

Comparison of the Accuracy and Sensitivity of Generation 1, 2 and 3 Toyota Event Data Recorders in Low-Speed Collisions

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ABSTRACT

The accuracy of the speed change reported by Generation 1 Toyota Corolla Event Data Recorders (EDR) in low-speed front and rear-end collisions has previously been studied. It was found that the EDRs underestimated speed change in frontal collisions and overestimated speed change in rear-end collisions. The source of the uncertainty was modeled using a threshold acceleration and bias model. This study compares the response of Generation 1, 2 and 3 Toyota EDRs from Toyota Corolla, Camry and Prius models. 19 Toyota airbag control modules (ACMs) were mounted on a linear sled. The ACMs underwent a series of frontal and rear-end haversine crash pulses of varying severity, duration and peak acceleration. The accuracy and trigger thresholds of the different models and generations of EDRs were compared. There were different accuracy trends found between the early Generation 1 and the more modern Generation 2 and 3 EDRs. There were also differences found in the threshold and trigger characteristics of the Generation 3 EDRs. This study extends the understanding of how Toyota EDRs respond in low speed collisions with various collision parameters.

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INTRODUCTION

Most modern vehicles sold in North America are equipped with airbag systems that record collision-related information. This information can be downloaded from the event data recorder (EDR) within the airbag control module (ACM) using the Bosch Crash Data Retrieval system (CDR) and can then be used by crash investigators to reconstruct the collision. Understanding the behaviour of these systems and quantifying the accuracy of the crash data are thus important factors in the quality of the subsequent reconstruction.

Chidester et al. [1] performed the first study that quantified the accuracy of EDR data and found that the EDR-reported longitudinal Delta-V data was within $\pm 10\%$ of the instrumentation-measured Delta-V during high speed collisions of General Motors vehicles. In 2005, Niehoff et al. [2] reported the average error between EDR-recorded data and instrumentation measurements over 28 frontal tests involving GM, Toyota, and Ford vehicles was less than 6%. In 2011, Comeau et al. [3] reported on 14 full frontal crash tests done at 25, 30, and 35 mph and found that the Delta-V's recorded by the Toyota EDR's on average under-reported by approximately 4%. More recently, Tsoi et al. [4] determined the average difference between EDR longitudinal Delta-V and reference instrumentation in 41 NCAP tests for Chrysler, Ford, GM, Honda, Mazda, Toyota, and Volvo modules to be about 7%.

While $\pm 10\%$ variation in EDR Delta-V data for high speed collisions has been generally accepted by the accident reconstruction community, the error in EDR Delta-V recorded during low speed

collisions may exceed 10% as observed by Lawrence et al. [5]. It is therefore important to quantify the absolute error of data retrieved by EDRs during low speed collisions.

Previous work focusing on low-speed crash data from 2005 - 2008 Toyota Corollas showed that the EDR data systematically underestimated the actual speed change for frontal collisions and overestimated the actual speed change for rear-end collisions [6]. The error was explained in part by the threshold acceleration needed to trigger a recorded event, as observed in prior studies of General Motors ACMs [5, 7, 8]. More specifically, the initial portion of the acceleration pulse below the ACM's 2 g acceleration threshold was not included in the integration performed to calculate the speed change. Correcting for the trigger threshold did not eliminate all of the error and a bias remained in the reported speed change.

Toyota has since introduced two new generations of EDRs and the US Department of Transportation has introduced legislation (49 CFR Part 563) that requires vehicles manufactured after September 2012 to provide a minimum set of crash related data from their EDRs [9]. The behaviour of these newer generation EDRs and the effect of the new regulations on the performance of these EDRs remain unknown. Moreover, the prior work focused only on the EDRs installed in Toyota Corollas [6], and the behaviour of the Generation 1 EDRs in other Toyota models also remains unknown.

