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ABSTRACT

This paper evaluates the accuracy of different methods for determining the speed change during vehicle-to-vehicle collisions from isolator compression and low-speed barrier data. A controlled regimen of 938 aligned, low-speed collisions was completed, including a series in which collision force data were collected to compare vehicle-to-barrier and vehicle-to-vehicle collisions. Five vehicles (four with isolators and one with a foam-core bumper) were tested against a rigid barrier and against each other in collisions below damage threshold. Three methods of assessing the speed change of a low-speed vehicle-to-vehicle collision are evaluated as alternatives to a fourth method: staging collisions with exemplar vehicles. For each of the three methods, the expected accuracy and limitations are presented.

INTRODUCTION

In response to increasing claims of injury in seemingly trivial low-speed collisions, there has been increased research in recent years which has focused on this phenomenon[1-7]. This research has been largely split into two areas: quantifying the severity of the collision (most often in terms of speed change), and attempting to understand the occupant dynamics and injury potential. In this paper, the focus is on quantifying collision severity.

Specifically, this paper explores the relationship between low-speed, vehicle-to-barrier and vehicle-to-vehicle collisions. Like the Federal Motor Vehicle Safety Standards (FMVSS) compliance testing conducted by the National Highway Traffic Safety Administration (NHTSA), barrier testing provides a controlled environment in which to gather vehicle-specific data. Studies of the higher speed data have demonstrated that these empirical data can be used to estimate the stiffness of a vehicle, which in turn can be used to estimate the energy absorbed and thus the speed change of vehicles in vehicle-to-vehicle collisions. The process of using barrier impact data is explored here for low-speed collisions.

COLLISION SEVERITY - VEHICLE The severity of a collision can be measured a number of ways. From a vehicle perspective, collision severity can be quantified by the energy required to cause the residual vehicle crush. This energy is often translated into a theoretical barrier impact speed required to cause the same amount of permanent crush assuming zero restitution. This theoretical value has alternately been called the Equivalent Barrier Speed (EBS) or Barrier Equivalent Velocity (BEV). The usefulness of EBS or BEV quickly diminishes if specific collision dynamics are of interest.

For collision dynamics, the velocity change of the impact is the most important measure of collision severity. The velocity change is the vector difference between the pre- and post-impact velocities of the vehicle, and when added to a vehicle's post-impact velocity, the vehicle's pre-impact speed can be calculated. Velocity change does not equal EBS except in specific circumstances (similar mass and stiffness) and two vehicles with the same EBS can have undergone very different velocity changes[8].

The process of translating high-speed barrier data into high-speed velocity changes is simplified because the collisions are essentially plastic, i.e., the coefficient of restitution (e) is close to zero. Low-speed impacts are not plastic and assuming zero restitution cannot be justified. Moreover, each vehicle has its own restitution behavior which varies with collision severity. For this reason, methods which assume restitution is zero, i.e., EBS or BEV, cannot be used to define the severity of low-speed impacts. Alternate methods of quantifying vehicle-to-vehicle collision severity have been developed and some are evaluated in this paper.

The speed change of a collision (a scalar) is the magnitude of the velocity change (a vector). In low-speed rear-end collisions, the terms are often used interchangeably because it is understood that the speed change is directed essentially parallel to the vehicles' longitudinal axes.

COLLISION SEVERITY - OCCUPANT For occupant dynamics and injury-potential analyses, velocity change (the vector) is often the best descriptor of collision severity because it describes both the direction and speed that the occupant initially moves with respect to the vehicle interior in response to a collision. Exceptions include collisions resulting in high angular velocities (where the speed of the occupant relative to their immediate area may differ significantly from the linear velocity change of the vehicle's center of mass), higher speed lateral collisions with near-side occupants (where the impact speed of the other vehicle and hence the speed of the door striking the occupant is a useful measure), and high-speed frontal impacts resulting in adverse intrusion (where again the speed of the intruding surface is important). In these exceptional cases, the speed change of the vehicle is an incomplete measure of severity for the occupant because it underestimates the relative speed between the occupant and the specific area of the vehicle with which they interact. The speed difference between the occupant and this specific area is still, however, a valid measure of severity.

EBS is of limited use in occupant analyses because the same EBS can result from a variety of speed changes depending on the other vehicle's mass and stiffness, the amount of rotation, and in the case of low-speed collisions, the restitution.

Both our testing and the literature indicate that in low speed rear impacts, most of the occupant's head kinematics occurs after the collision is essentially complete[6,9,10] (see Figure 1 and Figure 2). In these circumstances, the aggregate effect of the longitudinal acceleration and its duration, i.e., the speed change, is important and the exact shape and duration of the acceleration is less important. Acceleration of the vehicle (either as a peak or average) is often quoted as a measure of low-speed collision severity. However, without defining the shape of the acceleration pulse and duration of the collision, peak or average vehicle acceleration is an incomplete measure of collision severity because of the delay between collision and occupant motion.

For both vehicular and occupant reasons, our research has focused on speed change as the most complete descriptor of collision severity for aligned, low-speed rear-end collisions.

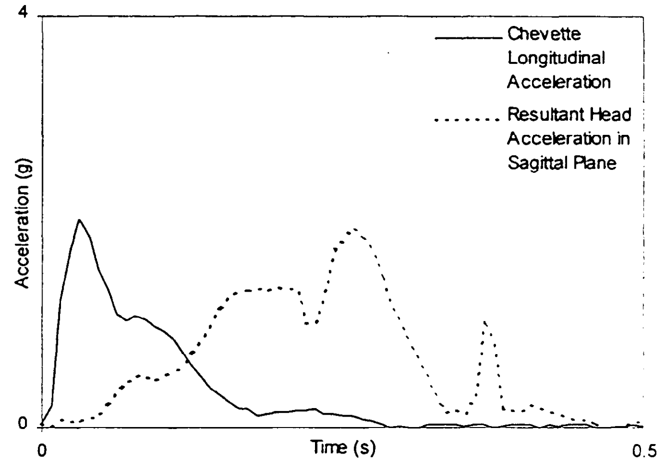


Figure 1. Phase of vehicle and head acceleration in Chevette barrier impact (Δv = 1.56 m/s)[10]

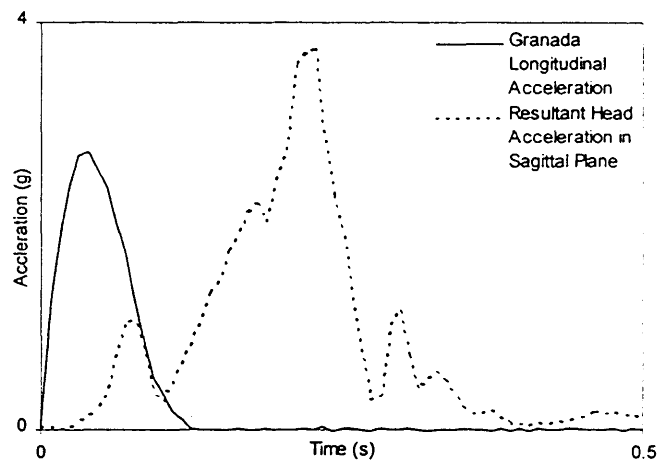


Figure 2. Phase of vehicle and head acceleration in Granada barrier impact (Δv = 1.40 m/s)[10]

TEST DESCRIPTION

EXPERIMENTAL METHOD - A total of 938 vehicle-to-vehicle and vehicle-to-barrier collisions were staged. Five different vehicles were used for this study resulting in 10 vehicle-to-vehicle and 5 vehicle-to-barrier data sets. The barrier data were used to determine speed change, restitution, and energy absorbed as a function of isolator compression for all five vehicles. These barrier-derived values were then used to predict the speed change of each vehicle-to-vehicle collision based on the resulting isolator compression. The predicted speed changes were then compared to the measured speed changes to evaluate each method of predicting vehicle-to-vehicle speed change.

The experimental procedure used for each collision is described in detail elsewhere[2]. Briefly however, all of the collisions were staged on dry, level concrete and each vehicle was in neutral with the parking brake disengaged. A fine coat of Double*Glo Sno Spray™ was applied to each isolator prior to each test in order to determine the maximum isolator compression. Tire air pressure was maintained according to the data placard, and roll-out tests were done before and after each test series to ensure that the rolling resistance of each vehicle did not vary over the testing period.

VEHICLES - Five different vehicles were used, four of which had bumpers equipped with isolators. The fifth vehicle, a 1985 Hyundai Stellar, had a polyurethane foam-core bumper. We understand that the Stellar was not sold in the United States. It is similar to the Hyundai Excel, except the Stellar is about 95 kg lighter and has a wheelbase 14 cm shorter than the Excel. Test vehicle data are given in Table 1. The vehicles were weighed on a certified full-vehicle scale. Isolator data for each of the so-equipped vehicles is given in Table 2.

Rolling resistance (Table 1) was determined from the average slope of the speed versus time graphs in tests where no collisions occurred. Rolling resistance tests were conducted from an initial speed of about 1 m/s. The rolling resistance values in Table 1 are the average for the number of rollout tests given in parentheses.

Two sets of data were acquired for this research. For the larger data set (833 collisions), the number of collisions staged for each vehicle combination, as well as the number of barrier tests conducted for each vehicle, are given in Table 3. An additional 105 collisions were staged with load cells to determine the collision force profiles. For this smaller data set, only the Chevette and Granada were used.

INSTRUMENTATION - The test vehicles were instrumented with an MEA 5th Wheel (Figure 3) to measure vehicle speed. Data were acquired at 128 Hz for about 1 second before and 4 seconds after impact. Speed resolution at this sampling frequency is about 0.01 m/s. Maximum isolator compression was measured manually after each test to the nearest millimeter.

Two Sensotec load cells were used for the 105 additional tests between the Chevette and Granada. Each load cell's capacity was 44 480 N (10,000 lb.) and the total acquisition system resolution was ±30 N. For this smaller set of tests, load cell and 5th wheel data were acquired at 200 Hz. Barrier-mounted load cells were used in the barrier impacts. The load cells were mounted between the Chevette's bumper and the isolators in the vehicle-to-vehicle tests.

DATA INTERPRETATION - Figure 4 shows a sample of the MEA 5th Wheel output for one collision. Note that the target vehicle (Mustang) is stationary before impact. After impact, damped oscillation of both vehicles on their suspensions is seen in the traces. Long post-impact sampling durations were necessary to allow the oscillations of some vehicles to settle. The straight lines drawn through the post-impact data in Figure 4 have been added to show how post-impact speeds were determined. For the collision shown in Figure 4, the post-impact speeds were determined to be 0.57 m/s for the bullet vehicle (Chevette) and 1.09 m/s for the target vehicle. The bullet vehicle's impact speed was 1.96 m/s.

