STUDY ON PRE-CRASH AND POST-CRASH INFORMATION RECORDED IN ELECTRONIC CONTROL UNITS (ECUS) INCLUDING EVENT DATA RECORDERS

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ABSTRACT

It is known that some Electronic Control Units (ECUs) that are installed in a vehicle can record pre-crash and/or post-crash information in an accident. The aim of this study is to understand the availability and usefulness of the ECU data and to develop various analysis methods enhancing the accident investigation.

With respect to ABS-ECU, engine-ECU, and Event Data Recorder (EDR), two types of crash test data are analyzed in this study. The first type is the J-NCAP crash tests, for understanding the EDR characteristics under standardized crash test conditions. The second type is the real-world accident reconstructions for evaluating the performance of those ECUs under highly complex and/or severe crash conditions, including multiple rear-end collisions, car-to-car side impacts, and frontal and side pole impacts. The data obtained from ECUs are compared with the results from the instrumented sensors.

The study concludes that, the pre-crash velocities recorded by the EDR were highly accurate and reliable when cars proceeded without braking prior to the collision. The accuracy and reliability of the EDR impact velocity could be affected by the braking conditions and the EDR time zero information. The accuracy and reliability of the maximum delta-V recorded by the EDR decreased under highly complex or severe crash conditions, especially in the pole impacts. The EDRs underestimated the maximum delta-V in almost all the J-NCAP tests. The difference between the EDR maximum delta-V and the reference value was greater than 10 % in 4 of 14 tests. One of the factors responsible for this result might be attributable to the characteristics of the accelerometers used in EDR.

Diagnosis freeze data recorded in ABS-ECU and engine-ECU have a potential to be utilized for the accident investigation by providing additional pre-crash vehicle information. However, further study is needed for understanding the reliability and accuracy of the diagnosis freeze data.

INTRODUCTION

Currently, many Electronic Control Units (ECUs) are used in a vehicle. Our preliminary study suggests that some ECUs such as ABS-ECU and engine-ECU could record pre-crash information in an accident [Nakano et al, 2008]. An ABS-ECU may record the tire wheel velocity when one of the four wheels is damaged at the collision. An engine-ECU could also record the engine control data including pre-crash vehicle speed when the engine is damaged at the collision.

Whereas, Event Data Recorder (EDR) is an additional function installed in airbag control module (ACM) to record vehicle and occupant information for a brief period of time before, during, and after a crash event. Accordingly, EDRs are promising for accident investigation. They record delta-V, indicated vehicle speed, engine speed, seat position and safety belt status; furthermore, they verify whether or not the brake was applied, to what extent the accelerator pedal was depressed.

The National Highway Traffic Safety Administration (NHTSA) in the USA published a final rule on EDRs in August 2006 [49 CFR Part 563, 2006]. In January 2008, NHTSA published a revised final rule on EDRs and responded to several petitions for reconsideration of the rule published in August 2006 [49 CFR Part 563, 2008]. The US EDR rule became effective in March 2008.

The Japanese Ministry of Land, Infrastructure, Transport and Tourism (J-MLIT) decided on the technical requirements for the application of EDRs to light vehicles (3500 kg GVWR or less) in March 2008 [J-MLIT website, 2008]. This requirement—so called J-EDR technical requirement—is comparable to the US Part 563. However, J-EDR is adding two data elements which are the pre-crash warning and the pre-crash brake operating status. EDRs are now being installed in ACMs by several automakers.

EDRs have the potential to enhance the accident investigation by adding the pre-crash and post-crash information. ABS-ECU and engine-ECU are expected to provide an additional pre-crash vehicle condition. However, if the read out data from these ECUs are to be utilized for accident investigation, it is first necessary to examine their reliability and accuracy.

OBJECTIVE

The objective of this study is to understand the availability and usefulness of the ECU recorded data and to develop analysis methods of those data for the improvement of accident investigation.

APPROACH

The analysis is based on two types of crash tests. The first type is the J-NCAP crash tests conducted in 2006–2007 by National Agency for Automotive Safety and Victim's Aid (NASVA). The analysis of the J-NCAP data is for understanding the EDR characteristics under standardized crash test conditions. The second type is the real-world accident reconstructions conducted by National Research Institute of Police Science (NRIPS) in 2007–2008 for evaluating the performance of the EDRs and investigating the diagnosis data of the ABS and engine ECUs under highly complex and/or severe crash conditions. The accident reconstruction tests consist of eight cases which are an offset frontal rigid barrier impact, multiple rear-end collisions (2 cases), car-to-car side impacts (2 cases), frontal pole impacts (2 cases) and a side pole impact.

RETRIEVAL OF DIAGNOSIS FREEZE DATA FROM ECUS

We used a scan tool (Denso DST-2) for retrieving the diagnosis data from the ECUs. Some ECUs such as ABS-ECU and engine-ECU record pre-crash information as a freeze data in an accident. When a system detects the engine failure during the collision, engine control data including vehicle velocity could be recorded as freeze data in an engine-ECU. A typical engine failure was reconstructed in our previous study, in which the engine was intentionally stopped by disconnecting the airflow meter [Nakano et al, 2008].

Figure 1 shows an example of the results in this study, indicating the velocity data recorded as freeze data in the engine-ECU. The difference between the velocity data recorded in the engine-ECU and the reference value measured by using a chassis dynamo was less than 1 m/s. However, further study is needed for understanding the reliability and accuracy of those diagnosis freeze data to be used for the accident investigation.

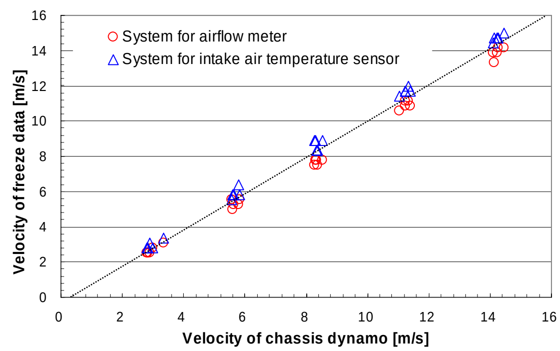


Figure 1. Velocity data recorded in engine-ECU.

ANALYSIS OF J-NCAP TEST DATA

The pre-crash velocity, maximum delta-V, and delta-V time history recorded in the EDRs are compared with the results obtained from instrumented sensors and high-speed video cameras. According to the test procedures, three or four accelerometers are attached to the cars tested, and high-speed video cameras are employed. Acceleration data are recorded with a sampling rate of 10 KHz. High-speed video cameras capture displacement with a recording rate of 500 or 1000 fps. The acceleration data from the sensors are integrated to obtain the delta-V during the collision. The displacement of the target marks on the cars captured by a high-speed video camera is differentiated to obtain the delta-V. An external optical speed sensor is employed to obtain the impact velocities of the cars.

Car models installed with EDRs are used for the analysis. The car velocities obtained as pre-crash data recorded in the EDRs are compared with the velocities obtained from the optical speed sensor and high-speed video cameras. The delta-V recorded in the EDR is compared with the delta-V calculated using the accelerometers and high-speed video cameras.

Fourteen separate crash tests involving seven vehicle models equipped with EDR were analyzed. The analysis was based on the data obtained from the J-NCAP full-lap frontal barrier (FLB) tests at 55 km/h along with 40% overlap offset frontal deformable barrier (ODB) tests at 64 km/h. The pre-crash velocity recorded in each EDR (V_{EDR}) was compared with the data obtained from the optical speed sensor placed in front of the barrier (V_{OP}).

The EDR pre-crash velocity data were aligned along the EDR time zero, the time of airbag deployment algorithm-wakeup. In the crash tests, the beginning of the event is the time when the test vehicle contacts the opposing barrier or vehicle. That is, EDRs and crash test procedures use different definitions for the beginning of the event. However, the time axis is not adjusted in our study.

The maximum delta-V and delta-V time history recorded in the EDRs were compared with the J-NCAP test data obtained from three accelerometers—placed on the left-side sill (A-L), right-side sill (A-R), and center floor (A-C)—and from a high-speed video camera (Video). In several tests, the values obtained from the accelerometers significantly differ from those obtained from the video. Accordingly, after an intensive analysis of the J-NCAP crash test data, reference J-NCAP data for comparisons with the EDR data were selected as follows:

- For the maximum delta-Vs, the data obtained from the video were selected as reference values.
- For the delta-V time histories, the data obtained from the center-floor accelerometer (A-C) and the video were selected. However, when the values of the delta-V time history obtained from the A-C significantly differed from those obtained from the video, the average of the delta-V time history obtained from the accelerometers at the left-side sill (A-L) and right-side sill (A-R) was used.