The goal of this study was to quantify the accuracy, threshold behavior and repeatability of the crash data reported by all three generations of Toyota ACMs installed in three different vehicle

models during low-speed frontal and rear-end collisions. To achieve this goal, we conducted sled tests using a variety of collision parameters to determine each ACM's threshold acceleration and to develop regression models to predict the actual speed change from the EDR-reported speed change for each EDR generation and vehicle model. Based on prior Toyota test data, we hypothesized that the speed change reported by the EDRs would be biased relative to the actual vehicle speed change, and that this bias would depend on the vehicle model, EDR generation, collision direction, peak acceleration and pulse duration.

In this paper, we define the Toyota EDRs with ECU Generation 00/02EDR as Gen1, 04/06/10EDR as Gen2, and 12/13/15EDR as Gen3.

METHODS

Airbag Control Modules (ACMs)

Nineteen Toyota ACMs were obtained from either Toyota dealers or from wrecking yards (Table 1). At least two ACMs from each generation (Gen1, Gen2, Gen3) and each model (Corolla, Prius, Camry) were tested except for Gen2 Corollas, which were excluded as only a small percentage of Toyota Corollas were manufactured with Gen2 ACMs and the required front satellite sensors were difficult to source. Boxes with ECU Generation 00EDR, 10EDR and 15EDR were not tested as they were difficult to source.

Table 1. List of the 19 ACMs tested. Repeatability tests were done on selected ACMs (see *).

Box #	Vehicle	VIN	Generation	Manufacturer
22*	2005 Camry	4T1BE32KX5U047896	1 (02EDR)	Denso
28	2005 Camry	4T1BF30K95U106064	1 (02EDR)	Denso
3	2006 Corolla	2T1BR32EX6C666189	1 (02EDR)	TRW
31	2006 Corolla	2T1BR32E36C570467	1 (02EDR)	TRW
32	2005 Corolla	2T1BR32E45C920395	1 (02EDR)	TRW
20*	2006 Prius	JTDKB22U063174561	1 (02EDR)	Denso
21	2007 Prius	JTDKB20U877686906	1 (02EDR)	Denso
26	2010 Corolla	2T1BU4EE6AC351026	1 (02EDR)	TRW
29*	2010 Corolla	2T1BU4EE9AC405676	1 (02EDR)	TRW
23*	2008 Camry	4T1BB46K68U052980	2 (04EDR)	Denso
27	2008 Camry	4T1BE46K38U731483	2 (04EDR)	Denso
11	2010 Prius	JTDKN3DU7A0040554	2 (06EDR)	Denso
17*	2010 Prius	JTDKN3DU6A0063162	2 (06EDR)	Denso
13*	2013 Corolla	2T1BU4EE2DC062231	3 (12EDR)	TRW
19	2013 Corolla	2T1BU4EE8DC082435	3 (12EDR)	TRW
14	2013 Prius	JTDKN3DU1D0348551	3 (13EDR)	Denso
15*	2013 Prius	JTDKN3DU9D5574999	3 (13EDR)	Denso
25	2015 Camry	4T1BF1FK4FU490543	3 (13EDR)	Denso
30*	2015 Camry	4T1BF1FKXFU910614	3 (13EDR)	Denso

Instrumentation

The linear sled was fitted with an uni-axial accelerometer (Endevco 7265A; ± 100 g, San Juan Capistrano, CA) oriented with its sensitive axis parallel to the sled direction. A rearward acceleration simulating a frontal impact was defined as a negative acceleration.

Accelerometer data was acquired at 2400 Hz using a 12-bit, simultaneous-sample-and-hold Win30 DAQ card (United Electronics Inc., Watertown, MA).

Test Procedure

The ACMs were tested in groups of 4 mounted in a 2x2 array to a steel plate that was then fastened to the sled (Figure 1). Front and rear impacts were simulated by rotating the steel plate 180° on the sled. Initial tests with Gen2 and Gen3 ACMs revealed that both front satellite impact sensors were needed for these ACMs to trigger on the sled.