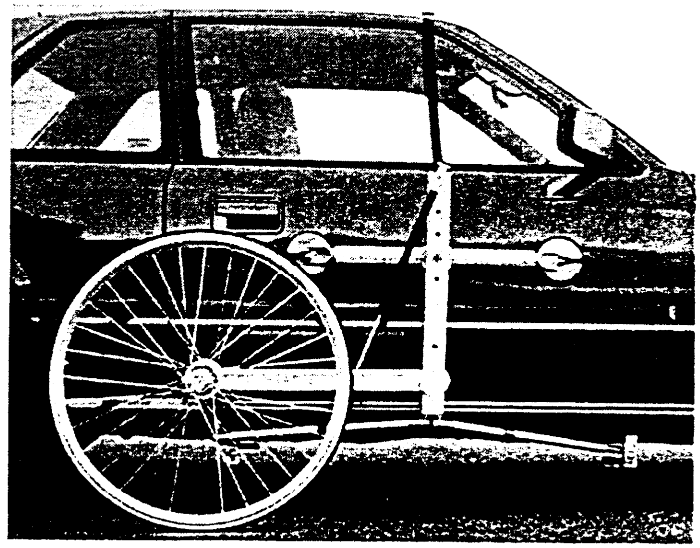


Figure 3. MEA 5th Wheel

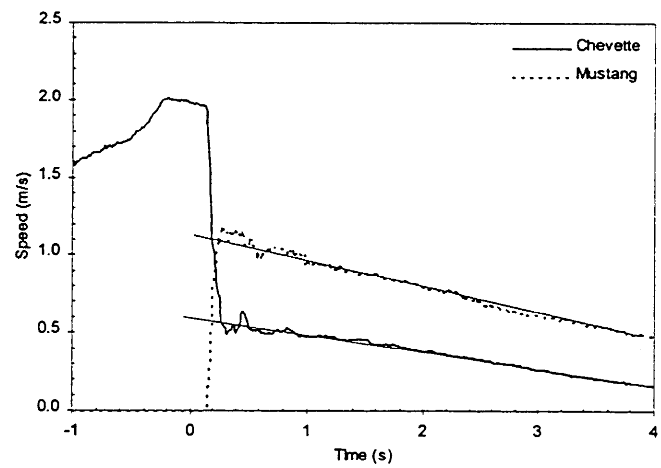


Figure 4. Sample collision data

Table 1. Test vehicle data

Year	Manufacturer	Model	Surface	VIN	Mass(kg)	Isol. Type*	RR** (m/s^2)
81	Chevrolet	Chevette, 4-door	Rear	1G1AB6890BA111061	970	I	0.114 (8)
82	Ford	Granada, 4-door	Rear	1FABP2785CG109076	1330	III	0.152 (4)
80	Ford	Mustang, 2-door	Front	0R02A153538	1140	III	0.116 (4)
85	Hyundai	Stellar, 4-door	Rear	KMHSF21K8FU054341	1100	Foam	0.12 (4)
76	Volkswagen	Rabbit, 4-door	Rear	1763166790	850	II	0.13 (4)

*See reference 1 for Isolator types ** RR = average rolling resistance of ( ) tests

Table 2. Isolator data.

	EPTL* (mm)	Max. Comp. (mm)	Isolator Part No. (left isolator first)
Chevette	87	47	254 80 1/2200 8562 252 80 1/2200 8562
Granada	68	56	D9BB-17D809 AA/Y1HA 3A D9BB-17D809 AA/Y1HA B4
Mustang	67	54	D9ZB-17D809-AE/?CDG 3 D9ZB-17D809-AE/??DC 3
Rabbit	65	56	171807 146 171807 147

*EPTL= Exposed Piston Tube Length / = new line of numbers

Table 3. Test summary

	Chevette	Granada	Mustang	Rabbit	Stellar
Barrier	43	39	39	41	37
Stellar	50	71	39	74	
Rabbit	49	105	83		
Mustang	49	62			
Granada	52				

COLLISION FORCE PROFILES

Force traces are shown in Figure 5 for varying barrier impact severities. The Chevette data in Figure 5a indicate that the force builds rapidly for all but the most minor impacts and reaches a maximum at between 20 and 25 ms. The slope is shallower during the unloading phase, which results in an asymmetrical force pulse. Collision duration varies between about 220 ms (at $\Delta v = 0.85$ m/s) and about 120 ms (at $\Delta v = 2.15$ m/s). Long collision durations occur at the lower severities because the vehicle is accelerated off the barrier by the isolators returning to their original length. Shorter collision durations may occur in the higher severity tests because the rebound speed off the barrier exceeds the return rate of the isolators.

The force traces for the Ford Granada (Figure 5b) are symmetrical about their vertical axes. Peak force occurs slightly later (about 30 to 50 ms) and the collision durations are relatively constant (about 120 ms) across all levels of isolator compression.

Figure 6 shows the force versus time traces for two vehicle-to-vehicle collisions and a corresponding barrier impact for each vehicle at about the same average isolator compression. The repeatability between the two vehicle-to-vehicle traces seen in Figure 6 was also observed in the barrier impacts. Figure 6 shows the differences between vehicle-to-vehicle and vehicle-to-barrier collisions for each vehicle. Although Figure 6b suggests that the collision force and duration is about the average of the two barrier force profiles, this is not as clearly demonstrated in Figure 6a. Additional examination of this phenomenon is needed.

ANALYSIS OF LOW-SPEED IMPACT SEVERITY

The authors have encountered a number of methods for estimating collision severity for aligned low-speed vehicle-to-vehicle collisions. Typically these methods use data from quasi-static isolator compression tests or vehicle-to-barrier impacts and it is these methods, their accuracy, and their limitations, that are explored in this paper.

What is not considered here is the notion that collision severity can be gauged from the presence or absence of damage in conjunction with the "5-mph" or "2½-mph" bumpers specified by FMVSS 581 or CMVSS 215. The authors have found no relationship between bumper damage threshold and the safety regulations in effect when the vehicle was produced.

The four methods of determining impact severity considered here are:

1. Quasi-Static Isolator Force Method - using the force to begin isolator compression or the quasi-static force at a given compression to calculate a vehicle's acceleration, and if duration is assumed, the vehicle's speed change;
2. Direct Barrier Data Method - using barrier data to directly determine a vehicle's speed change from isolator compression (and using conservation of linear momentum to calculate the other vehicle's speed change);
3. MER Method - using momentum, energy and restitution with the barrier data to indirectly determine a vehicle's speed change from isolator compression; and,
4. Staged Collision Method - staging vehicle-to-vehicle collisions using the actual or exemplar vehicles.

Method 4 is the most reliable method of determining the actual speed change in a specific collision. Methods 1 to 3 have evolved because Method 4 is not economical for most low-speed collision reconstructions. In this paper, the first three methods are compared with staged collision data (Method 4) to quantify their accuracy and limitations.

ANALYSIS

Methods 1 to 3 of determining the speed change in vehicle-to-vehicle collisions are evaluated in order. Method 1 was only evaluated using the small data set (105 collisions involving the Chevette, Granada, and barrier). Methods 2 and 3 are evaluated using the larger data set (833 collisions between all five vehicles plus the barrier)

METHOD 1: QUASI-STATIC ISOLATOR FORCE - This method of calculating speed change relies on the quasi-static force needed to compress the isolators. The force to initiate isolator compression and the force at maximum compression have been reported previously[1,2]. A hand-operated hydraulic press applied axial force to a

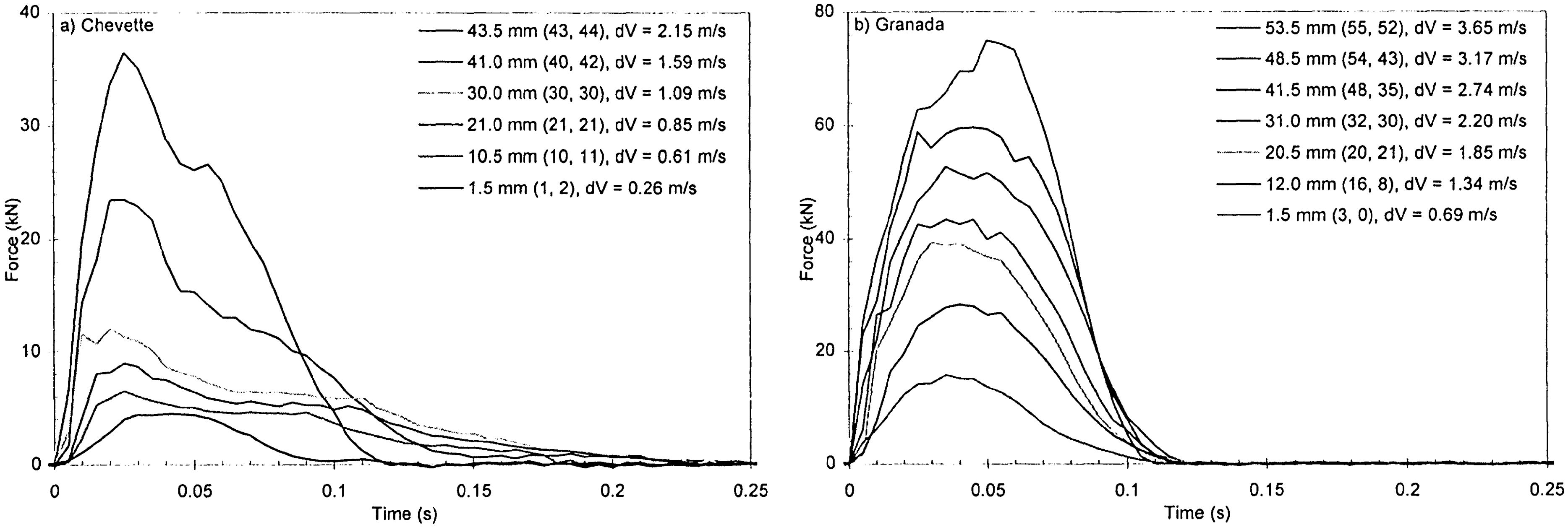


Figure 5. Barrier collision force variation with incremental increase in isolator compression for the Chevette and Granada

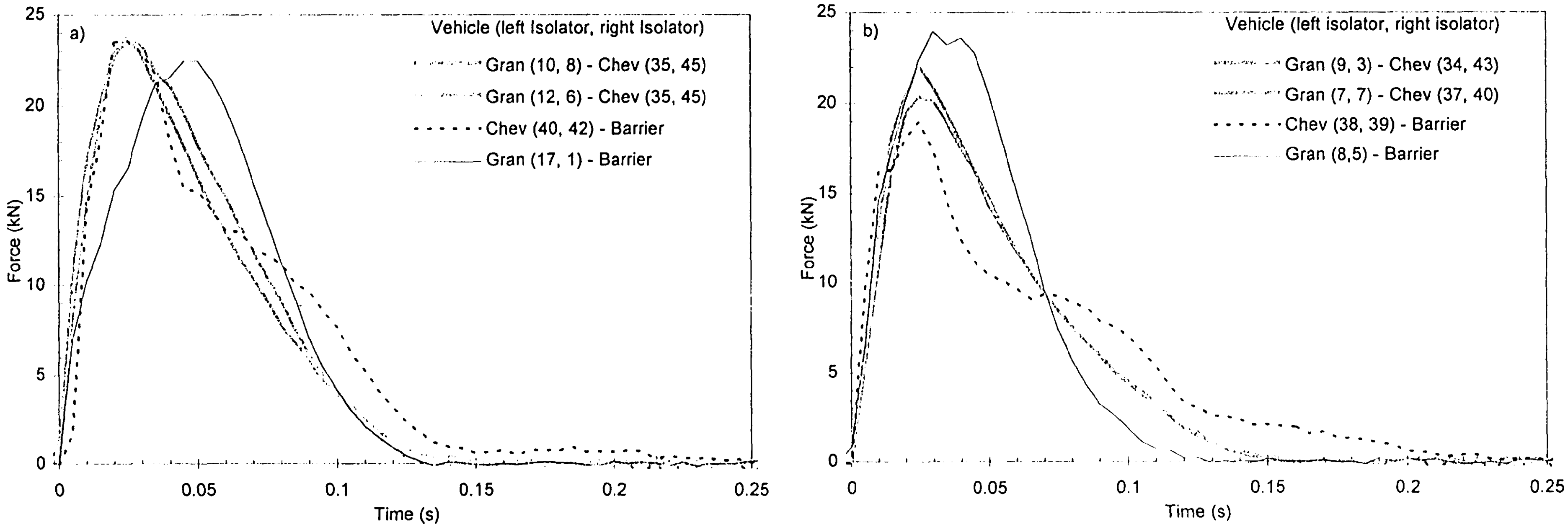


Figure 6. Two comparisons of vehicle-barrier and vehicle-vehicle force profiles at similar isolator compressions for the Chevette and Granada

single isolator which had been removed from the vehicle. Each compression test was performed slowly (over a period of minutes) and therefore only measured the spring-force portion of the spring-damper combination that constitutes most isolators.