EDR Pre-Crash Velocity in J-NCAP Tests

Table 1 compares the results obtained for the pre-crash velocity. In all the cases, the difference between the EDR pre-crash velocity (V_{EDR}) and the J-NCAP test velocity (V_{OP}) is less than 4% (average: approximately 2%). The EDR pre-crash velocities are highly accurate and reliable but generally lower than the optically derived velocities (V_{OP}).

Table 1
Comparison results of pre-crash velocity (J-NCAP)

Test	Model	V_{OP}	V_{EDR}	Difference	
		m/s	m/s	m/s	%
FLB	PC-1	15.3	15.0	-0.3	-2.0
	PC-2	15.3	15.6	0.3	2.0
	PC-3	15.3	15.0	-0.3	-2.0
	PC-4	15.3	15.0	-0.3	-2.0
	PC-5	15.3	15.0	-0.3	-2.0
	Mv-1	15.3	15.0	-0.3	-2.0
	Mv-2	15.3	14.9	-0.4	-2.6
ODB	PC-1	17.9	17.2	-0.7	-3.9
	PC-2	17.8	17.8	0.0	0.0
	PC-3	17.8	17.2	-0.6	-3.4
	PC-4	17.8	17.2	-0.6	-3.4
	PC-5	17.8	17.2	-0.6	-3.4
	Mv-1	17.9	17.8	-0.1	-0.6
	Mv-2	17.7	17.1	-0.6	-3.4
Average				-0.3	-1.8
Root mean square				0.4	2.6

EDR Post-Crash Delta-V in J-NCAP Tests

Table 2 compares the results for the post-crash maximum delta-V. The maximum delta-Vs recorded by the EDR (Max delta-V_{EDR}) shows uncertainty in measurement in several cases when compared with the results obtained from the video (Max delta-V_{Video}) or the reference value. The difference is greater than 5 % in 10 of 14 tests and greater than 10 % in 4 of 14 tests. The average difference in the maximum delta-V is approximately 7 %, and the mean square difference 8.4 %. The maximum delta-V values recorded by the EDR are generally lower than those measured by the high speed video (Max delta-V_{Video}).

We also examined the degree of deviation of the maximum delta-Vs calculated by accelerometer signals (A-C, Ave. A-R and A-L) from the video results. As shown in Table 2, the deviation of the maximum delta-V calculated by A-C from the video results is greater than 5 % in 8 of 14 tests and greater than 10 % in 4 of 14 tests. Whereas, the deviation of the maximum delta-V calculated by average of A-R and A-L from the video results is less significant, that is, the deviations is less than 5 % in 10 of 14 tests.

Accordingly, the accuracy and reliability of the EDR maximum delta-V appeared to be of the same order as the data obtained by the single accelerometer in the crash tests. The accelerometers utilized in the EDRs could have the same performance as that of the instrumented accelerometers used in the crash tests. However, the maximum delta-Vs recorded by the EDRs were slightly lower than those obtained by the video and accelerometers in the J-NCAP tests (See Table 2), that is, the EDRs underestimated the maximum delta-V in almost all the tests. One of the factors responsible for this result might be attributable to the characteristics of the accelerometers to be used for an airbag sensor.

In general, every accelerometer has its unique characteristics under the exposed environment. One of the typical characteristics of the accelerometer is the temperature dependency. An accelerometer signal contains an apparent acceleration due to the temperature dependency besides the actual acceleration. The apparent acceleration is a signal including the DC and/or low frequency components in frequency domain. The airbag sensor should have a function to cut the low frequency signal off by using a high-pass or band-pass filter, accordingly. The deletion of the low frequency components including the DC acceleration from the original acceleration signal affects the delta-V calculation. The characteristics of the filter designed in the airbag sensor plays an important role in the reliability and accuracy of the delta-V recorded by the EDR.

Figure 2 compares the delta-V time history curves obtained by EDR with those from the accelerometers and video in the FLB and ODB tests . In many cases, there was an apparent difference between the EDR data and the results from the accelerometers and video. However, when we focused on the initial short time window of the delta-V curve, the EDR data were very comparable with those from the accelerometers. This initial short time window was up to about 60 ms in the FLB test and about 100 ms in the ODB test. This result suggests that the acceleration calculated by the EDR data agrees well with the accelerometer signal in these short time windows.

Table 2
Comparison results of post-crash maximum delta-V (J-NCAP)

Test	Model	Max ΔV_{Video} [A]	Max $\Delta V_{A\text{-}C}$ [B]	Max $\Delta V_{Ave.\ A\text{-}R\ and\ A\text{-}L}$ [C]	Max ΔV_{EDR} [D]	Difference [B]-[A]		Difference [C]-[A]		Difference [D]-[A]	
		m/s	m/s	m/s	m/s	m/s	%	m/s	%	m/s	%
FLB	PC-1	17.2	17.0	17.7	16.5	-0.2	-1.2	0.5	2.9	-0.7	-4.1
	PC-2	16.9	17.1	17.8	15.3	0.2	1.2	0.9	5.3	-1.6	-9.5
	PC-3	17.1	16.4	18.1	14.9	-0.7	-4.1	1.0	5.8	-2.2	-12.9
	PC-4	17.3	17.9	18.5	16.2	0.6	3.5	1.2	6.9	-1.1	-6.4
	PC-5	17.0	18.8	17.6	16.7	1.8	10.6	0.6	3.5	-0.3	-1.8
	Mv-1	17.1	21.4	17.1	14.7	4.3	25.1	0.0	0.0	-2.4	-14.0
	Mv-2	17.0	18.1	17.5	15.2	1.1	6.5	0.5	2.9	-1.8	-10.6
OBD	PC-1	20.3	19.0	19.3	19.1	-1.3	-6.4	-1.0	-4.9	-1.2	-5.9
	PC-2	19.4	22.1	19.4	19.2	2.7	13.9	0.0	0.0	-0.2	-1.0
	PC-3	20.0	21.7	19.4	18.4	1.7	8.5	-0.6	-3.0	-1.6	-8.0
	PC-4	20.7	20.2	19.9	18.7	-0.5	-2.4	-0.8	-3.9	-2.0	-9.7
	PC-5	20.1	19.4	19.4	18.7	-0.7	-3.5	-0.7	-3.5	-1.4	-7.0
	Mv-1	18.4	22.4	20.8	18.5	4.0	21.7	2.4	13.0	0.1	0.5
	Mv-2	19.9	18.8	20.1	17.5	-1.1	-5.5	0.2	1.0	-2.4	-12.1
Average						0.9	4.9	0.3	1.9	-1.3	-7.3
Root mean square						1.9	10.5	0.9	5.0	1.5	8.4

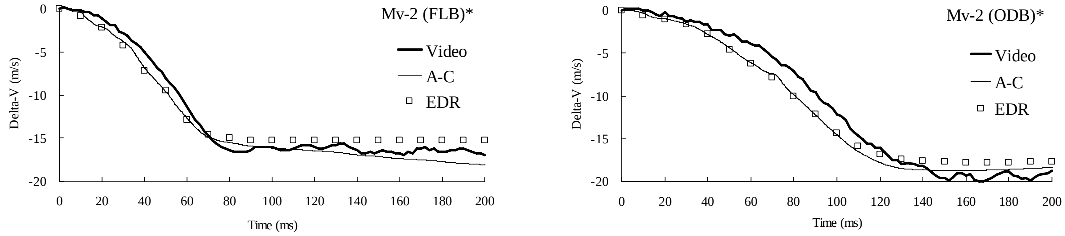


Figure 2. Comparison of delta-V time histories from EDR, video and accelerometer.
(*: Max ΔV_{EDR} differed more than 10 percent compared with Max ΔV_{Video}.)

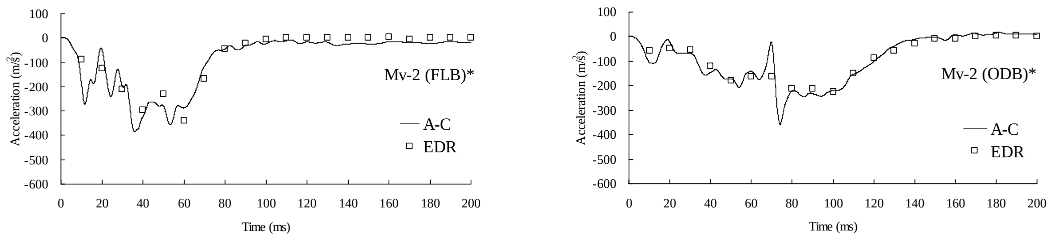


Figure 3. Comparison of acceleration time histories from EDR and accelerometer.
(*: Max ΔV_{EDR} differed more than 10 percent compared with Max ΔV_{Video}.)

