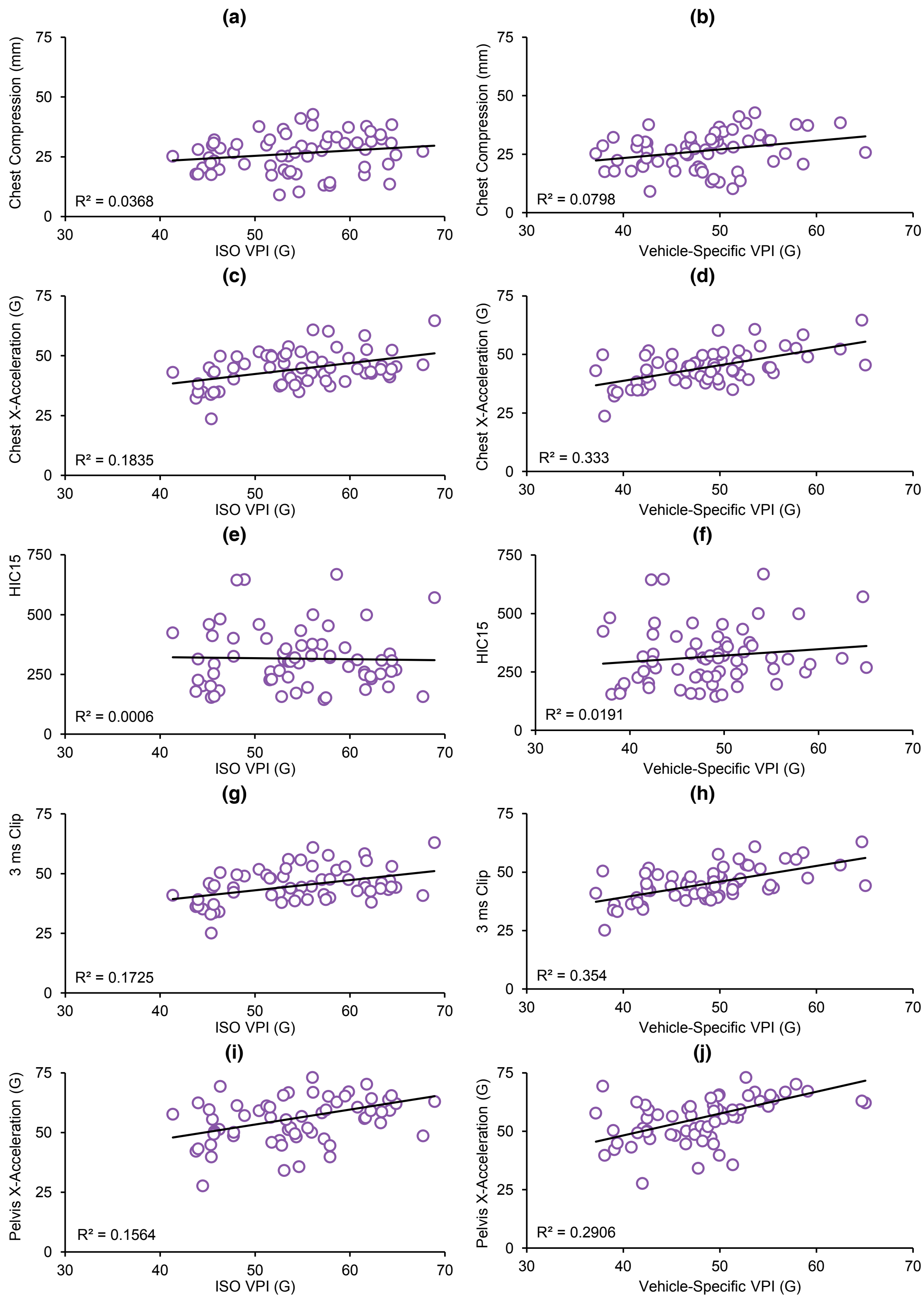


Figure A.10 (a,c,e,g,i) ISO VPI and (b,d,f,h,j) vehicle-specific VPI determined from frontal (56 kph) New Car Assessment Program crash tests, relative to occupant kinematics and injury metrics.