With this method, the force transferred through an isolator is typically estimated by assuming linear force-versus-displacement behavior between the force at the onset of compression and the force at maximum compression and then interpolating between the two endpoints. The force for each isolator (typically two per bumper) is summed and Newton's Second Law is used to calculate vehicle acceleration. If a collision duration is assumed, a speed change can then be calculated. Some users of this method assume the interpolated isolator force is a peak collision force (and assume a triangular or sinusoidal force profile), while others simply assume it is an average collision force and use a square wave.

To assess the assumption that static and dynamic isolator forces are similar, both static and dynamic data for the Chevette and Granada isolators were obtained (see Figure 7). The static data was obtained in a hydraulic press while the dynamic data was obtained from whole-vehicle barrier tests. The quasi-static force-versus-compression behavior for each isolator was measured and the sum of each pair of isolators is shown. While these data indicate the straight-line assumption between initial and maximum compression for the static compression force is reasonable for these two vehicles, previous work[11] has shown that the static force-compression curves for Honda Civic and Volkswagen Rabbit isolators are not linear.

Both peak and average dynamic forces for the Chevette and Granada isolators are shown in Figure 7. Peak force is simply the maximum force measured, whereas average dynamic force is calculated by dividing the area under the force-time trace by the collision duration. Cutoff levels of 250 N were used to identify the bounds of the collision pulse and the impulse (ΣFdt) was calculated using trapezoidal integration.

The average dynamic force for the Chevette isolators is slightly less than their quasi-static force until about 40 mm of compression, beyond which the average dynamic force climbs rapidly. The Chevette's average dynamic force is less than its quasi-static force because of the Chevette's prolonged collision duration. For the Granada, the average dynamic force and the quasi-static force are similar for the first 10 mm of compression, beyond which the average dynamic force increases more rapidly than the quasi-static force. Figure 7 shows that quasi-static isolator compression force does not accurately model the dynamic isolator compression and that dynamic damping effects are present even at low isolator compressions for the Granada's isolators.

The speed change predicted by Method 1 for each of the 18 vehicle-to-vehicle collisions in the small data set was compared to the speed change measured by the MEA 5th Wheel (see Figure 8). Figure 8 shows all three variations of Method 1 (square, sinusoidal and triangular) as well as the result of integrating the dynamic load cell data for every vehicle-to-vehicle test.

The integrated load cell data compare well with the 5th wheel speed change for both vehicles. The square, sinusoidal and triangular shaped pulses based on static isolator force values do not compare well. In each case, the interpolated static force for a given compression was used and the actual collision duration of each vehicle-to-vehicle collision was used for these calculations. If the collision duration is simply assumed, the accuracy of this method will decrease. Despite this use of actual collision durations, the horizontal trend for each variation of Method 1 demonstrates the inaccuracy of this method for predicting speed change.

To further underscore the problems of Method 1, the onset of isolator compression for the Granada during an impact with the Chevette can be examined. Based on the static force-compression data in Figure 7, the Granada isolators would not begin to compress until the Chevette isolators were fully compressed. However, Figure 9a shows that the Granada isolators begin to compress when the Chevette isolators are compressed about 26 mm. The Chevette's peak dynamic force at this level of compression is about equal to the intercept of the Granada's peak dynamic force data (see Figure 7). This observation shows that even at the onset of isolator compression, the use of static isolator force can be misleading. The corresponding isolator compression for each vehicle-to-vehicle pair in the large data set has also been included in Figure 9.

METHODS 2 AND 3 - Both Methods 2 and 3 have been assessed with the large collision set. The results of these collisions are summarized here and will be used in both the Method 2 and Method 3 analyses.

Figure 10 and Figure 11 summarize the isolator compression and restitution as a function of speed change for all 833 tests in the large data set. The vehicle-to-vehicle data, when compared to the barrier data, indicates that direct use of barrier data will not provide an accurate estimate of a vehicle's speed change in all cases.

Figure 12 shows the barrier data for each vehicle, along with fitted equations, and their coefficients of determination (r^2). The type of equation used for each data set was not based on analytical models of each type of isolator, but rather on obtaining equations which fit the barrier data well. Since the isolator compression in all of the vehicle-to-vehicle tests was within the range obtained in the barrier tests, the equations were not extrapolated outside the data used to define them. For this reason, higher order polynomials could be used without concern for high-order behavior outside the range of the data. These equations cannot be used for an isolator compression beyond the range used to define the equation.

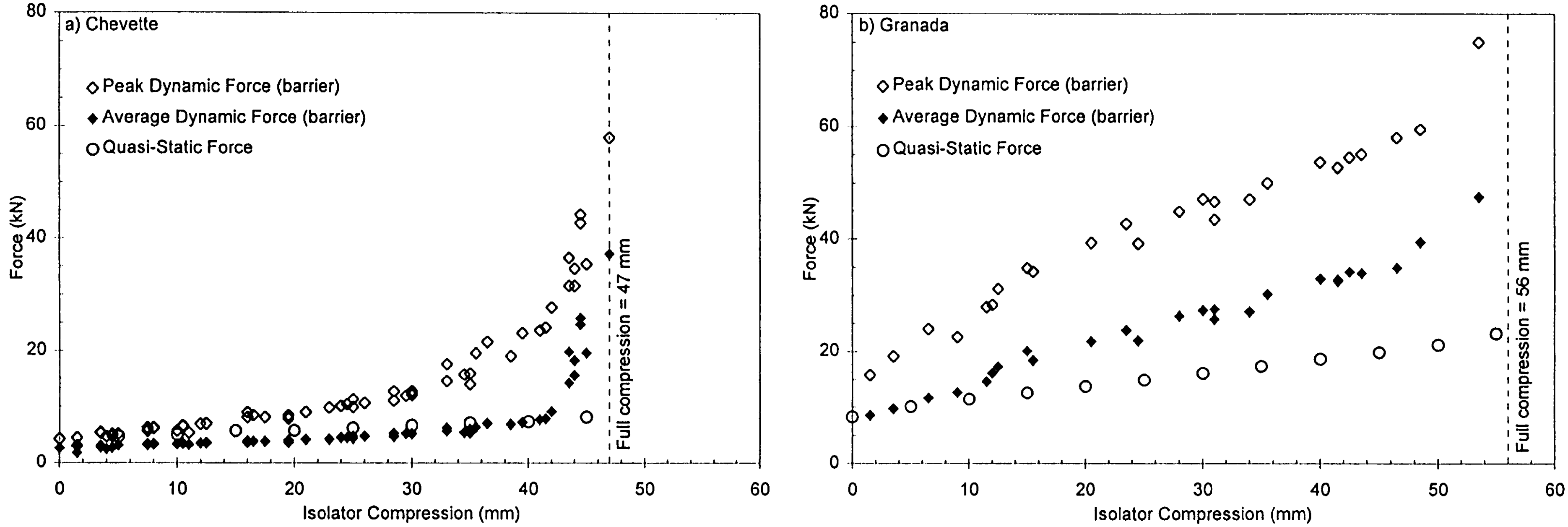


Figure 7. Peak and average dynamic force and quasi-static force for Chevette and Granada.