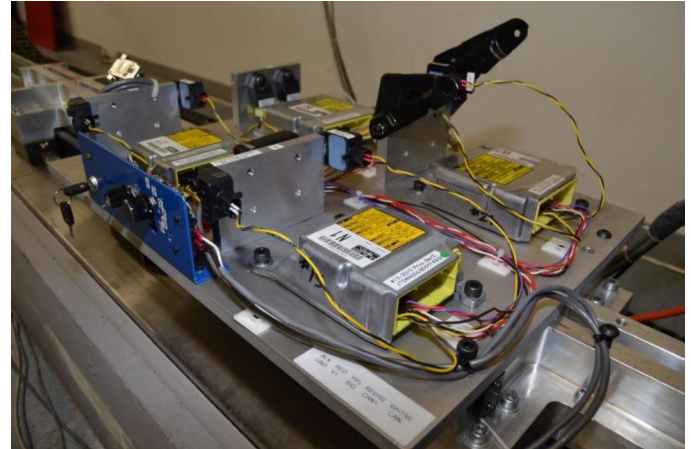


Figure 1. ACM test setup for the sled tests.

The sensitivity of different ACM generations and vehicle models to various collision pulse parameters were assessed using a haversine acceleration pulse followed by 0.5 s at a constant speed and then brought to rest at a deceleration at 0.5 g to rest. The acceleration pulses varied in duration (80, 120, 160, 200 ms) and peak accelerations (0.17 g to 4.59 g) to yield a range of speed changes (0.9 km/h to 13.0 km/h) (Figure 2). To determine the acceleration threshold for each ACM, we varied the acceleration level to find pulses just below and just above the level necessary to trigger a recorded event. This process was done for 80, 120, 160, and 200 ms pulses to determine if the threshold was sensitive to pulse duration or speed change.

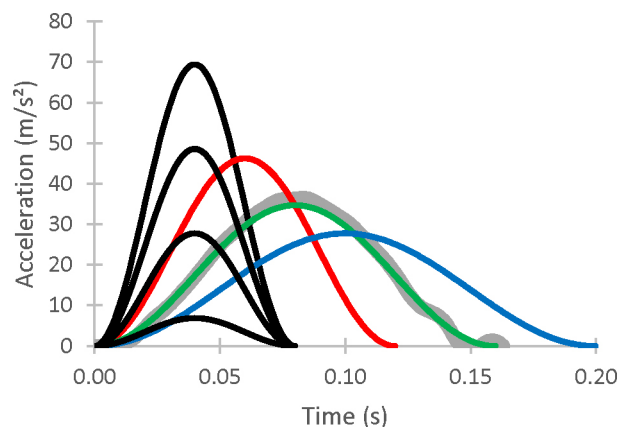


Figure 2. Idealized haversine pulse of 80 ms with speed change of 1, 4 and 7 km/h (black) and 10 km/h at 80 ms (black), 120 ms (red), 160 ms (green) and 200 ms (blue). A filtered acceleration pulse with 10 km/h speed change at 160 ms as recorded by external accelerometer is overlaid in grey.

Repeatability tests were performed on a subset of the ACMs (see * in Table 1) using a 10 km/h speed change and 200 ms haversine pulse.

Twelve repetitions were performed for frontal impacts and ten for

rear impacts. These tests provided data regarding the repeatability within a single ACM and within a single generation of ACM. Repeatability was expressed as the coefficient of variation, which was calculated by dividing the standard deviation by the mean and expressing this as a percentage.

Following each test, data were downloaded from the ACMs directly using a Bosch CDR system (Version 16.1.1). The trigger count of each ACM was compared to the previous test and used to determine whether a new event had been recorded. For each collision event, the maximum longitudinal speed change (ΔV_{ACM}) from the full duration of the ACM recorded longitudinal crash pulse data, i.e., the speed change versus time table, was recorded in units of kilometers per hour (km/h).

Data Reduction and Analysis

The sled accelerometer signal was filtered using a 4th-order 100 Hz Butterworth low-pass filter, in accordance to SAE J211 Channel Frequency Class 60 standards [10], before extracting the peak acceleration (a_{peak}). The sled speed change was calculated by integrating the filtered acceleration signal over the duration (Δt) of the programmed sled pulse and then used as the reference speed change (ΔV_{ref}) for subsequent analyses. The difference (ΔV_{error}) between the reference speed change and the ACM-reported speed change was then calculated, and the minimum speed change and peak acceleration required to trigger an event on each box were tabulated.