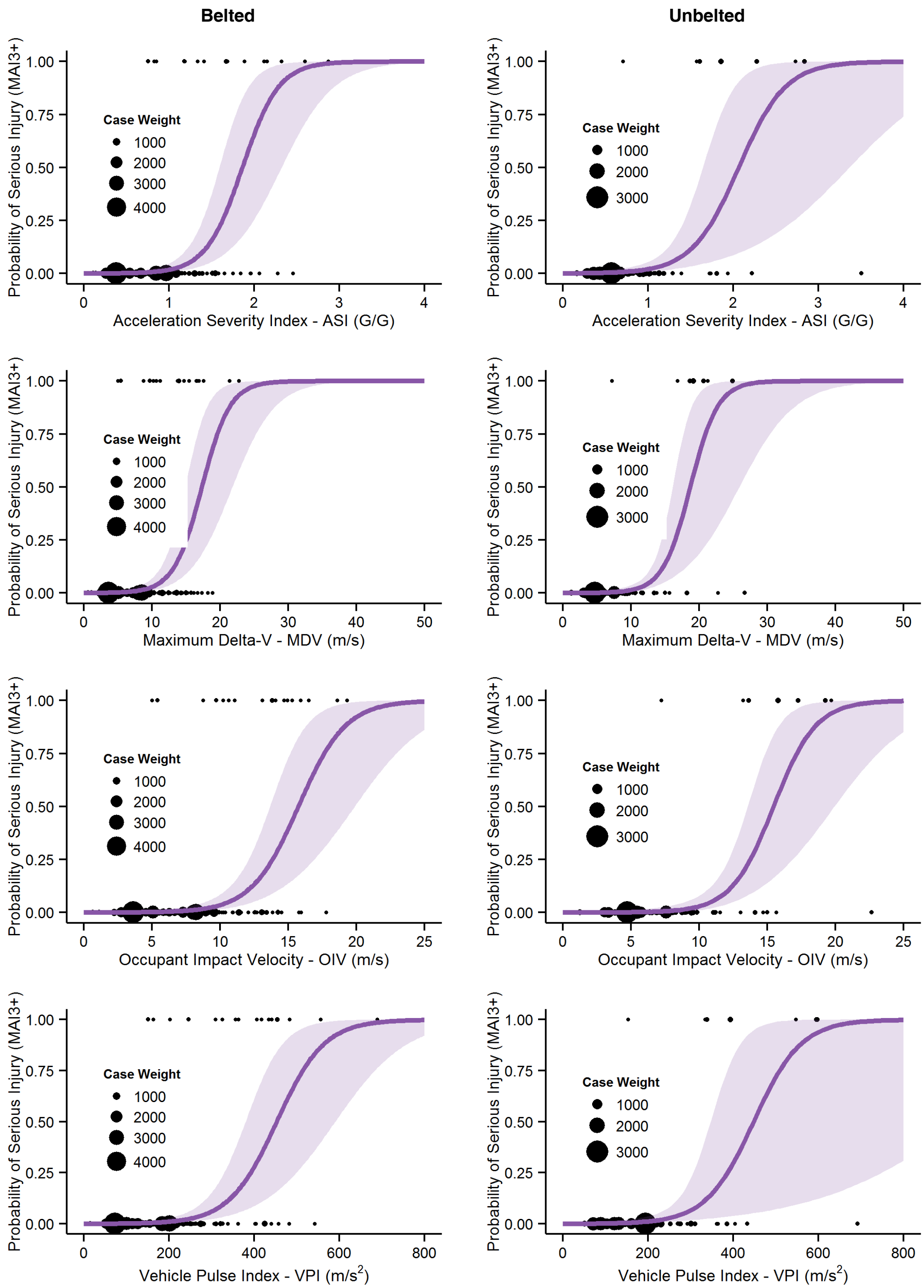


Figure A.11 Serious-injury risk as a function of ASI, delta-v, OIV, and VPI, separated by belt use