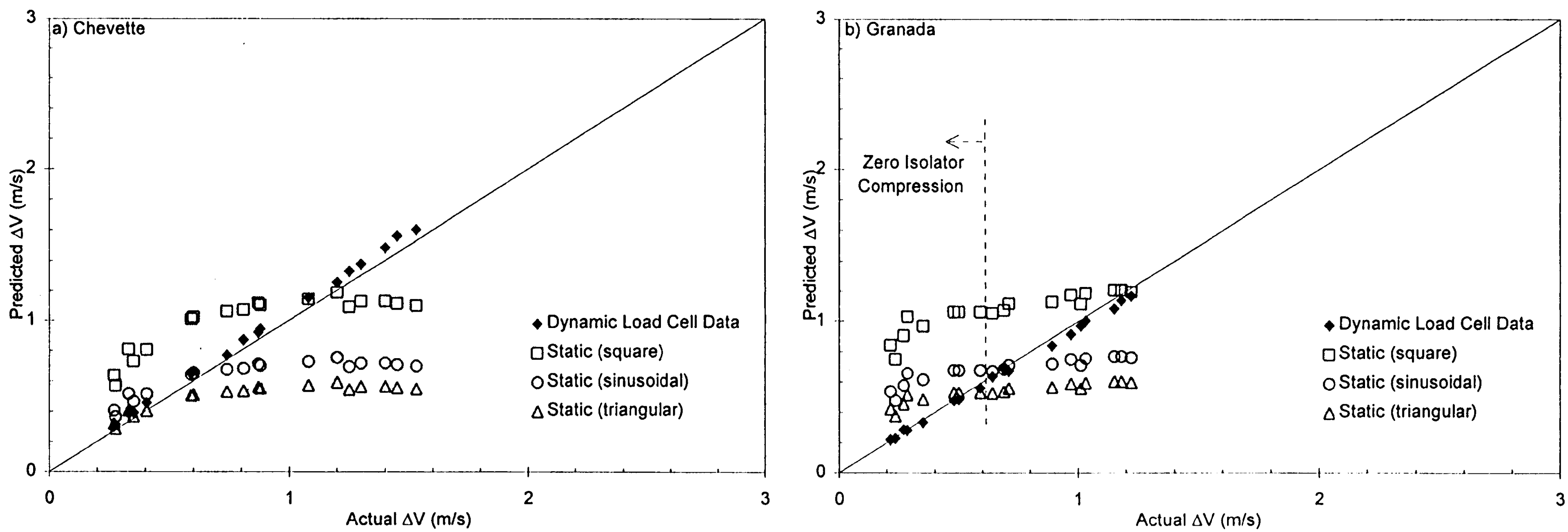


Figure 8. Predicted versus actual speed change calculated using Method 1

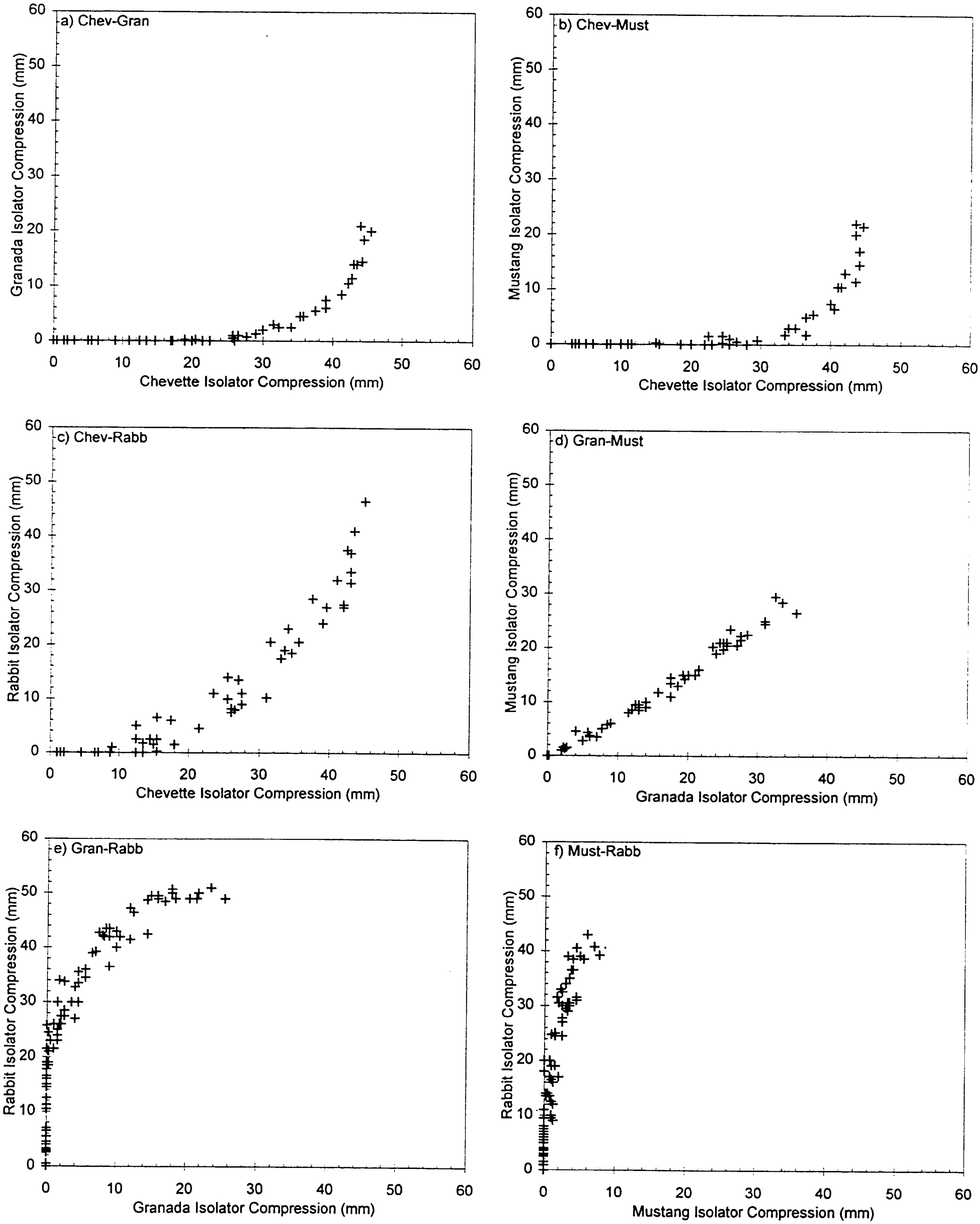


Figure 9. Isolator compression corresponding to each collision pair

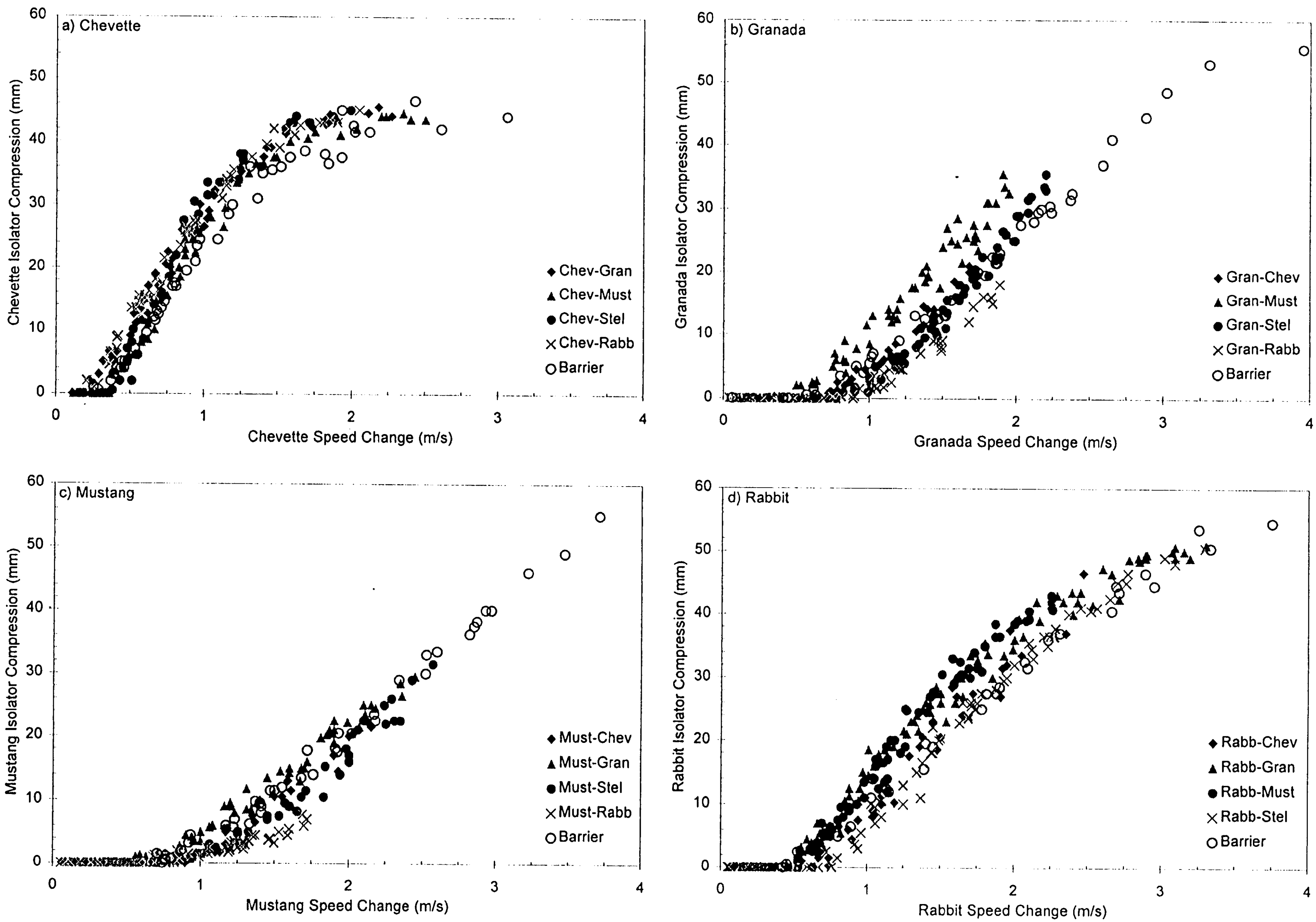
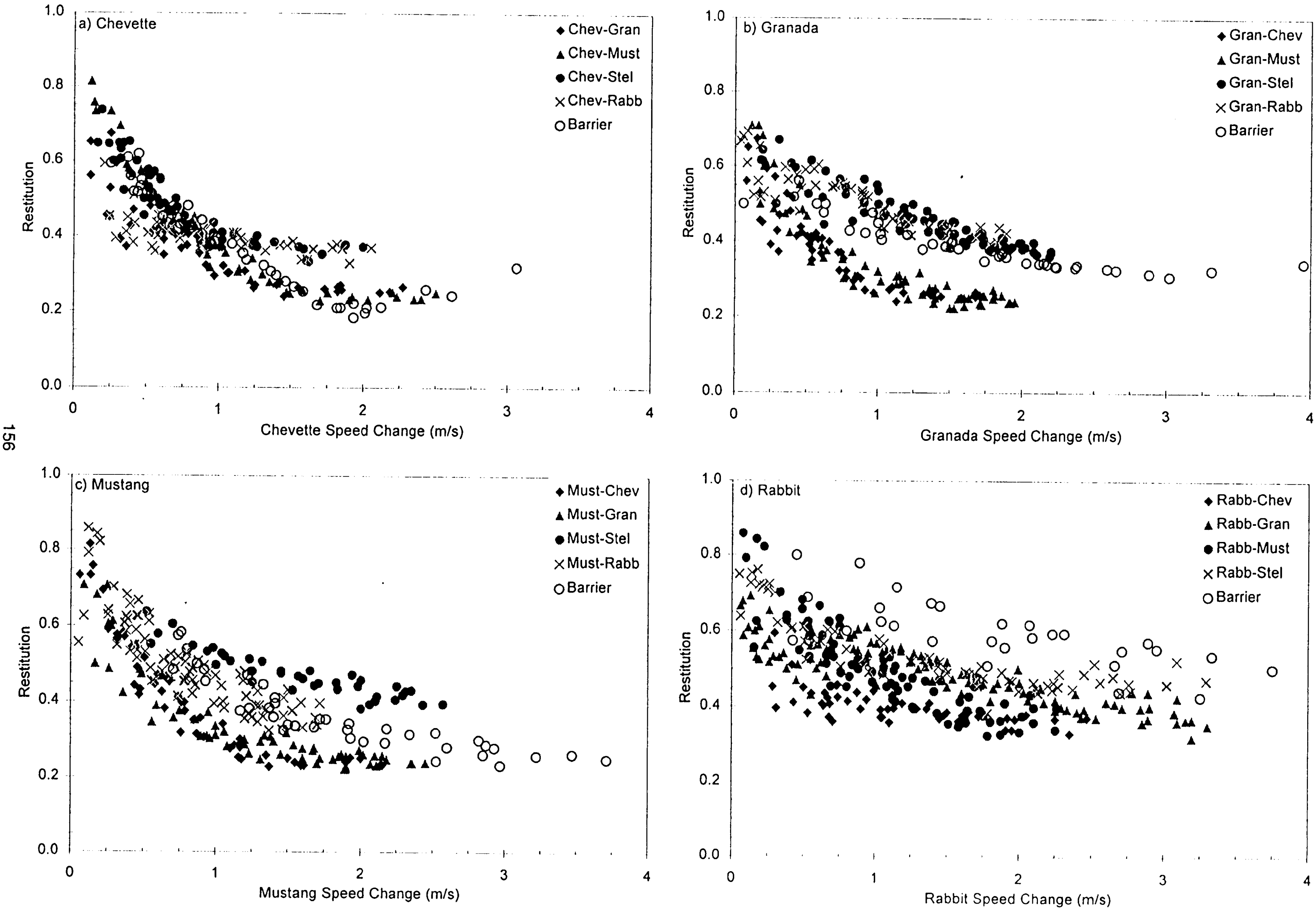
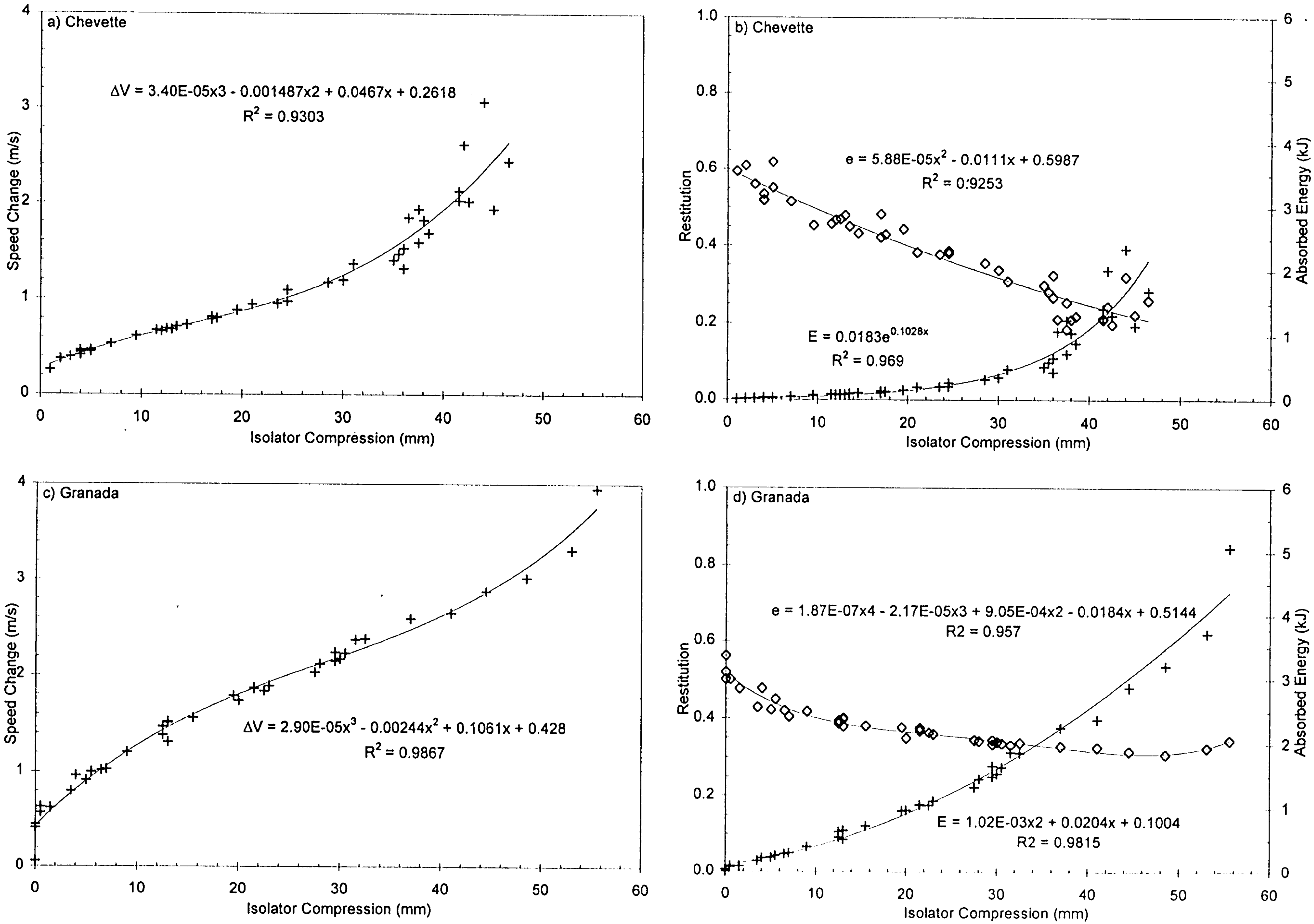