Figure 3 compares the calculated EDR acceleration and the accelerometer signal. The calculated EDR acceleration agreed well with the accelerometer signal for the entire period of 200 ms. Even in the worst cases (PC-3(FLB) , Mv-1(FLB), Mv-2(FLB) and Mv-2(ODB)), in which the EDR maximum delta-V (Max ΔV_{EDR}) differed by more than 10 percent from the video results (Max ΔV_{EDR}), the calculated EDR acceleration plots were almost comparable with the accelerometer signals.

A previous study [Niehoff et al, 2005] on EDRs produced results similar to those in our study; the difference between the pre-crash velocities was less than 1 mph in all the cases (average difference: 1.1 %). The average difference in the maximum delta-V was approximately 6 %, and in nearly all the cases, the maximum delta-V recorded by the EDRs was less than the delta-V obtained by the instrumented accelerometers. In the previous study, it was explained that the EDR data loss was responsible for the difference in the delta-Vs, because the majority of the EDRs did not record the entire event. In contrast, although the EDRs used in our study recorded the entire event up to 200 ms, the EDRs underestimated the maximum delta-V in almost all the tests.

ACCIDENT RECONSTRUCTIONS

Typical real world accidents such as single car collisions against a road facility, car-to-car collisions at an intersection and multiple rear-end collisions on a freeway were reconstructed in order to understand the performance of an EDR. Diagnosis data from ABS-ECU and engine-ECU were also investigated in the accident reconstruction tests. In our instrumented laboratory tests, an offset frontal rigid barrier impact (See Fig. 4), car-to-car 90-degree side impacts (See Fig. 5), multiple rear-end collisions (See Fig. 6), and frontal and side pole impacts (See Fig. 7) were conducted, and their test data were analyzed.
The analysis method was similar to that used in the J-NCAP data analysis. The pre-crash velocity recorded by each EDR (V_{EDR}) was compared with the data obtained from the optical speed sensor (V_{OP}). Four accelerometers were used for calculating the post-crash delta-V. The maximum delta-V and the delta-V time history recorded in the EDRs were compared with those obtained from four instrumented accelerometers—placed on the left-side sill (A-L), right-side sill (A-R), center floor (A-C), and airbag control module or ACM (A-EDR)—and from a high-speed video camera (Video). The average acceleration measured by A-R and A-L (ave. A-R and A-L) was also used for obtaining the delta-V.

Toyota Corolla (E140) equipped with EDR and front, side and curtain airbags (model year 2007 - 2008) was mainly used for the tests. In Figures 4-7, the test cars indicated as O-1, A-1, A-2, A-4, R-2, R-3, R5, R-6, P-1, P-2 and P-3 were Toyota Corolla (E140). Cars (R-1 and R-4) used for the multiple rear-end collisions in the front-most position were Toyota Progress (G10) equipped with EDR and front, side, and curtain airbags. A bullet car (A-3) used in the case 2 car-to-car side impact was Toyota Corolla previous model (AE110) not equipped with EDR. After the crash tests, the ACMs were removed for downloading the EDR data.

Offset Frontal Rigid Barrier Impact

As shown in Figure 4, the target velocity was 17.8 m/s. The test was successfully conducted under the targeted conditions. O-1 collided against the rigid barrier with 40% overlap. After the collision, O-1 rotated approximately 45° clockwise, and rebounded approximately 2 m from the barrier. Front airbags were deployed at the instant of the crash.

Car To Car 90-Degree Side Impact

As shown in Figure 5, the target velocity was 15.3 m/s for both cars. Impact angle was 90-degree. Two tests (case 1 and case 2) were successfully conducted under the targeted conditions.

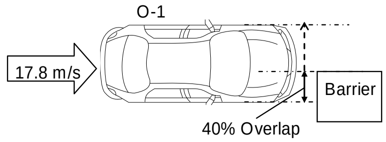


Figure 4. 40% overlap offset frontal rigid barrier test.

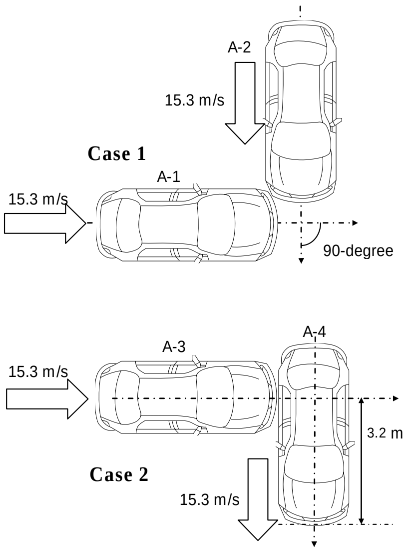


Figure 5. Car to car 90-degree side impact tests

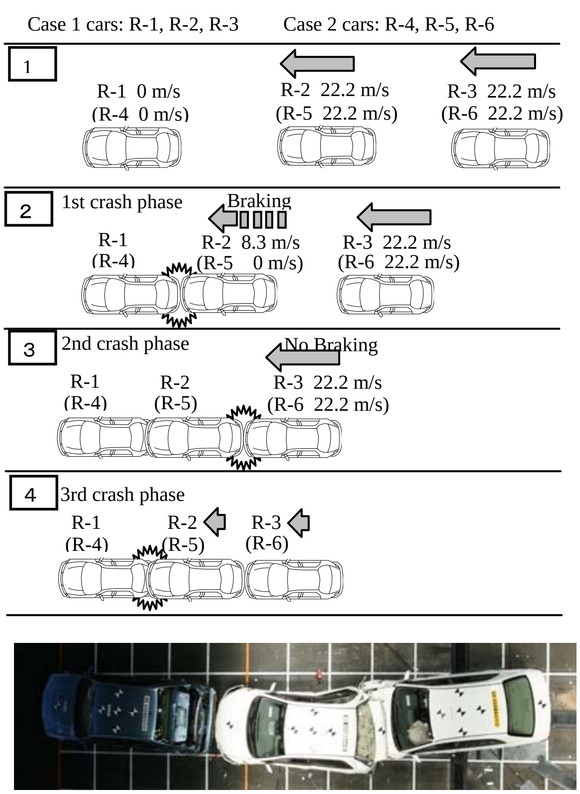
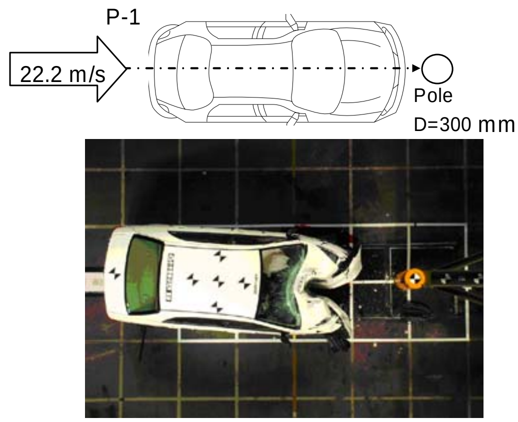
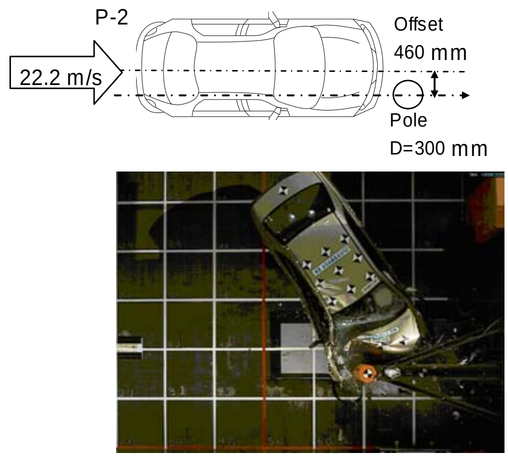


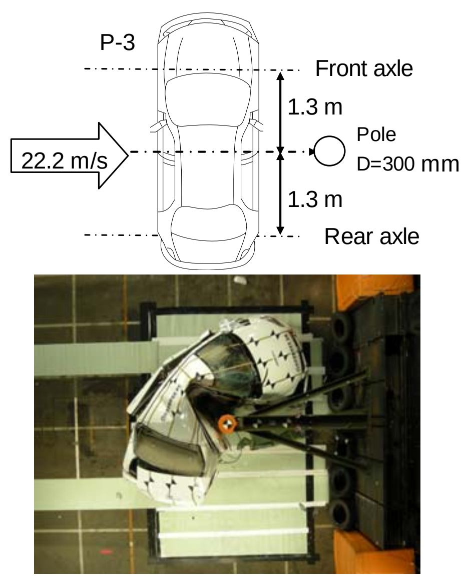
Figure 6. Multiple rear-end collision.