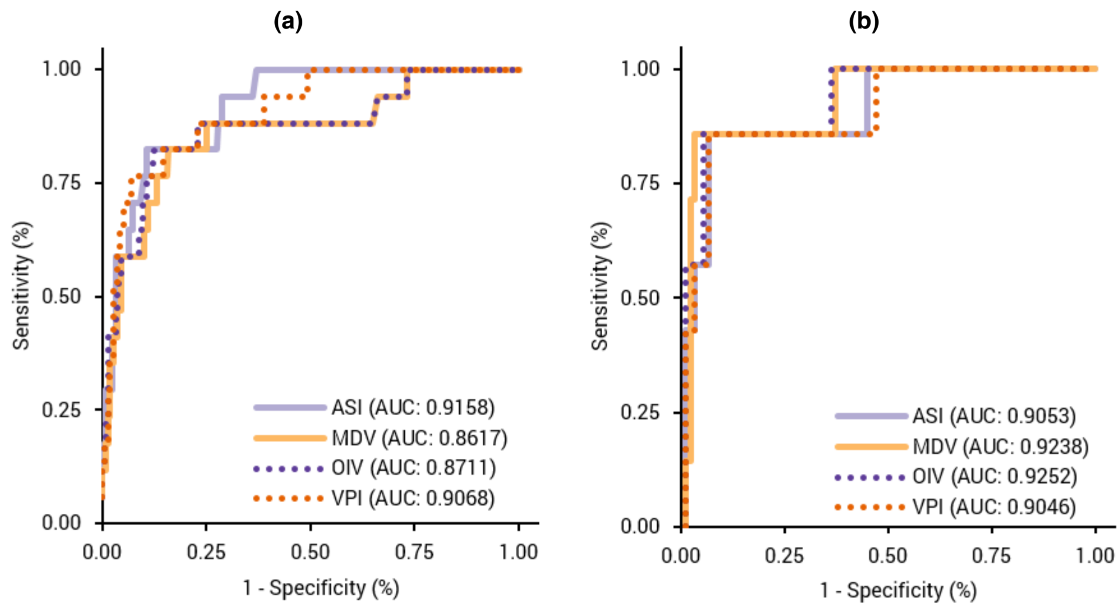


Figure A.12 Receiver operator characteristic (ROC) curves for (a) belted and (b) unbelted drivers

Table A.14. Vehicle-specific slack and stiffness values for calculation of vehicle pulse index (VPI)