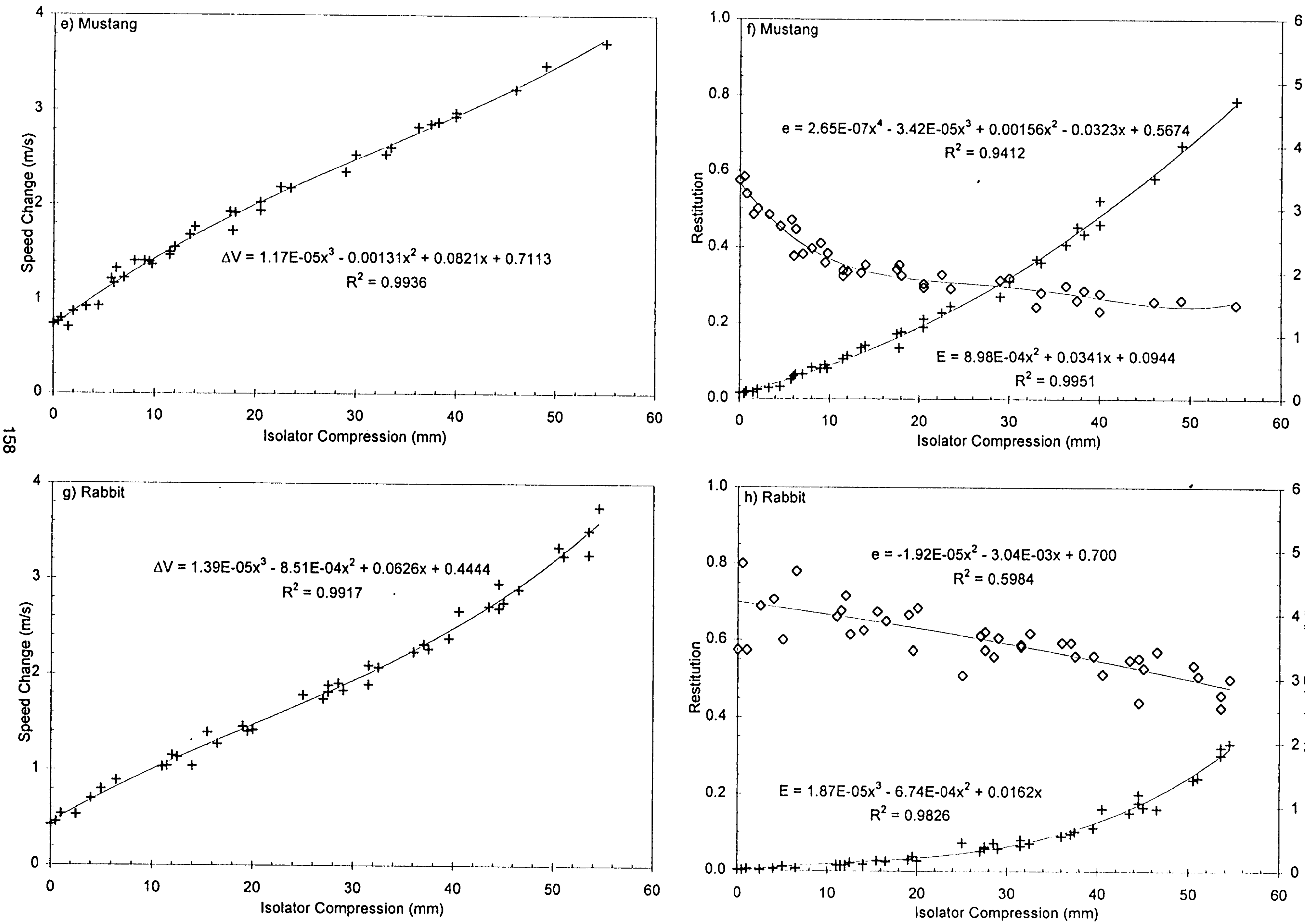
Figure 10. Isolator compression v. speed change for all collisions



Figures 11a - 11d. Restitution v. speed change for all collisions (see Figure 9e for Stellar data)



Figures 12a - 12d. Barrier data (speed change, restitution, and absorbed energy) for Chevette and Granada



Figures 12e - 12h. Barrier data (speed change, restitution, and absorbed energy) for Mustang and Rabbit

Both Figure 11 and Figure 12 consist of multiple graphs. In each case, an extra graph is needed for the Stellar data and these graphs are presented below.

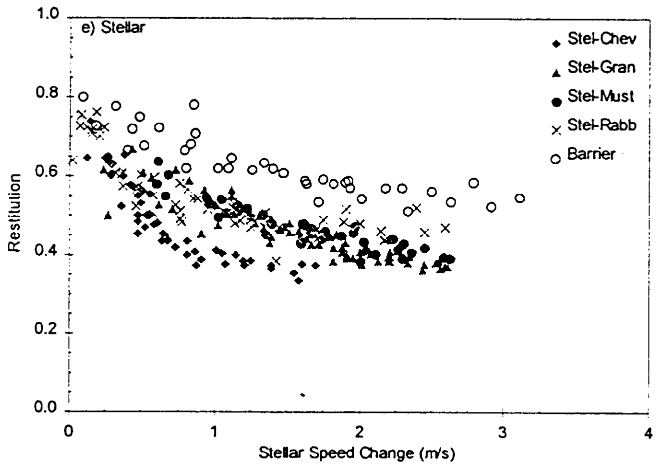


Figure 11e. Restitution v. speed change for Stellar

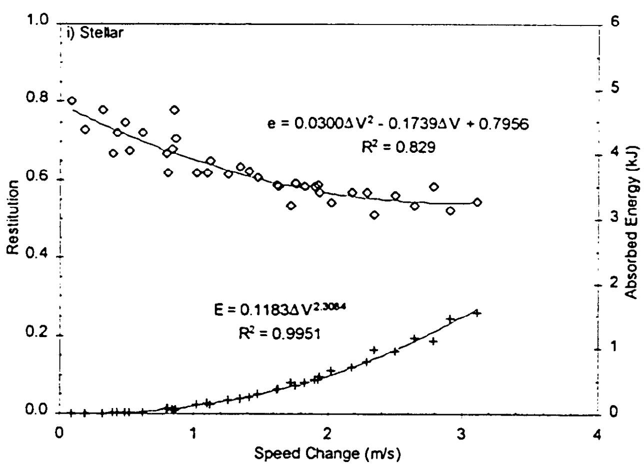


Figure 12i. Restitution and absorbed energy versus speed change for Stellar

METHOD 2: DIRECT BARRIER DATA - The second method of determining the speed change of a vehicle in a vehicle-to-vehicle collision from barrier data is by directly applying data in graphs of barrier speed change versus isolator compression. The authors have published barrier data in this form and it is a quick method of determining speed change from isolator compression. Early tests conducted by the authors suggested that barrier data could be directly applied to vehicle-to-vehicle collisions, however more detailed testing has now shown that in some cases this direct application can be inaccurate (see Figure 10).