Multiple linear regression models were used to predict the reference speed change (ΔV_{ref}) using two sets of predictors: i) a full model including the speed change reported by the ACM (ΔV_{ACM}), the pulse duration (Δt), the peak acceleration (a_{peak}), and the vehicle model (Prius, Corolla, Camry), and ii) a simple model including only the speed change reported by the ACM and the vehicle model. The regression models were limited to main effects, i.e., no interactions, and then evaluated to ensure that they captured most of the variance in the data. Separate regressions were performed for each combination of ACM generation (Gen1, Gen2, Gen3) and collision direction (front, rear) because there was no a priori reason to expect the three generations to be interrelated and because examination of the raw data showed that combining collision direction required the inclusion of multiple interaction terms that increased the complexity of the models without improving their explanatory ability.

The full model was used to explore the sensitivity of the ACM response to various collision parameters, whereas the simple model was generated for reconstruction purposes where the collision duration and peak acceleration are not known beforehand. The ACM-reported speed change, collision duration and peak acceleration were continuous predictors and the vehicle model was a categorical predictor. The regression coefficients (β_0, β_1 , etc.) in each model (Equations 1 and 2) were calculated and analyzed to determine if they were significantly different from zero. When using these equations, only the appropriate vehicle-specific coefficient (β_{Prius} , β_{Camry} or $\beta_{Corolla}$), in addition to β_0 , should be included in the calculation. Adjusted coefficients of determination (r^2) and the 95th percentile prediction intervals were also calculated for each model. All regressions were performed using Statistica (v6.0, Statsoft, Tulsa,

OK) with significance set to $p < 0.05$. No correction for multiple comparisons was made because all data within each model were from independent test series.

$$\Delta V_{ref} = \beta_0 + \beta_1 \Delta t + \beta_2 \Delta V_{ACM} + \beta_3 a_{peak} + \left\{ \begin{matrix} \beta_{Prius} \\ \beta_{Camry} \\ \beta_{Corolla} \end{matrix} \right\} + \epsilon \quad (1)$$

$$\Delta V_{ref} = \beta_0 + \beta_1 \Delta V_{ACM} + \left\{ \begin{matrix} \beta_{Prius} \\ \beta_{Camry} \\ \beta_{Corolla} \end{matrix} \right\} + \epsilon \quad (2)$$

A model generated from the Generation 1 study [6] attributed differences between the ΔV_{ACM} and ΔV_{ref} to the ACMs beginning to calculate ΔV only after a 2 g threshold acceleration was reached. For each sled test, the speed change according to the hypothesized model (ΔV_{model}) was compared to ΔV_{ACM} to determine if the model reproduced the ACM values.

RESULTS

Repeatability

Repeatability within individual ACMs varied from $\pm 0.0\%$ to $\pm 5.3\%$ (Table 2, Appendix A). Similarly low coefficients of variation were seen within ACM generation, except for the Gen2 rear impact tests. The Gen2 Prius and Camry ACMs reported different speed changes, with the Gen2 Prius mean speed change behaving more like a Gen3 ACM and the Gen2 Camry behaving more like a Gen1 ACM. Across all repeatability tests, the largest inter-ACM difference in reported speed change was 2.1 km/h for front impacts and 3.3 km/h for rear impacts (Appendix C). On average the ACMs underestimated the speed change of the front impacts by 0.89 km/h and overestimated the speed change of the rear impacts by 0.65 km/h (Table 2).

Table 2. Repeatability test results expressed as the mean $\pm$ standard deviation (SD) and coefficient of variation (CoV) within each ACM, within each generation of ACMs (All) and across all generations.