(1) Frontal pole impact



(2) Frontal offset pole impact



(3) Side pole impact

Figure 7. Pole impact tests.

In the case 1, A-1 and A-2 collided with each other at their front corner. Each car rotated along its outer direction (clockwise for A-1 and counterclockwise for A-2) and separated from each other at approximately 150 ms. The two cars maintained the rotation and impacted their rear sides again at approximately 300 ms. The front airbags of both A-1 and A-2 were deployed at the instant of the crash.

In the case 2, A-3 impacted the right side of A-4 near the rear wheel. Each car rotated along its outer direction (clockwise for A-3 and counterclockwise for A-4) and separated from each other at approximately 150 ms. A-3 and A-4 maintained the rotation for approximately 2 seconds. The angular displacement of A-3 at the final rest position was about 230-degree and that of A-4 about 410-degree. The front airbags of A-3 and the driver side curtain airbag of A-4 were deployed at the crash.

Multiple Rear-End Collision

As shown in Figure 6, two tests (case 1 and case 2) were conducted under the similar impact configuration. The case 1 was successfully conducted under the targeted conditions. The car (R-1) in the front-most position kept stopping by using the foot brake. The car in the middle position (R-2) and the car in the rearmost position (R-3) approached R-1. R-2 activated full braking and then crashed into the rear end of R-1 (1st crash phase), and both the cars moved forward by approximately 1 m. Airbags of R-1 and R-2 were not deployed in the 1st crash phase. Then, R-2 stopped and moved backward. Approximately 800 ms after the 1st impact, R-3 crashed into the rear end of R-2 (2nd crash phase). The impact center of R-3 was off to the right side by approximately 0.2 m. The driver side curtain airbag of R-2 and the front airbags of R-3 were deployed in the 2nd crash phase. R-3 pushed R-2 forward and R-2 crashed into the rear end of R-1 again (3rd crash phase). Approximately 2 seconds after the 1st crash phase, all the cars came to a stop. R-1 moved forward by approximately 4.5 m from the initial position. Airbags of R-1, R-2 and R-3 were not deployed in the 3rd crash phase.

In the case 2, the car in the middle position (R-5) intended to avoid the rear end collision against the car (R-4) in the front-most position, however R-5 crashed into the rear end of R-4 (1st crash phase) at 4.1 m/s, and both the cars moved forward by approximately 0.2 m. The impact center of R-5 was off to the right side by approximately 0.2 m. Airbags of R-4 and R-5 were not deployed in the 1st crash phase. Then, R-4 and R-5 stopped. Approximately 1.5 seconds after the 1st impact, the car in the rearmost position (R-6) crashed into the rear end of R-5 (2nd crash phase). The impact center of R-6 was off to the right side by approximately 0.1 m. Only the front airbags of R-6 were deployed in the 2nd crash phase. R-6 pushed R-5 forward and R-5 crashed into the rear end of R-4 again (3rd crash phase). Approximately 3 seconds after the 1st crash phase, all the cars came to a stop. R-4 moved forward by approximately 3.5 m from the initial position. Airbags of R-4, R-5 and R-6 were not deployed in the 3rd crash phase.

Frontal and Side Pole Impacts

As shown in Figure 7, the target velocity was 22.2 m/s for each car and the pole diameter was 300 mm. Three tests were successfully conducted under the targeted conditions.
In the frontal pole impact, the body center of P-1 collided against the rigid pole. After the collision, P-1 rebounded approximately 1.5 m from the pole. Front airbags were deployed at the instant of the crash.

In the frontal offset pole impact, the front right side-member (driver-side) of P-2 collided against the rigid pole (offset of 460 mm) with the engine idling. After the collision, P-2 rotated clockwise and crashed into the cushion barrier from the rear end. Front airbags were deployed at the instant of the crash.

In the side pole impact, the driver-side of P-3 collided against the rigid pole laterally with the engine idling. Impact center was the wheel base center of P-3. During the collision, P-3 wrapped around the pole and the body deformation was recovered significantly after the collision. Driver side curtain airbag was deployed at the instant of the crash.

Pre-Crash EDR Data in Accident Reconstruction

Table 3 shows the pre-crash data recorded by the EDRs in the accident reconstruction tests. Table 4 summarizes the comparison results of the impact velocities recorded by the EDRs with those from the optical speed sensor and video.

In the offset frontal rigid barrier impact, the test car (O-1) did not brake; hence, all pre-crash velocities had the same value of 17.8 m/s, whereas the optical speed sensor (V_{OP}) indicated 17.9 m/s. The difference between the EDR impact velocity (V_{EDR}) and V_{OP} was 0.1 m/s, that is, a difference of less than 1%.

Table 3.
EDR pre-crash data in accident reconstruction tests

Optical speed sensor: O-1 = 17.9 m/s

Offset frontal rigid barrier impact	1	Model	O-1					
		Time(sec)*	-4.1*	-3.1*	-2.1*	-1.1*	-0.1*	0*
		Velocity(m/s)	17.8	17.8	17.8	17.8	17.8	17.8
		Brake	Off	Off	Off	Off	Off	Off

Optical speed sensor: A-1 = 15.4 m/s, A-2 = 15.4 m/s, A-3 = 15.4 m/s, A-4 = 15.4 m/s

Car to car 90-degree side impact	1	Model	A-1 (front-left side crash)					
		Time(sec)*	-4.7*	-3.7*	-2.7*	-1.7*	-0.7*	0*
		Velocity(m/s)	12.8	14.4	15.6	15.6	15.6	15.6
		Brake	Off	Off	Off	Off	Off	Off
		Model	A-2 (front-right side crash)					
		Time(sec)*	-4.3*	-3.3*	-2.3*	-1.3*	-0.3*	0*
		Velocity(m/s)	13.3	15.0	15.6	15.6	15.6	15.6
		Brake	Off	Off	Off	Off	Off	Off
	2	Model	A-4 (side-right crash)					
		Time(sec)*	-4.6*	-3.6*	-2.6*	-1.6*	-0.6*	0*
		Velocity(m/s)	13.9	15.0	15.6	15.6	15.6	15.6
		Brake	Off	Off	Off	Off	Off	Off

Optical speed sensor: P-1 = 22.4 m/s, P-2 = 22.2 m/s, P-3 = 22.3 m/s

Frontal and side pole impacts	1	Model	P-1 (frontal pole impact)					
		Time(sec)*	-4.3*	-3.3*	-2.3*	-1.3*	-0.3*	0*
		Velocity(m/s)	21.1	22.2	22.8	22.8	22.8	22.8
		Brake	Off	Off	Off	Off	Off	Off
	2	Model	P-2 (frontal offset pole impact)					
		Time(sec)*	-4.7*	-3.7*	-2.7*	-1.7*	-0.7*	0*
		Velocity(m/s)	16.1	18.3	20.6	21.7	22.2	22.2
		Brake	Off	Off	Off	Off	Off	Off
		Accelerator	Off	Off	Off	Off	Off	Off
		Engine(rpm)	400	400	400	400	400	400
	3	Model	P-3 (side pole impact)					
		Time(sec)*	-4.7*	-3.7*	-2.7*	-1.7*	-0.7*	0*
		Velocity(m/s)	0.0	0.0	0.0	0.0	0.0	0.0
		Brake	Off	Off	Off	Off	Off	Off
		Accelerator	Off	Off	Off	Off	Off	Off
		Engine(rpm)	400	400	400	400	400	400

* EDR time zero is the time of airbag deployment algorithm-wakeup.