In order to evaluate Method 2, the equations in Figure 12a, c, e, and g were used to calculate the speed change for each vehicle directly from the barrier data. Figure 13 shows the direct-barrier-predicted speed change versus actual speed change for the vehicle-to-vehicle collisions of the large data set. Separate graphs for each combination of vehicles, as well as summary graphs for each vehicle, a summary graph for all isolator-equipped vehicles, and a summary graph of all of the tests are presented.

Also shown in Figure 13 is a graph of the best-fit line through the data, excluding those collisions in which there was zero isolator compression on one vehicle. The equation of the best-fit line, the coefficient of determination (r^2), and the 90-percentile prediction interval of actual speed change for a given predicted speed change are also shown. Note that the equation is given in the form of x = f(y) rather than y = f(x). These statistical measures must be used cautiously because they are not based on 833 randomly-distributed points, but rather on 20 different distributions each made up of related points. These same cautions apply to the other similar figures presented in this paper.

In cases where both vehicles have isolators, direct use of the speed change versus isolator compression graphs for both vehicles can give two different collision speed changes for each vehicle. This difference can be handled by averaging the barrier-derived momentum change of both vehicles and then recalculating the speed change of each vehicle from this average momentum change:

$$\Delta p = \frac{1}{2}\left(m_1 \Delta v_{B1} + m_2 \Delta v_{B2}\right)$$

$$\Delta v_{VV1} = \frac{\Delta p}{m_1} \quad \text{and} \quad \Delta v_{VV2} = \frac{\Delta p}{m_2} \qquad (1)$$

where m_1 and m_2 are the vehicle masses, Δv_{B1} and Δv_{B2} are the barrier-derived speed changes for each vehicle isolator compression, Δp is the change in momentum and Δv_{VV1} and Δv_{VV2} are the speed changes of the two vehicles in the vehicle-to-vehicle collision.

The results of this modified portion of Method 2 are summarized in Figure 14 (only collisions between isolator-equipped vehicles are shown). The results depicted in Figure 14 indicate that this modified method of predicting speed change for collisions between two isolator-equipped vehicle improves the accuracy of the speed change prediction.

METHOD 3: MOMENTUM, ENERGY AND RESTITUTION METHOD (MER) - This method relies on the momentum, energy, and restitution equations. Howard et al[12] have summarized and provided a limited validation of the MER method. Briefly, a collision restitution is calculated from the barrier restitution of both vehicles using the following equation:

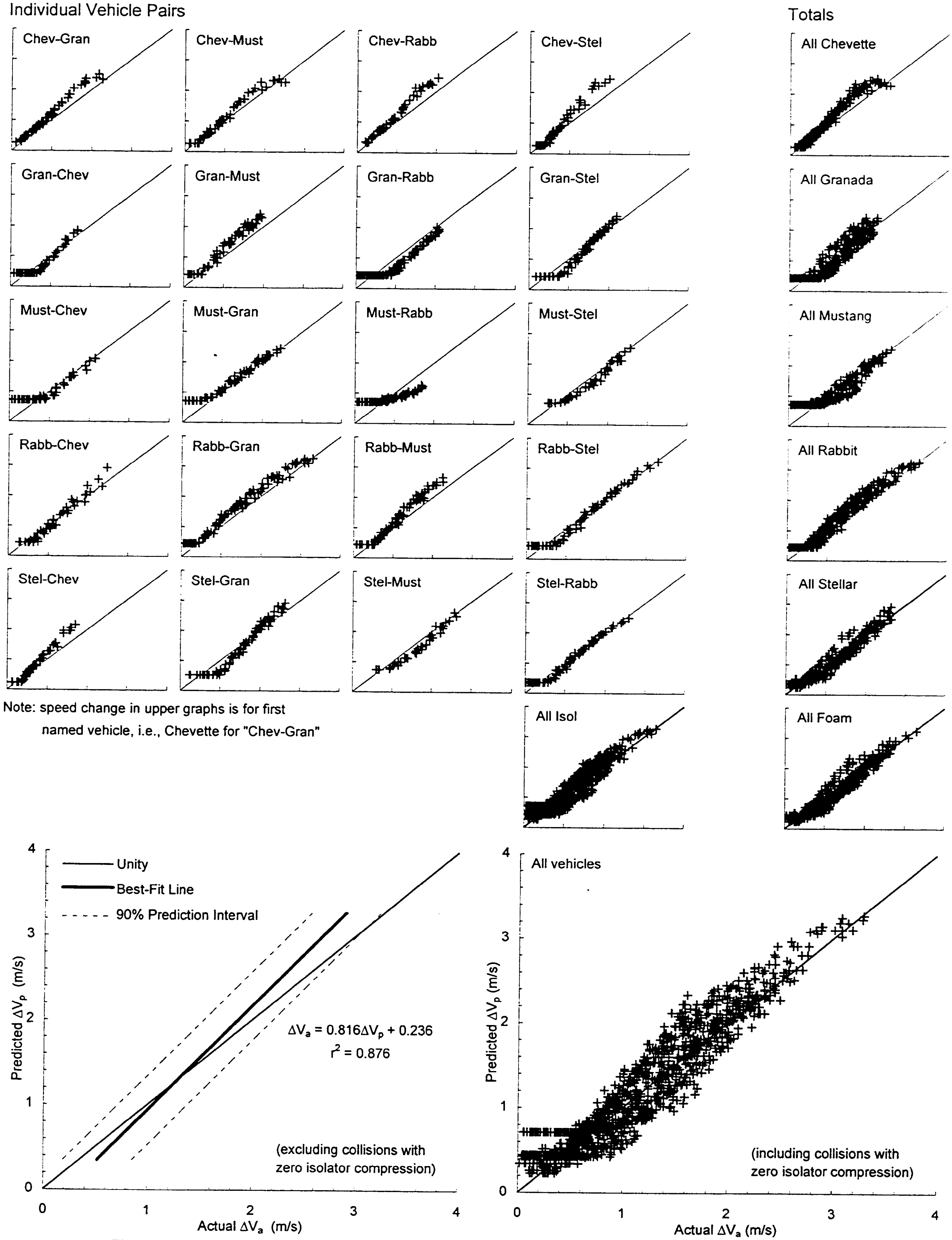


Figure 13. Comparison of predicted and actual speed change using the Direct Barrier Method 2

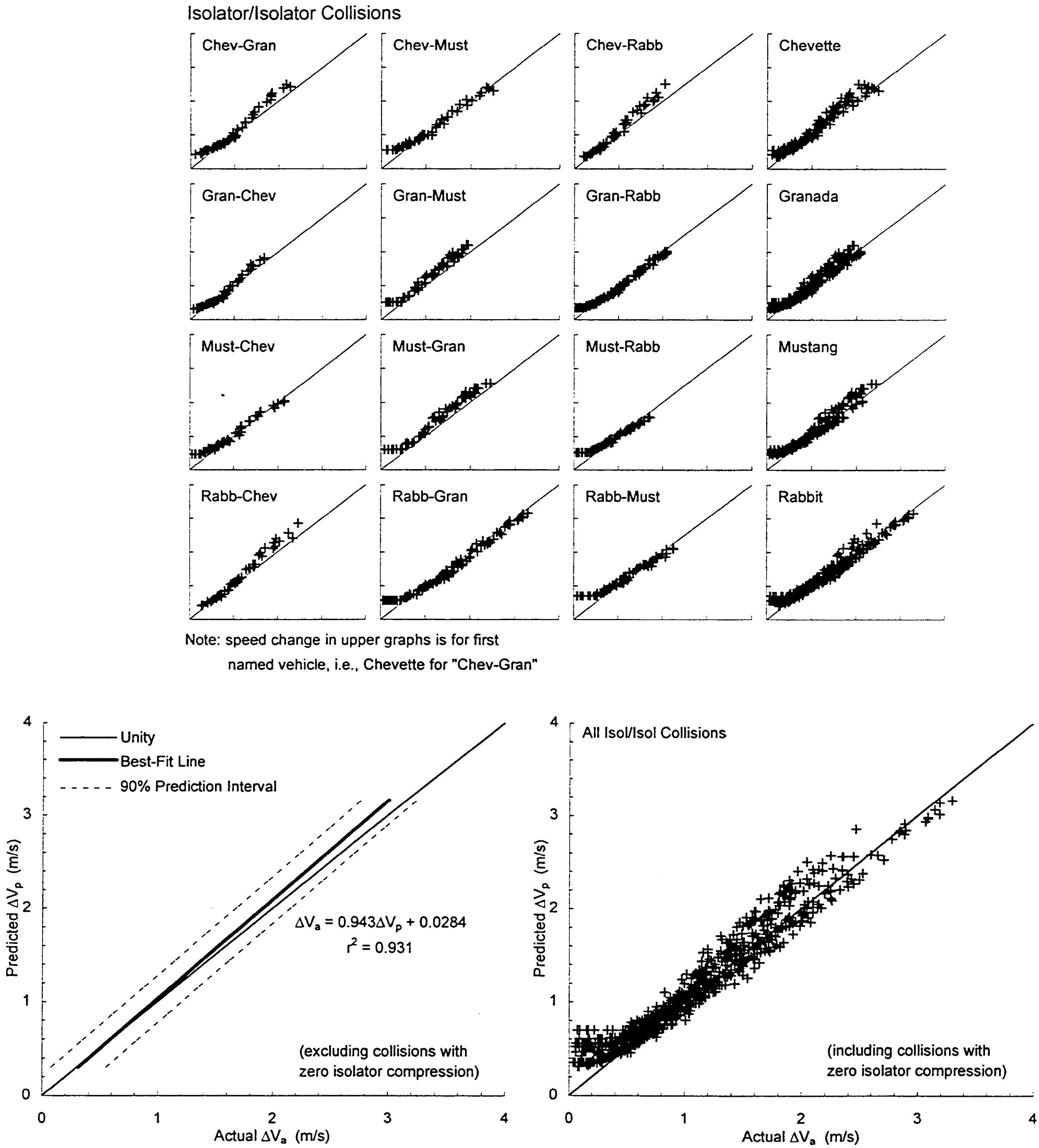


Figure 14. Comparison of predicted and actual speed change using the Modified Direct Barrier Method 2

$$e_W = \sqrt{1 + \frac{m_1\left(e_{B2}^2 - 1\right) + m_2\left(e_{B1}^2 - 1\right)}{m_1 + m_2}} \qquad (2)$$

where e_W = collision restitution,
m_1, m_2 = vehicle masses, and
e_{B1}, e_{B2} = barrier restitutions.

The speed change of each vehicle is then calculated[13]:

$$\Delta v_1 = \left(\frac{m_2(1+e_W)}{m_1 + m_2}\right)\sqrt{\frac{2(E_{B1}+E_{B2})(m_1+m_2)}{\left(1-e_W^2\right)m_1 m_2}} \qquad (3)$$

$$\Delta v_2 = \frac{m_1}{m_2}\Delta v_1$$

where Δv_1, Δv_2 = speed change of vehicles,
e_W = collision restitution,
m_1, m_2 = vehicle masses, and
E_{B1}, E_{B2} = energy absorbed (from barrier).