		Front	CoV (%)	Rear	CoV (%)
		Mean $\pm$ SD		Mean $\pm$ SD	
Gen1	Prius	-9.58 $\pm$ 0.10	1.1	11.62 $\pm$ 0.23	2.0
	Camry	-9.36 $\pm$ 0.50	5.3	11.63 $\pm$ 0.42	3.6
	Corolla	-8.90 $\pm$ 0.00	0.0	11.84 $\pm$ 0.19	1.6
	All	-9.26 $\pm$ 0.41	4.4	11.70 $\pm$ 0.31	2.6
Gen2	Prius	-8.76 $\pm$ 0.39	4.4	9.11 $\pm$ 0.03	0.3
	Camry	-8.93 $\pm$ 0.40	4.4	11.89 $\pm$ 0.20	1.7
	All	-8.84 $\pm$ 0.39	4.4	10.50 $\pm$ 1.43	13.6
Gen3	Prius	-8.98 $\pm$ 0.44	4.9	9.71 $\pm$ 0.29	3.0
	Camry	-9.10 $\pm$ 0.00	0.0	10.05 $\pm$ 0.16	1.6
	Corolla	-9.39 $\pm$ 0.08	0.8	9.36 $\pm$ 0.05	0.6
	All	-9.16 $\pm$ 0.31	3.3	9.71 $\pm$ 0.34	3.5
All Gens		-9.11 $\pm$ 0.40	4.4	10.65 $\pm$ 1.15	10.8



Trigger Threshold

The peak acceleration to generate a new event for both front and rear impacts in the Gen1 and Gen2 ACMs was around 2 g and did not vary with pulse duration (Table 3, Appendix B). The range of maximum accelerations that did not trigger an event in these ACMs varied from 1.63 g to 2.16 g, and the range of minimum accelerations that triggered an event varied from 1.80 g to 2.41 g. The peak accelerations to trigger new events in Gen3 ACMs did vary with collision duration, but appeared to occur consistently at a speed change of about 8 km/h (minimum: 7.42 km/h, maximum: 9.32 km/h; Table 4, Appendix B). On average, the rear sled tests required slightly higher speed changes to trigger compared to the frontal tests.

Table 3. Range of peak accelerations (in g) that bound the trigger threshold for each ACM generation in front and rear impacts.

	80 ms	120 ms	160 ms	200 ms
Front				
Gen1	1.82 to 2.05	1.85 to 2.03	1.84 to 2.05	1.88 to 2.07
Gen2	1.94 to 2.04	1.84 to 2.03	1.90 to 2.05	1.93 to 2.04
Gen3	5.63 to 5.97	3.79 to 4.07	2.81 to 3.11	2.32 to 2.60
Rear				
Gen1	1.63 to 2.44	1.59 to 2.02	1.54 to 1.95	1.84 to 2.13
Gen2	1.98 to 2.22	1.85 to 2.06	1.89 to 2.62	1.85 to 2.01
Gen3	5.99 to 6.71	3.86 to 4.46	2.89 to 3.41	2.42 to 2.78

Table 4. Range of speed changes (in km/h) that bound the trigger threshold for each ACM generation in front and rear impacts.

	80 ms	120 ms	160 ms	200 ms
Front				
Gen1	2.31 to 2.69	3.66 to 4.05	4.90 to 5.39	6.16 to 6.99
Gen2	2.44 to 2.49	3.69 to 3.98	5.07 to 5.31	6.38 to 6.79
Gen3	7.41 to 8.06	7.92 to 9.07	7.45 to 8.43	7.72 to 8.48
Rear				
Gen1	2.19 to 3.08	3.14 to 4.07	4.13 to 5.40	6.11 to 7.11
Gen2	2.53 to 2.76	3.67 to 4.17	5.01 to 5.46	6.11 to 6.80
Gen3	7.47 to 8.74	7.73 to 8.97	7.73 to 9.16	8.16 to 9.32

Accuracy

In most front impacts, the ACMs underestimated the reference speed change (Figure 3, Table 5) and the amount of this underestimate generally increased with longer pulse durations (Table 6). For rear impacts, the pattern of over/underestimating varied between ACM generations and between vehicles within the Gen2 ACMs (Figure 3), but a pulse duration effect still appeared to be present in the data. In general, the Gen3 ACMs appeared to be more accurate and less influenced by collision pulse duration than the Gen1 and Gen2 ACMs, however they also generated data only at the upper range of our test severities.