** Result from video analysis

Optical speed sensor: R-2 = 8.5 m/s, R-3=21.5 m/s, R-5=4.1** m/s, R-6=22.0 m/s

Multiple rear-end collision	1	Model	R-1 in 1st crash phase(rear crash)					
		Time(sec)*	-4.9*	-3.9*	-2.9*	-1.9*	-0.9*	0*
		Velocity(m/s)	0.0	0.0	0.0	0.0	0.0	0.0
		Brake	On	On	On	On	On	On
		Model	R-1 in 3rd crash phase(rear crash)					
		Time(sec)*	-4.7*	-3.7*	-2.7*	-1.7*	-0.7*	0*
		Velocity(m/s)	0.0	0.0	0.0	0.0	0.0	0.0
		Brake	On	On	On	On	On	On
		Model	R-2 in 1st crash phase(frontal crash)					
		Time(sec)*	-4.6*	-3.6*	-2.6*	-1.6*	-0.6*	0*
		Velocity(m/s)	21.7	22.2	22.2	22.2	16.1	11.1
		Brake	Off	Off	Off	Off	On	On
		Model	R-2 in 2nd crash phase(rear crash)					
		Time(sec)*	-4.4*	-3.4*	-2.4*	-1.4*	-0.4*	0*
		Velocity(m/s)	22.2	22.2	22.2	16.1	3.3	1.7
		Brake	Off	Off	Off	On	On	On
		Model	R-3 in 2nd crash phase(frontal crash)					
		Time(sec)*	-4.2*	-3.2*	-2.2*	-1.2*	-0.2*	0*
		Velocity(m/s)	22.2	22.2	22.2	21.7	21.7	21.7
		Brake	Off	Off	Off	Off	Off	Off
	2	Model	R-4 in 1st crash phase(rear crash)					
		Time(sec)*	-4.5*	-3.5*	-2.5*	-1.5*	-0.5*	0*
		Velocity(m/s)	0.0	0.0	0.0	0.0	0.0	0.0
		Brake	On	On	On	On	On	On
		Model	R-4 in 3rd crash phase(rear crash)					
		Time(sec)*		-4.0*	-3.0*	-2.0*	-1.0*	0*
		Velocity(m/s)		0.0	0.0	0.0	0.0	0.0
		Brake		On	On	On	On	On
		Model	R-5 in 1st crash phase(frontal crash)					
		Time(sec)*	-4.8*	-3.8*	-2.8*	-1.8*	-0.8*	0*
		Velocity(m/s)	19.4	21.7	22.2	22.2	12.8	4.4
		Brake	Off	Off	Off	On	On	On
		Model	R-5 in 2nd crash phase(rear crash)					
		Time(sec)*	-4.3*	-3.3*	-2.3*	-1.3*	-0.3*	0*
		Velocity(m/s)	22.2	22.2	12.8	4.4	0.0	0.0
		Brake	Off	On	On	On	On	On
		Model	R-6 in 2nd crash phase(frontal crash)					
		Time(sec)*	-4.3*	-3.3*	-2.3*	-1.3*	-0.3*	0*
		Velocity(m/s)	22.2	22.8	22.8	22.2	22.2	22.2
		Brake	Off	Off	Off	Off	Off	Off

Table 4.
Comparison results of EDR pre-crash impact velocities in accident reconstruction tests

Test type	No.	Model	Impact-direction	Brake	V_{OP} m/s	V_{EDR} m/s	Difference m/s	Difference %
Offset frontal	1	O-1	front-right	Off	17.9	17.8	-0.1	-0.6
Car to car 90 degree side impact test	1	A-1	front-left	Off	15.4	15.6	0.2	1.3
		A-2	front-right	Off	15.4	15.6	0.2	1.3
	2	A-3	front	Off	15.4	N/A	N/A	N/A
		A-4	side-right	Off	15.4	15.6	0.2	1.3
Multiple rear-end	1	R-1 (1st crash phase)	rear	On	0.0*	0.0	0.0	0.0
		R-1 (3rd crash phase)	rear	On	0.0*	0.0	0.0	0.0
		R-2 (1st crash phase)	front	On	8.5	11.1	2.6	30.6
		R-2 (2nd crash phase)	rear	On	0.6*	1.7	1.1	–**
		R-3(2nd crash phase)	front	Off	21.5	21.7	0.2	0.9
	2	R-4 (1st crash phase)	rear	On	0.0	0.0	0.0	0.0
		R-4 (3rd crash phase)	rear	On	0.0	0.0	0.0	0.0
		R-5 (1st crash phase)	front	On	4.1*	4.4	0.3	7.3
		R-5 (2nd crash phase)	rear	On	0.0*	0.0	0.0	0.0
		R-6(2nd crash phase)	front	Off	22.0	22.2	0.2	0.9
Pole	1	P-1	front-center	Off	22.4	22.8	0.4	1.8
	2	P-2	front-right	Off	22.2	22.2	0.0	0.0
	3	P-3	side-right	Off	22.3	N/A	N/A	N/A
Average							0.4	3.2
Root mean square							0.7	8.5

*:Data from video Analysis

**: V_{OP} and V_{EDR} are so small that percentage is excluded

In the case 1 of the car to car 90-degree side impact**,** the two cars (A-1 and A-2) were accelerated and maintained the same velocity for approximately 3 seconds immediately before the impact, without braking. For the two cars, the impact velocity (V_{EDR}) recorded by their EDRs was 15.6 m/s and the optical speed sensor velocity (V_{OP}) was 15.4 m/s. The difference in the impact velocity between the EDR and laboratory test data was 0.2 m/s, a difference of approximately 1 %.

In the case 2 of the car to car 90-degree side impact, only the target car (A-4) was equipped with the EDR. The EDR pre-crash data of A-4 indicated that A-4 was accelerated and maintained the same velocity for approximately 3 seconds immediately before the impact, without braking. The impact velocity (V_{EDR}) recorded by the EDR was 15.6 m/s and the optical speed sensor velocity (V_{OP}) was 15.4 m/s for each car. The difference (0.2 m/s) in the impact velocity between the EDR and laboratory test data was approximately 1 %.

In the case 1 of the multiple rear-end collision, the car (R-1) in the front-most position was impacted twice by the middle car (R-2). In both the events for R-1, the impact velocity of R-1 recorded by the EDR was 0 m/s, and this value agreed with the results obtained by the video. At the first impact, the impact velocity of R-2 recorded by the EDR was 11.1 m/s, and this value differed by 2.6 m/s (31%) from the results obtained by the optical sensor (8.5 m/s). At the second impact, the impact velocity of R-2 recorded by the EDR was 1.7 m/s, and this value differed by 1.1 m/s from the results obtained by the video (0.6 m/s). In the cases with braking on, the EDR overestimated the impact velocity by 1.1–2.6 m/s. One of the factors responsible for this difference should be the different definitions between EDRs and crash test procedures for the beginning of the crash event. In the second crash phase, the EDR impact velocity of R-3 was 21.7 m/s, and this value differed by 0.2 m/s (1%) from the result obtained by the optical sensor (21.5 m/s). The EDR pre-crash velocities of R-3 had almost similar values since R-3 did not brake.

In the case 2 of the multiple rear-end collision, the car (R-4) in the front-most position was impacted twice by the middle car (R-5). In both the events for R-4, the impact velocity of R-4 recorded by the EDR was 0 m/s, and this value agreed with the result obtained by the video. At the first impact, the impact velocity of R-5 recorded by the EDR was 4.4 m/s, and this value differed by 0.3 m/s (7.3 %) from the results obtained by the video (4.1 m/s). At the second impact, the EDR impact velocity of R-5 was 0.0 m/s, and this value was the same result obtained by the video (0.0 m/s). In these cases, the EDR recorded the impact velocity accurately even if the brake was used. In the second crash phase, the EDR impact velocity of R-6 was 22.2 m/s, and this value differed by 0.2 m/s (1%) from the result obtained by the optical sensor (22.0 m/s). All the EDR pre-crash velocities of R-6 had almost similar values.

In the case of the frontal pole impact, the EDR of the test car (P-1) indicated that P-1 was accelerated and maintained the same velocity for approximately 3 seconds immediately before the impact, without braking. The impact velocity (V_{EDR}) recorded by the EDR was 22.8 m/s and the optical speed sensor velocity (V_{OP}) was 22.4 m/s. The difference in the impact velocity between the EDR and laboratory test data was 0.4 m/s, a difference of approximately 2 %.

In case of the frontal offset pole impact, the EDR of the test car (P-2) indicated that P-2 was accelerated immediately before the impact, with the engine idling at 400 rpm, braking off and accelerator off. The impact velocity (V_{EDR}) recorded by the EDR was 22.2 m/s and the optical speed sensor velocity (V_{OP}) was 22.2 m/s. The EDR pre-crash data corresponded to the laboratory impact conditions.

In case of the side pole impact, the EDR of the test car (P-3) indicated that the P-3 was stationary with the engine idling at 400 rpm, braking off and accelerator off. P-3 was accelerated laterally before the impact with the engine idling, without brake. Accordingly, the P-3 EDR recorded data corresponded to the targeted test condition.

As shown in Table 4, the difference between the EDR impact velocity (V_{EDR}) and that obtained from the optical speed sensor (V_{OP}) is less than 0.5 m/s in almost all the tested cars except for R-2. The difference in R-2 was 2.6 m/s for the first crash and 1.1 m/s for the second crash. In the case of R-2, the EDR time zero could significantly affect the pre-crash velocity recorded by the EDR because R-2 decelerated by braking before the impact. Even a slight shift in the time zero can cause a significant deviation in the impact velocity obtained by the EDR. It should be noted that the pre-crash velocities recorded by the EDR were highly accurate and reliable when cars proceeded without braking prior to the collision. The accuracy and reliability of the EDR pre-crash velocity might be affected by the braking condition and the time zero definition of the EDR.