The barrier energies (E_{B1} and E_{B2}) correspond to the energy absorbed by each vehicle during a barrier impact with the same deformation, which for low-speed impacts is often the isolator compression. The barrier restitutions (e_{B1} and e_{B2}) corresponding to the isolator compression on each vehicle in the vehicle-to-vehicle collision were also used. Howard et al, did not use isolator compression to determine barrier restitution values, but instead used restitution values from a barrier collision with a pre-impact speed equal to the pre-impact speed of each vehicle relative to the system center of mass.

For our study, we used the isolator compression to determine both the energy absorbed and the restitution of both vehicles for two reasons: First, the energy absorbed and restitution have both been shown to vary with isolator compression. And second, energy absorbed as a ratio available energy is a mathematical function of restitution (available energy is the difference between the total pre-impact energy of the system, in this case two vehicles, minus the energy of the system center of mass). From this perspective, it is appropriate to use the restitution which corresponds to the energy absorbed, both of which correspond to the amount of isolator compression resulting from the vehicle-to-vehicle collision.

To examine the difference between Howard et al's method and the method used here, a sample calculation was performed using both methods (see Figure 15). This figure shows that there is little difference between the pre-impact speed method (Howard et al) and the isolator compression method used in this study.

The restitution and absorbed-energy characteristics as a function of isolator compression for each vehicle's barrier data were determined from the equations shown in Figure 12b, d, f, and h. Using these equations, e_B and E_B for a given isolator compression could be calculated for each isolator-equipped vehicle. In the case of the foam-core-equipped Stellar (Figure 12i), e_B and E_B were plotted against speed change.

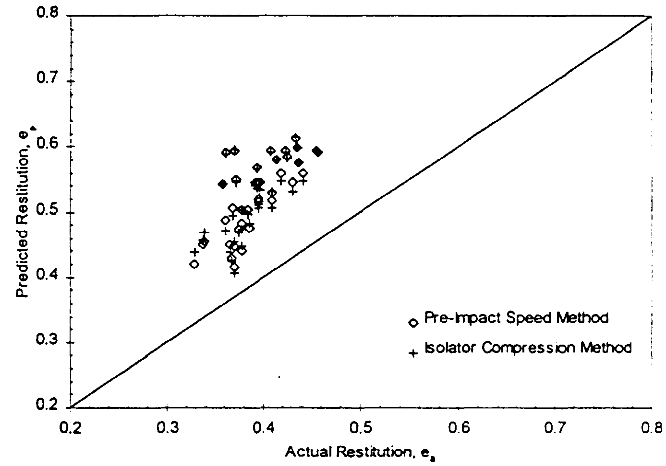


Figure 15. Comparison of predicted restitution using pre-impact speed and isolator compression methods

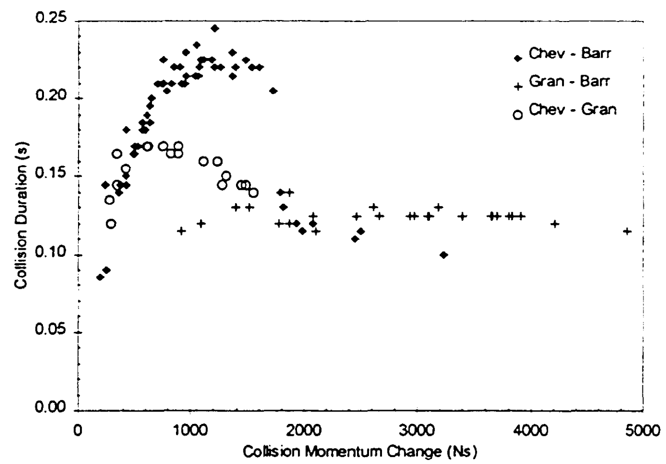


Figure 16. Collision duration versus collision momentum change for Chevette and Granada collisions.

The derivation of the MER method is based on two assumptions: a) the derivation of e_W assumes that the collision duration of both barrier collisions and the actual collision are the same; and b) the total energy absorbed in the vehicle-to-vehicle collision is equal to the sum of the energy absorbed by each vehicle in its barrier tests at the same level of isolator compression. Each of these assumptions is evaluated individually before the aggregate validity of the MER method is assessed.

Data presented in Figure 16 and in previous research[2] show that the duration of barrier impacts vary with speed change. Therefore, the assumption that vehicle-to-barrier and vehicle-to-vehicle collision durations are similar is not supportable.

The collision duration assumption is used to derive the vehicle-to-vehicle restitution from the two vehicle-to-barrier restitutions. Figure 17 directly compares the predicted restitution (e_{VV}) to the actual restitution in the collisions of the ten vehicle pairs. The same cautions apply to the statistical data of Figure 17 as for Figure 13.

All of the calculated restitutions exceed the actual restitutions. This difference between the actual and predicted restitution values indicates that Equation 2 does not accurately predict the vehicle-to-vehicle restitution from the vehicle-to-barrier data when isolator compression is used.

The second assumption of the MER method is that the energy absorbed by the vehicles in the vehicle-to-vehicle collision is the sum of the energy absorbed by the two involved vehicles in their barrier tests. Figure 18 compares the energy absorbed ($E_{B1} + E_{B2}$) to the actual energy absorbed for all collision pairs.

The graphs in Figure 18 indicate that using barrier data to estimate the energy absorbed in the vehicle-to-vehicle collisions is on average appropriate, however it can be inappropriate for specific vehicle pairs (see "Must-Rabb" and "Chev-Stel" in Figure 18).

Figure 19 depicts the predicted versus actual speed changes for the MER method. The results indicate that on average the MER method predicts a slightly higher speed change than measured for the vehicle-to-vehicle collisions. Again, significant differences are visible between the different vehicle pairs and using the apparent overall accuracy can be incorrect for a specific vehicle pair.

In the case of the foam-core bumper of the Stellar, an iterative solution was required for the MER method. For the data presented, the speed change of the Stellar was initially estimated from the other vehicle's barrier data and conservation of momentum, i.e., Method 2. Then, using the Stellar equations in Figure 12i (note that e_b and E_b are a function of speed change and not isolator compression), an initial restitution and absorbed energy were calculated. With these values, a revised speed change was calculated using Equation 3, and then iterated until the Stellar's predicted speed change converged. A similar approach can be used if the barrier force versus both restitution and energy absorbed data is available, although in this case a collision duration must be assumed.

ACCURACY OF EACH METHOD

Of the three methods evaluated here, Method 1 was the least accurate and it is not recommended for any situation. Methods 3 predicted the actual speed changes of the vehicle-to-vehicle collisions better than Method 2, however Modified Method 2 most accurately predicted the actual speed change. It is the authors' view that each of these methods is subordinate to conducting actual collisions with the actual or exemplar vehicles. When staged collisions cannot be performed, Methods 2 and 3 can be used to estimate each vehicle's collision speed change. Because each method can only be applied in certain circumstances, Table 4 summarizes when it may be appropriate to use each of the methods evaluated here.

Table 4. Method Use Summary

# of vehicles with isolators	# of vehicles with barrier data	Order of preferred methods for predicting speed change
2	2	1. use Modified Method 2
2	1	1. test second vehicle and use Modified Method 2 2. use Method 2
2	0	1. test both vehicles and use Modified Method 2 2. test one vehicle and use Method 2 3. use damage threshold
1	2	1. use Method 3
1	1	1. test second vehicle and use Method 3 2. use Method 2
1	0	1. test vehicle and use Method 2 2. use damage threshold speed change
neither	-	1. stage collision and reproduce collision-specific damage 2. use damage threshold speed change

Barrier data from vehicles with similar isolators must be used cautiously. The potential error resulting from using data from isolators with similar but not the same part numbers is highlighted by the Granada and Mustang data (see Figure 9d, 12d and 12f).

The actual accuracy expected from each method is difficult to determine. The error range for each method can be estimated by either consulting the summary graphs of predicted versus actual speed change or alternatively, errors in the barrier data can be estimated and carried through the calculation. Given the different results between different vehicle pairs for a given method, no blanket statement regarding the expected uncertainty in any predicted speed change can be made.

LIMITATIONS OF EACH METHOD

All three methods presented in this paper have limitations. The obvious limitation on all of the methods presented is that at least one of the involved vehicles must have isolators or some correlation between physical evidence and speed change, restitution and energy absorbed. If not, then the only conclusion that can be drawn is that the speed change of the vehicles in the collision is less than that implied by the vehicle with the lower of the two damage threshold speed changes, some of which are published elsewhere[3]. If there is collision damage unique to the vehicle pair, i.e., localized damage from a trailer hitch, this damage can be used to determine a severity, however case-specific tests are normally required (see Table 4).

A second limitation of all methods is that the isolators must be functional. Seized isolators should always be suspected when there is no isolator compression, unless