Table 5. Mean, minimum and maximum of the speed change error ($\Delta V_{\text{error}} = \Delta V_{\text{ACM}} - \Delta V_{\text{ref}}$) in km/h.

	Gen1		Gen2			Gen3	
	Front	Rear	Front	Camry Rear	Prius Rear	Front	Rear
Mean	1.52	1.00	1.55	0.79	-1.18	0.65	-0.59
Min	-0.72	-1.29	-0.48	-1.22	-2.60	-0.48	-1.33
Max	3.81	2.61	3.38	2.24	-0.18	1.59	0.29

Table 6. Average speed change error (ΔV_{error}) in km/h as a function of pulse duration.

	Gen1		Gen2		Gen3		
Δt (ms)	Front	Rear	Front	Camry Rear	Prius Rear	Front	Rear
80	0.52	1.34	0.60	0.65	-0.77	0.13	-0.48
120	1.06	1.32	1.16	1.27	-1.12	0.74	-0.39
160	2.09	0.81	2.09	0.44	-1.67	0.63	-0.69
200	2.76	0.25	2.70	0.08	-2.17	0.91	-0.92

All of the full regression models yielded coefficients for the ΔV_{ACM} term (i.e., β_2) that were significantly different from zero (Tables C1 and C2, and Figure C1 in Appendix C). The full regression models also yielded significant coefficients for the other terms and showed that the ACM-reported speed change was also sensitive to collision duration, peak acceleration and vehicle model. Some full regression models contained only one of the three parameters (Gen2 Front and Gen3 Front), whereas other full models contained all three parameters (Gen2 Rear and Gen3 Rear). Collision duration (Δt) was a significant predictor in all models except for the Gen3 Front, peak acceleration was a significant predictor in 3 of 6 models (Gen1 Rear, Gen2 Rear and Gen3 Rear), and vehicle model was a significant predictor in 3 of the 6 models (Gen1 Front, Gen2 Rear and Gen3 Rear). The regressions explained between 98% and 99% of the variance in the data for Gen1 and Gen2 ACMs, but only 87% to 92% of the variance the Gen3 ACMs.

The simple regression models, which can be used for accident reconstruction purposes, yielded similar results for the coefficients related to ΔV_{ACM} and vehicle model, but the absence of the collision duration and peak acceleration terms resulted in models that explained less of the variance in the data (Tables 7 and 8; Figure 4). The simple models for the Gen1 and Gen2 ACMs explained between 88% and 94% of the variance in the data, whereas the simple models for the Gen3 ACMs explained only 81% to 87% of the variance in the data. The 95th percentile prediction intervals were ± 0.69 km/h to 1.73 km/h for frontal pulses and ± 0.50 km/h to 1.30 km/h for rear pulses (Figure 3).

Table 7. P-values for each variable and intercept in the simple regression model and the coefficient of determination (r^2). Bold values represent $p < 0.05$.

	Gen1		Gen2		Gen3	
Effect	Front	Rear	Front	Rear	Front	Rear
Intercept	0.0000	0.0013	0.0000	0.0000	0.0006	0.0000
ΔV_{ACM}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Vehicle Model	0.0000	0.6815	0.7394	0.0000	0.1913	0.0000
Adjusted r^2	0.886	0.934	0.905	0.936	0.817	0.865

Table 8. Coefficients for each parameter in the simple regression model. Bold values represent coefficients significantly different from zero. Coefficients with bolded values should be included when applying the regression model.

	Gen1		Gen2		Gen3	
	Front	Rear	Front	Rear	Front	Rear
β_0	-2.1764	0.3084	-2.3203	1.2546	-1.0207	2.0099
β_1	0.8668	0.8375	0.8671	0.8586	0.9566	0.8275
β_{Prius}	0.1667	0.0202	-0.0187	0.0000	-0.0531	-0.0863
β_{Camry}	0.0000	0.0176	0.0000	-0.0111	0.0000	-0.0000
β_{Corolla}	-0.3255	0.0000	NA	NA	0.0579	0.1915