Post-Crash EDR Data in Accident Reconstruction

Table 5 compares the results obtained for the post-crash longitudinal maximum delta-V. The maximum delta-Vs recorded by the EDR (Max delta-V_{EDR}) shows uncertainty in measurement in several cases when compared with the results obtained by the video (Max delta-V_{Video}) and/or the accelerometers.

In case of P-1 in the frontal pole impact, the EDR maximum delta-V (Max delta-V_{EDR} (17.5 m/s)) was approximately 30 % lower value as compared to the results from the video and accelerometer (Max delta-V_{Video} (24.8 m/s), Max delta-$V_{A\text{-}C}$ (25.0 m/s)). In case of P-2 in the frontal offset pole impact, the difference between those velocities was less than 10 %. Front airbag sensors were located in the front side members of the tested cars and the side member of P-2 directly crashed against the pole. Accordingly, the airbag sensors of P-2 could detect the crash event much earlier as compared to those of P-1. Airbag deployment could be delayed in this type of frontal pole impact and the time delay affects the safety performance of the airbag system. During the initial contact against the pole, the airbag deployment algorithm may not wakeup, and the vehicle driver and passengers could move forward according to the vehicle deceleration or velocity change.

When excluding the pole impacts, the differences between the EDR maximum delta-Vs and the reference values (Max delta-V_{Video}, Max delta-$V_{A\text{-}C}$) were less than 2 m/s. The deviation of the EDR maximum delta-Vs from the reference values was approximately 2 m/s by the root mean square velocity.

The results indicate that the accuracy and reliability of the maximum longitudinal delta-V obtained by the EDR decreased under more complex crash conditions as compared to the standardized crash tests or the J-NCAP test. However, the errors in the data obtained by the video and accelerometer should be considered.

Table 6 compares the results obtained for the post-crash lateral maximum delta-V. The lateral maximum delta-Vs (Max delta-V_{EDR}) obtained by the EDR showed lower values as compared to the data obtained by the accelerometer (Max delta-$V_{A\text{-}EDR}$) and the difference was less than 2 m/s when excluding the side pole impact (P-3). In case of the side pole impact (P-3), the EDR lateral maximum delta-Vs was approximately 4 m/s lower value than the reference (Max delta-$V_{A\text{-}EDR}$). The difference between the maximum lateral delta-Vs was greater than 20 % in 2 of 4 tests (average: approximately 18 %).

Figure 8 shows the post-crash longitudinal delta-V time histories obtained from the EDR, video and accelerometers in offset frontal rigid barrier impact. During the initial time window, the delta-V time history obtained from the video showed a phase delay as compared with the data obtained from the EDR and accelerometers.

Table 5.
Comparison results of longitudinal maximum delta-V in accident reconstruction tests

Test type	No.	Model (crash)	Impact-direction	MaxΔV_{Video} [A] m/s	Max$\Delta V_{A\text{-}EDR}$ [B] m/s	MaxΔV_{EDR} [C] m/s	Difference [C]-[A]		Difference [C]-[B]		Difference [B]-[A]	
							m/s	%	m/s	%	m/s	%
Offset frontal	1	O-1	front-right	20.5	17.4	20.2	-0.3	-1.5	2.8	16.1	-3.1	-15.1
Car to car 90 degree side impact test	1	A-1	front-left	6.1	8.3	8.0	1.9	31.1	-0.3	-3.6	2.2	36.1
		A-2	front-right	6.3	8.8	7.9	1.6	25.4	-0.9	-10.2	2.5	39.7
	2	A-3	front	4.0	4.5	N/A	N/A	N/A	N/A	N/A	0.4	11.1
		A-4	side-right	N/A	3.8	3.5	N/A	N/A	-0.4	-9.2	N/A	N/A
Multiple rear-end	1	R-1 (1st)	rear	3.6	3.8	4.2	0.6	16.7	0.4	10.5	0.2	5.6
		R-1 (3rd)	rear	6.6	6.6	6.9	0.3	4.5	0.3	4.5	0.0	0.0
		R-2 (1st)	front	7.0	5.7	6.1	-0.9	-12.9	0.4	7.0	-1.3	-18.6
		R-2 (2nd)	rear	5.7	7.5	6.9	1.2	21.1	-0.6	-8.0	1.8	31.6
		R-3 (2nd)	front	17.6	17.7	16.8	-0.8	-4.5	-0.9	-5.1	0.1	0.6
	2	R-4 (1st)	rear	1.9	1.9	1.9	0.0	0.0	0.0	0.0	0.0	0.0
		R-4 (3rd)	rear	6.4	6.3	6.7	0.3	4.7	0.4	6.3	-0.1	-1.6
		R-5 (1st)	rear	4.1	4.2	3.2	-0.9	-21.5	-1.0	-23.4	0.1	2.4
		R-5 (2nd)	front	8.3	8.3	9.1	0.8	9.9	0.8	9.9	0.0	0.0
		R-6 (2nd)	front	17.0	16.8	16.0	-1.0	-6.1	-0.8	-5.0	-0.2	-1.2
Pole	1	P-1	front-center	24.8	*25.0	17.5	-7.3	-29.4	-7.5	-29.9	0.2	0.8
	2	P-2	front-right	23.2	22.5	20.9	-2.3	-9.8	-1.6	-7.0	-0.7	-3.0
	3	P-3	side-right	N/A	8.0	7.9	N/A	N/A	-0.1	-1.7	N/A	N/A
Average							-0.5	1.8	-0.5	-2.9	0.1	5.5
Root mean square							2.2	16.6	2.0	11.9	1.3	17.0

* Data of center floor acceleration (A-C)

Table 6.
Comparison results of lateral maximum delta-V in accident reconstruction tests (0 to 80 ms)

Test type	No.	Model	impact-direction	MaxΔV_{A-EDR} m/s	MaxΔV_{EDR} m/s	Difference m/s	Difference %
car to car 90 degree side impact test	1	A-1	front-left	8.9	7.8	-1.1	-12.4
		A-2	front-right	9.1	7.2	-1.9	-20.9
	2	A-4	front-right	2.0	1.8	-0.2	-9.7
Pole	3	P-3	side-right	15.7	11.4	-4.3	-27.2
Average						-1.9	-17.5
Root mean square						2.4	18.9

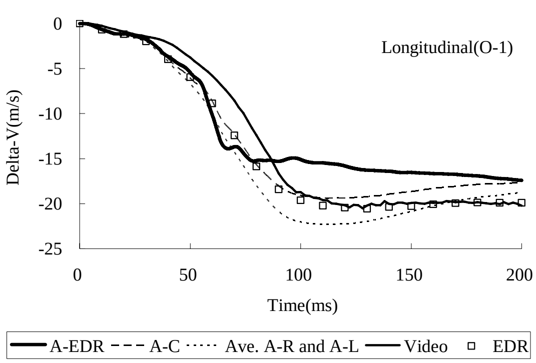


Figure 8. Delta-V time history curves obtained from EDR, video and accelerometers for longitudinal direction in offset frontal rigid barrier test.

The delta-V time history obtained from the EDR reached a constant value and was approximately similar to the result obtained from the video after 100 ms. However, the delta-Vs obtained from the instrumented accelerometers indicated a different tendency after 100 ms as compared with the data obtained from the EDR and video. The delta-V_{A-EDR} differed significantly from the other data. The factors responsible for these differences in velocities were estimated to be the large deformation at the location of ACM. It can be noted that this deformation could cause the distortion against the ACM outer cover and the accelerometer case since the accelerometer was bonded on the ACM. The distortion of the outer case of the accelerometer could affect the internal strain gage sensor.

Figure 9 compares the post-crash longitudinal delta-V time history obtained by the EDR with that obtained from the accelerometer on the ACM (A-EDR) for the three cars (A-1, A-2 and A-4) in car-to-car 90-degree side impacts. In these cars, the delta-V time history obtained by the EDR was comparable with that obtained from the accelerometer on the ACM for the entire period of 200 ms. The difference between the maximum delta-V_{EDR} and the maximum delta-V_{A-EDR} was less than 1 m/s (0.3 m/s for A-1, 0.9 m/s for A-2 and 0.4 m/s for A-4) in the three cars.

Figure 10 compares the post-crash lateral delta-V time history obtained by the EDR with that obtained from the accelerometer on the ACM (A-EDR) in car-to-car 90-degree side impact tests. For the time window from 0 to 50 ms, the lateral delta-V time history obtained by the EDR agreed well with the data obtained by the accelerometer (A-EDR) for the three cars (A-1, A-2 and A-4). After 50 ms, the difference between the curves started to increase. This tendency is very similar to the result obtained when comparing the EDR longitudinal delta-V curve with the corresponding accelerometer data in the analysis of the J-NCAP full lap barrier (FLB) tests.