Makmod Code	Model Year Range	Test No.	Make & Model	Slack (m)	Stiffness (N/m)
18002	2000-2005	3520	Buick Lesabre	0.0009	1,996
18003	1997-2005	3534	Buick Park Avenue	0.0239	1,688
18010	2011-2015	7740	Buick Regal eAssist	0.0005	1,644
18022	2010-2015	7370	Buick Lacrosse	0.0007	1,604
18023	2006-2011	7066	Buick Lucerne	0.0007	1,433
18401	2002-2007	5310	Buick Rendezvous	0.0466	2,135
19003	2000-2004	4837	Cadillac De Ville	0.0007	1,347
19018	2008-2014	7521	Cadillac CTS	0.0000	1,259
19020	2004-2013	8066	Cadillac SRX	0.0007	1,556
19021	2005-2011	6070	Cadillac STS	0.0000	1,323
19022	2006-2011	5569	Cadillac DTS	0.0003	1,178
20001	2008-2012	6998	Chevrolet Malibu	0.0007	1,885
20002	2000-2005	3471	Chevrolet Impala	0.0007	1,310
20002	1999-2006	7488	Chevrolet Impala	0.0007	1,709
20002	2014-2015	8290	Chevrolet Impala	0.0007	1,851
20009	2010-2013	7494	Chevrolet Camaro	0.0007	1,103
20016	1995-2005	4445	Chevrolet Cavalier	0.0000	1,412
20020	1995-2001	2742	Chevrolet Lumina	0.0007	1,144
20022	2005-2010	5326	Chevrolet Cobalt	0.0000	1,337
20023	2006-2011	5602	Chevrolet HHR	0.0000	1,389
20024	2002-2009	5303	Chevrolet Trailblazer	0.0054	3,215
20024	2002-2009	5572	Chevrolet Trailblazer Ext	0.0161	3,035
20024	2009-2013	8125	Chevrolet Traverse	0.0007	1,455
20025	2008-2014	8043	Chevrolet Cruze	0.0192	2,615
20026	2011-2015	7393	Chevrolet Volt	0.0049	3,351
20036	2000-2005	3524	Chevrolet Monte Carlo	0.0005	1,328
20036	2006-2007	5578	Chevrolet Monte Carlo	0.0007	1,505
20037	2004-2007	4863	Chevrolet Malibu	0.0140	4,372
20037	2008-2012	6268	Chevrolet Malibu	0.0000	1,614
20039	2002-2011	5873	Chevrolet Aveo	0.0298	2,870
20401	1995-2005	3901	Chevrolet Blazer	0.0001	1,952
20402	2003-2003	2376	Geo Tracker	0.0131	2,515
20402	2003-2003	3521	Chevrolet Tracker	0.0170	3,828
20404	2010-2015	6788	Chevrolet Equinox	0.0007	838
20421	2007-2014	7026	Chevrolet Tahoe	0.0002	2,192
20431	2006-2014	7509	Chevrolet Suburban	0.0109	2,927
20441	1995-2005	3029	Chevrolet Astro	0.0176	2,314
20442	1997-2005	3676	Chevrolet Venture	0.0005	1,096
20444	2005-2009	5264	Chevrolet Uplander	0.0112	1,602
20461	1996-2014	5265	Chevrolet Express	0.0000	2,329
20471	1994-2004	3252	Chevrolet S-10	0.0101	2,909

Table A.14 (Cont'd) Vehicle-specific slack and stiffness values for calculation of vehicle pulse index (VPI)

Makmod Code	Model Year Range	Test No.	Make & Model	Slack (m)	Stiffness (N/m)
20473	2004-2012	5603	Chevrolet Colorado	0.0265	2,523
20481	1987-1998	2809	Chevrolet C1500 Pickup	0.0005	1,263
20481	1999-2006	5318	Chevrolet Silverado	0.0000	1,843
20481	2007-2013	5907	Chevrolet Silverado	0.0074	2,698
20481	2007-2013	8026	Chevrolet Silverado 2500	0.0096	3,118
20481	2014-2015	8316	Chevrolet Silverado 1500	0.0102	3,225
20482	2007-2013	5856	Chevrolet Avalanche	0.0000	2,735
21022	2001-2003	3481	Oldsmobile Aurora	0.0144	2,417
21023	1999-2003	3007	Oldsmobile Intrigue	0.0007	1,347
22018	1999-2005	3617	Pontiac Grand Am	0.0000	1,264
22020	2004-2008	5468	Pontiac Grand Prix	0.0000	1,358
22022	2005-2010	5250	Pontiac G6	0.0007	1,221
22023	2006-2010	5859	Pontiac Solstice	0.0007	1,261
22401	2001-2005	3552	Pontiac Aztek	0.0233	1,974
22441	1999-2005	5324	Pontiac Montana	0.0000	1,349
23401	2002-2009	4918	GMC Envoy Xuv	0.0179	2,816
23421	2000-2006	4567	Chevrolet Suburban	0.0050	3,070
24007	2003-2007	4487	Saturn Ion	0.0007	1,524
24009	2007-2010	5844	Saturn Aura	0.0007	1,126
24010	2007-2010	5914	Saturn Outlook	0.0007	1,174
24401	2002-2007	4931	Saturn Vue	0.0005	1,193