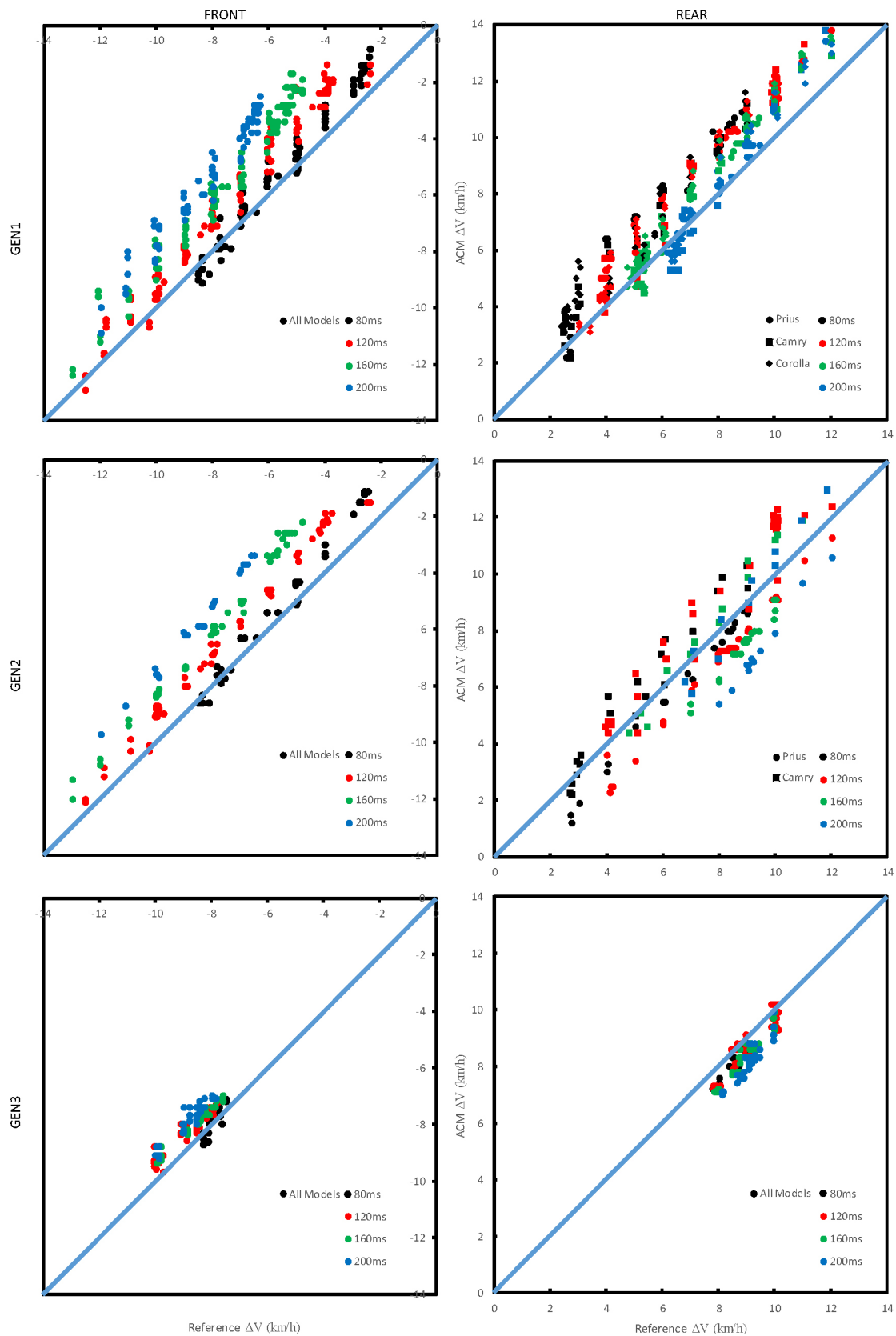


Figure 3. Six panels showing the ACM-reported speed change plotted against the actual speed change for the front and rear impacts (columns) and for the three generations (rows). All frontal plots and rear Gen3 plots have vehicle models combined into one series, the rear Gen1 and Gen2 have vehicle models separated into separate series.