Figure 11 compares the longitudinal delta-V time histories obtained by the EDR with those obtained from the accelerometers and video in multiple rear-end collision tests. The EDRs of R-1 and R-4 recorded the longitudinal delta-V for 150 ms. This limitation may not affect the data analysis since the time duration of a car-to-car collision is approximately 150 ms in general.

In the case 1 of the multiple rear-end collision test, the EDR delta-V time history of R-1 in the first crash phase agreed well with the results obtained by the accelerometers and video. In the third crash phase, according to the different definitions for the beginning of the crash event, the delta-V time histories of R-1 obtained from the accelerometers and video showed a phase delay from the EDR data. The phase delay can be adjusted by shifting the EDR time zero. The difference between the values of delta-Vs of R-1 in the third crash phase became minimal by shifting the EDR time zero.

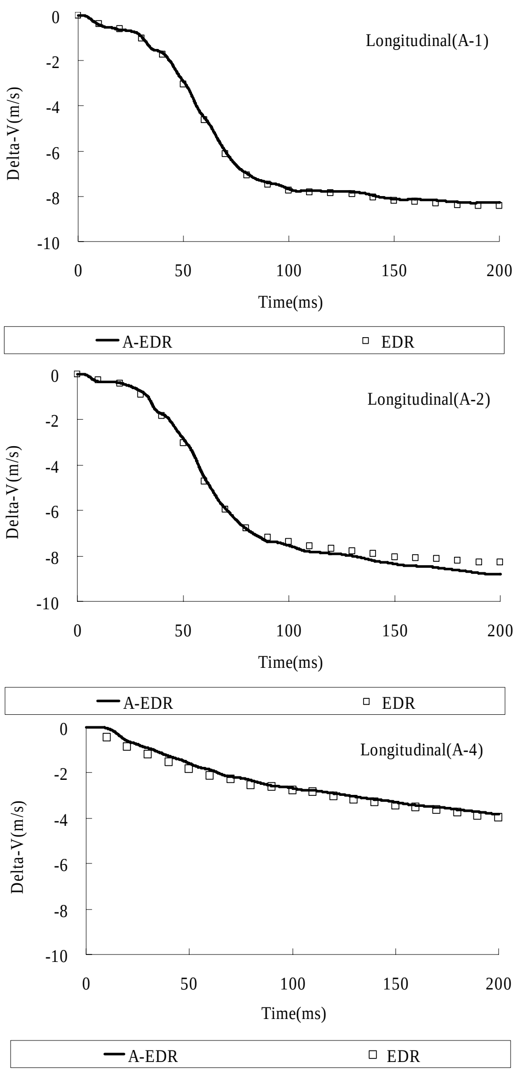


Figure 9. Delta-V time history curves obtained from EDR and A-EDR for longitudinal direction in car-to-car 90-degree side impacts.

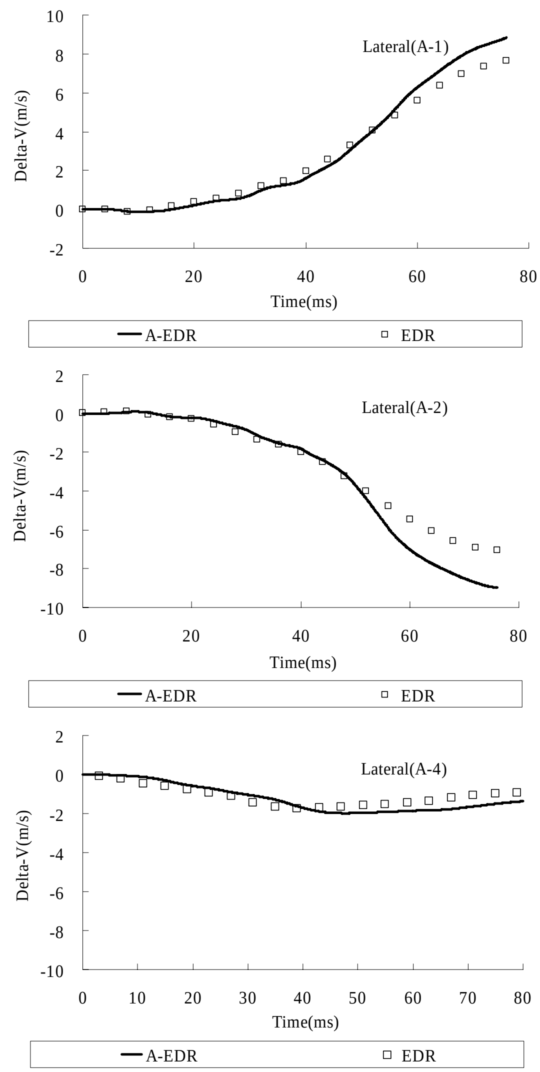


Figure 10. Delta-V time history curves obtained from EDR and A-EDR for lateral direction in car-to-car 90-degree side impacts.

In the first crash phase, the delta-V time histories of R-2 obtained from the EDR and video were comparable for the entire period of 200 ms. In the second crash phase, the delta-V time histories of R-2 obtained from the EDR and accelerometers were comparable for 100 ms, however the data obtained from the center floor accelerometer (A-C) was not usable after 120 ms due to the measurement error. In the second crash phase, the delta-V time histories of R-2 obtained from the video was significantly different from the data obtained from the EDR and accelerometers. High speed video analysis indicated the independent motion between the outer body shell (on which the target marks for video analysis were attached) and the inner main body (in which the EDR and accelerometers were fixed). The independent body motion could be possible since R-2 was sandwiched between R-1 and R-3 in the second crash phase.

In the second crash phase, the delta-V time histories of R-3 obtained from the EDR, video and accelerometers were comparable for the entire period of 200 ms.

In the case 2 of the multiple rear-end collision test, the EDR delta-V time history of R-4 in the first crash phase agreed well with the results from the video and accelerometers. In the third crash phase, the delta-V time histories of R-4 obtained from the accelerometers and video showed an apparent phase delay from the EDR data again according to the different definitions of time zero.