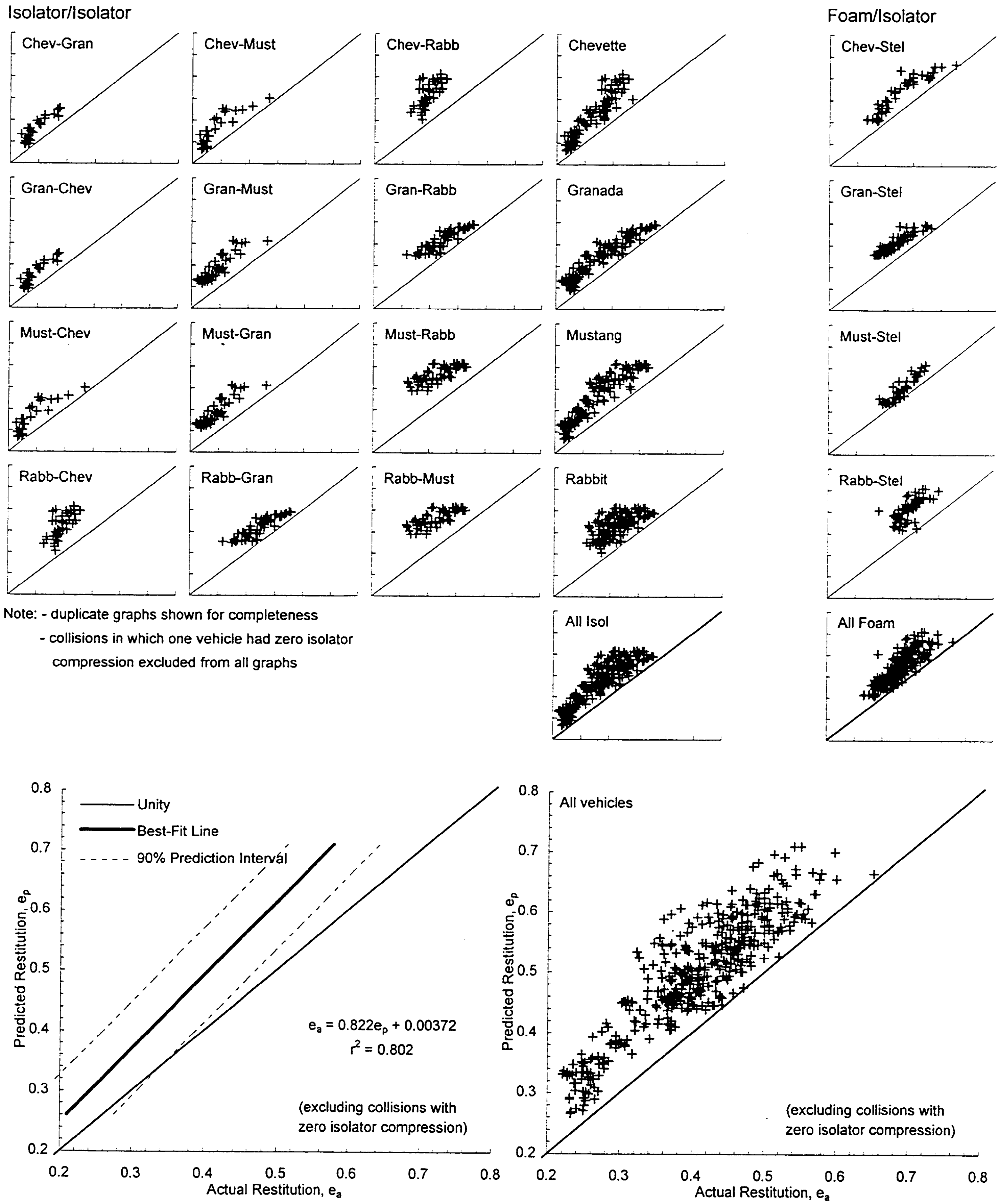


Figure 17. Comparison of predicted and actual restitution using MER Method 3

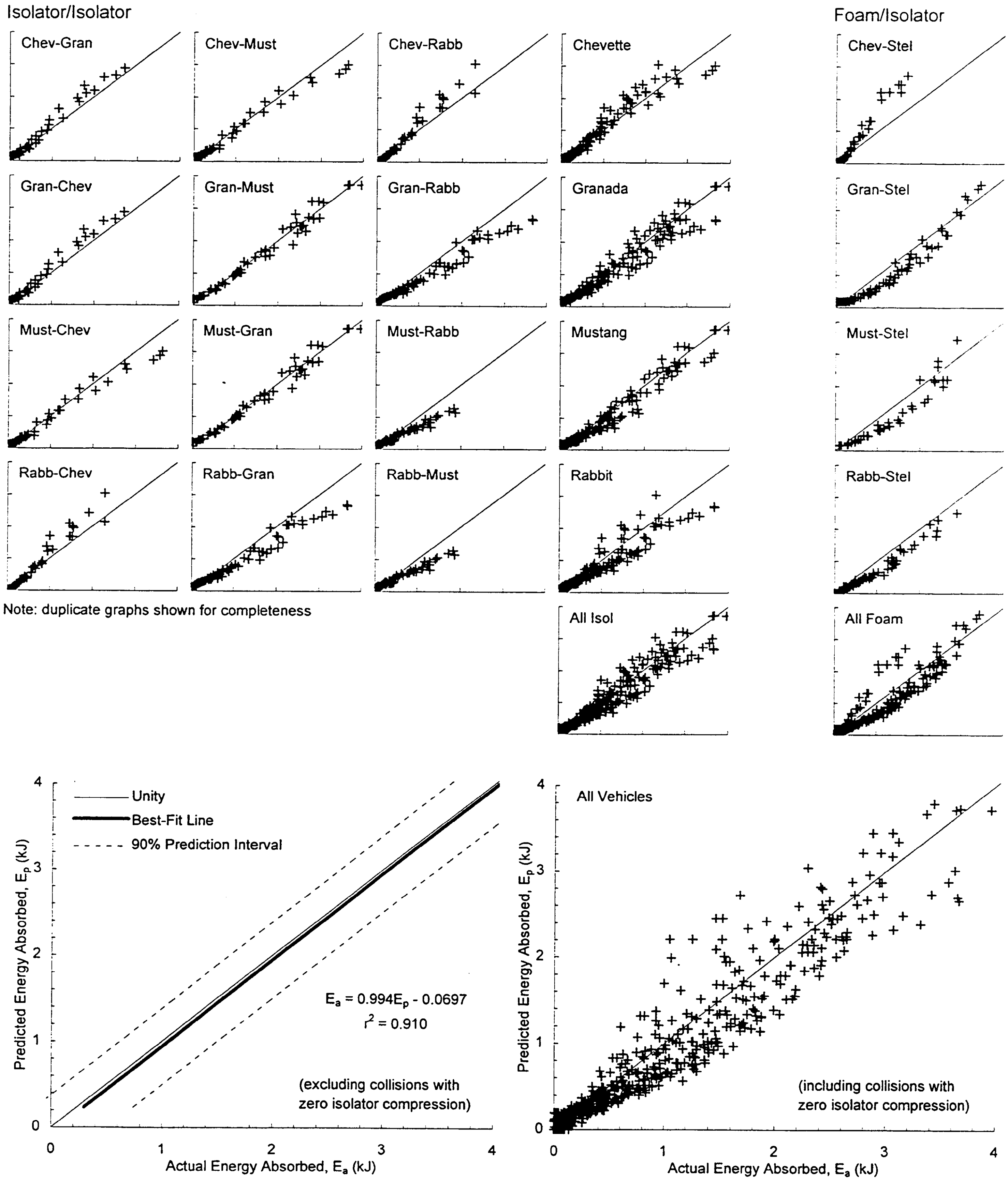


Figure 18. Comparison of predicted and actual absorbed energy for MER Method 3

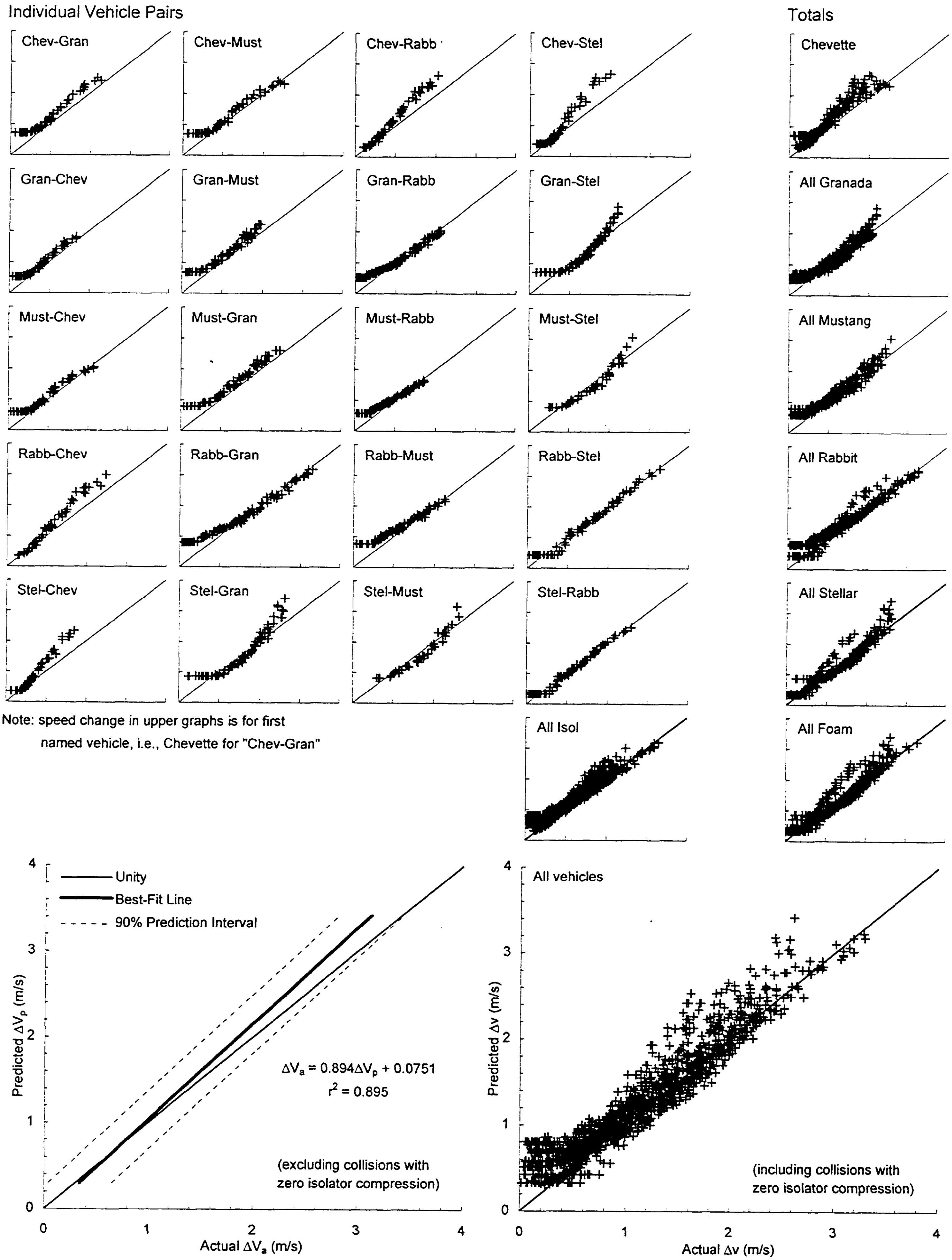


Figure 19. Comparison of predicted and actual speed change using the MER Method 3

there is a particularly stiff pair of isolators on one vehicle compared to the other (see Figure 7).

In cases where one vehicle has functional isolators and the other vehicle has a non-isolator equipped bumper for which restitution and absorbed energy data are available, the MER method is the only method examined here which can yield a solution using all of the available data. Despite the higher restitutions predicted by the MER method, it appears to predict collision speed change satisfactorily.

DISCUSSION

All of the methods assume that both isolators are compressed less than their full compression and less than the amount where they significantly stiffen. Average isolator compression is only valid when both isolators have compressed less than this amount. If one isolator is at or above the knee, the speed change predicted by Methods 2 and 3 can only be considered a minimum speed change.

Comparing the MER results to those of modified Method 2 (Figure 14), there are some vehicle combinations for which the two methods yield very similar results. In both cases, the minimum velocity change is indicated by the short horizontal portion extending from the y-axis. When there was no isolator compression, the minimum velocity change at which the isolators for that vehicle just begin to show motion is used as the upper limit of the velocity change. Using these data for an actual collision requires the assumption that the isolators are functional on both vehicles.

This validation of these methods is based on a large but still limited data set. Not all of the available types of isolators are represented, nor are the different models of isolators used by a single manufacturer represented.

CONCLUSIONS

Three methods of estimating vehicle-to-vehicle speed change from vehicle-to-barrier data have been evaluated.

Method 1, the Quasi-Static Isolator Force Method, is not recommended by this analysis.

Method 2, the Direct Barrier Method, and Method 3, the Momentum, Energy, Restitution (MER) Method, both provide reasonable predictions of the actual speed change sustained by the vehicles in a vehicle-to-vehicle collision. A modified form of Method 2 yields the best overall prediction of actual speed change, but requires that both vehicles have isolators. The ability of Methods 2 and 3 to predict the actual speed change is assessed statistically, however it should be noted that the data are not truly random.

Table 4 suggests when to use each of the methods.

RECOMMENDATIONS

Only three manufacturer's isolators are represented in this study. Validation of other manufacturer's isolators as well as different isolators among a specific manufacturer should be examined.

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