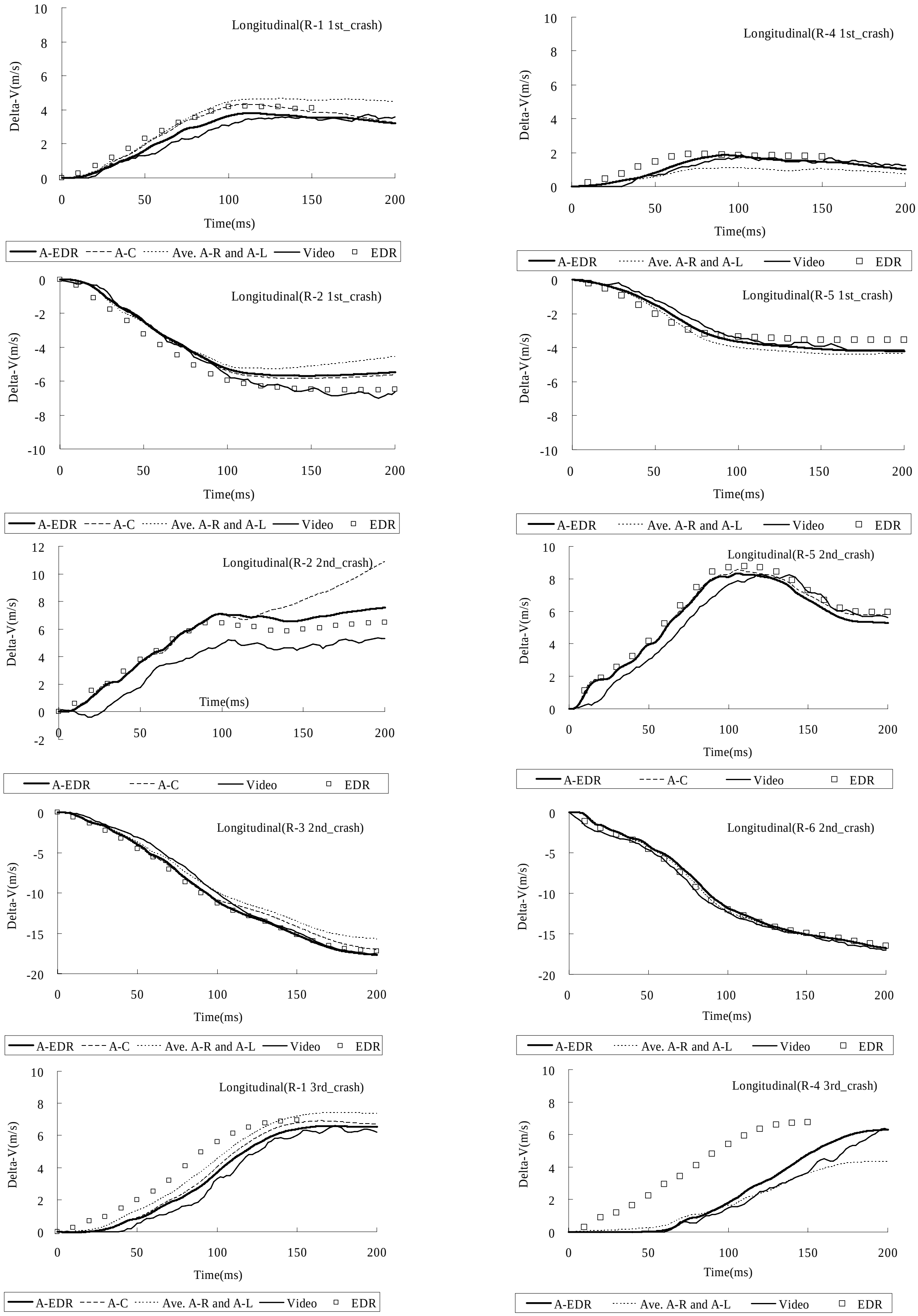


Figure 11. Delta-V time history curves in multiple rear-end collision tests.

Accordingly, the difference between the values of delta-Vs of R-4 in the third crash phase became minimal by shifting the EDR time zero for about 50 ms.

In the first crash phase, the delta-V time histories of R-5 obtained from the EDR, video and accelerometers were comparable for the entire period of 200 ms. In the second crash phase, the delta-V time histories of R-5 obtained from the EDR and accelerometer (A-EDR) were almost comparable for 200 ms. However, the data obtained from the video was different from those obtained by the EDR and accelerometers. One of the reasons causing this difference was previously mentioned for the R-2 second crash.

In the second crash phase, the delta-V time histories of R-6 obtained from the EDR, video and accelerometers were comparable for the entire period of 200 ms.

Figure 12 compares the longitudinal delta-V time histories obtained by the EDR with those obtained by the accelerometers and video in the pole impacts. The EDR longitudinal delta-V time history of P-1 was significantly different from the data obtained from the video and accelerometers. One of the factors responsible for this difference was the delay detecting the crash event by the airbag sensors located in the front side members. The data obtained from the accelerometer attached on the ACM (A-EDR) was not usable after 50 ms due to the measurement error.

In the cases of P-2 and P-3, the EDR longitudinal delta-V time history was comparable with that obtained from the accelerometer attached on the ACM (A-EDR)

Figure 13 compares the lateral delta-V time histories obtained by the EDR with those obtained by the accelerometer (A-EDR) and video in the side pole impact. The EDR delta-V time histories in lateral direction of P-3 were obtained for 80 ms at the positions of ACM, B-pillar and C-pillar where the airbag sensors were installed. Each of the EDR lateral delta-V time history was different according to the location of the measurement. The EDR lateral delta-V time history curve recorded in the ACM was comparable with that of the C-pillar. At about 70 ms, each of the EDR lateral delta-V became a similar value. The slope of the EDR lateral delta-V curves of the ACM and C-pillar was less steep as compared with the result obtained by the video and accelerometer.

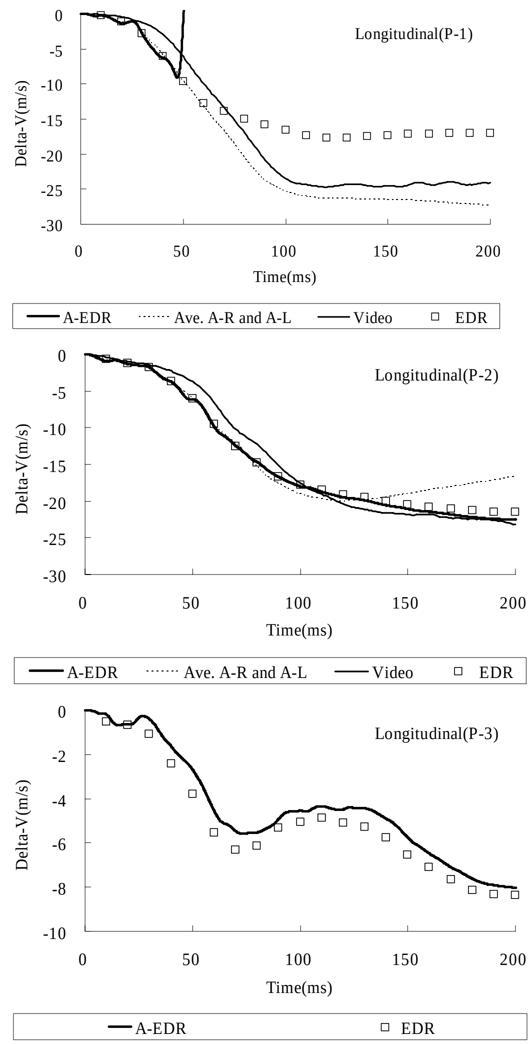


Figure 12. Longitudinal delta-V time history curves in frontal and side pole impacts.

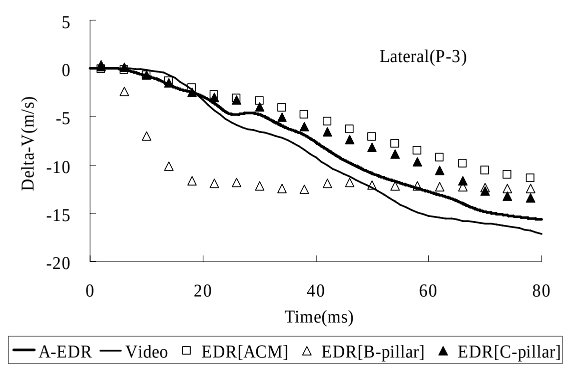


Figure 13. Lateral delta-V time history curves in side pole impact.

ABS-ECU and Engine-ECU Data in Accident Reconstruction

Diagnosis data recorded in the ABS-ECU and engine-ECU were downloaded by using a scan tool (Denso DST-2) from the cars that were tested. Two cars (P-2 and P-3) were crashed with the engine idling and the remaining cars were tested with the engine stopped. In the cases of P-2 and P-3, onboard diagnosis (OBD) connectors were severely damaged and the ABS-ECU and engine-ECU were not diagnosed by the scan tool. In other cases, the diagnoses for the ECUs were conducted successfully by the scan tool; however, useful information, including pre-crash vehicle conditions, was not available from the ECUs except in one case (A-4). In the case of A-4, the diagnosis data, including the vehicle speed, were downloaded from the ABS-ECU successfully.

A-4 was the target car in the car-to-car 90-degree side impact test and its right rear wheel was damaged during the collision. The diagnosis data included the vehicle speed and the rotational velocity of the four wheels as follows:

Vehicle velocity: 15.6 m/s
R. F. wheel: 14.4 m/s, L. F. wheel: 15.6 m/s
R. R. wheel: 4.4 m/s, L. R. wheel: 16.1 m/s

The vehicle velocity recorded in the ABS-ECU (15.6 m/s) corresponded to the EDR impact velocity (15.6 m/s). When one of the ABS sensors is damaged during collision, the ABS-ECU may record the vehicle speed and wheel velocities at the event of the ABS malfunction.

CONCLUSIONS

With respect to ABS-ECU, engine-ECU, and Event Data Recorder (EDR), two types of crash test data are analyzed in this study. The first type is the J-NCAP crash tests. The analysis of the J-NCAP data is for understanding the EDR characteristics under standardized crash test conditions. The second type is the real-world accident reconstructions for evaluating the performance of those ECUs under highly complex and/or severe crash conditions. The conclusions are summarized as follows:

- The pre-crash velocities recorded by the EDR were highly accurate and reliable when cars proceeded without braking prior to the collision. The accuracy and reliability of the EDR impact velocity could be affected by the braking conditions and the EDR time zero information.
- The accuracy and reliability of the maximum delta-V recorded by the EDR decreased under highly complex or severe crash conditions, as compared to the results obtained from the standardized crash tests. The factors responsible for this result were attributable to the characteristics of the accelerometers used in EDR, the large deformation at the location of the airbag control module, vehicle body rotation in a collision, etc.
- When one of the ABS sensors installed in an impacted vehicle was damaged during collision, the ABS-ECU recorded the vehicle speed and the tire rotational velocity of the four wheels at the event of an ABS malfunction.
- The engine-ECU could record the vehicle speed information when the engine was damaged during collision. In order to obtain and understand the information of the engine-ECU, crash tests are recommended to be carried out with the engine running.

ACKNOWLEDGMENTS

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