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Sintra Engineering Inc.

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Practical Analysis Methodology for Low Speed Vehicle Collisions Involving Vehicles with Modern Bumper Systems

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ABSTRACT

This paper presents and validates a practical analysis method for assessing the collision severity of real world low speed motor vehicle collisions based upon post-collision observations of vehicles with modern bumper systems. To achieve this, a series of low speed vehicle-vehicle and vehicle-barrier collisions were staged using five modern (1998 to 2000 model) vehicles equipped with different non-isolator bumper structures (e.g. foam impact absorber). The collision parameters of each vehicle-vehicle impact were compared with the results obtained from vehicle-barrier impacts involving the same vehicles. The analysis method was applied to predict the results of the vehicle-vehicle collisions and was found to be a valid method for correlating the collision severity of a low speed vehicle-vehicle impact from barrier test data.

INTRODUCTION

Low speed collisions can be defined as collisions that involve very minor or non-visible vehicle damage. As different vehicle models have varying points at which they begin to exhibit visible crush, it can be difficult to assess the severity of an impact where the involved vehicles do not exhibit any significant damage. For example, a 1999 Dodge Durango can sustain significant damage (about $1700 USD) in an aligned 8 km/h frontal barrier test whereas a 1999 Pontiac Grand Am will exhibit little or no damage[9] in a similar aligned impact test. An untrained individual may incorrectly assume that a Dodge Durango with $500 USD worth of required repairs sustained an impact of greater severity than a Pontiac Grand Am with the same dollar amount of damage. Thus, forensic engineers and collision reconstructionists are frequently required to assess the severity of low speed motor vehicle collisions.

Insurance adjusters and plaintiff lawyers are particularly interested in understanding the magnitude of low speed collisions in order to correlate the potential for occupant injury. In these types of collisions, vehicle occupants frequently claim they have sustained soft tissue injuries and insurance adjusters and lawyers look for some evidence to indicate whether or not the occupants could have been injured. At higher impact severities, vehicles begin to exhibit more noticeable damage (i.e. crush) and the severity of the impact becomes more apparent to the layperson. Therefore, the focus of this paper is to provide a methodology for quantifying the severity of low speed impacts involving little or no vehicle damage.

Of particular interest in the area of low speed vehicle collisions are aligned frontal and rear impacts as they represent the majority of these collision types. During an aligned frontal or rear collision, a vehicle accelerates in the direction of the net applied force at a rate proportional to the applied force. The resulting vehicle motion affects the occupants situated within the vehicle. Thus, the collision force and vehicle acceleration are important parameters for assessing the severity of a low speed impact. These parameters and collision duration vary depending on the vehicles involved. In order to describe collision severity in terms of force and/or acceleration, the shape of the force/acceleration pulse and the collision duration must be understood.

The force/acceleration data are typically unobtainable for real world collisions and determinable only from instrumented vehicles in staged tests. Furthermore, it becomes complex to explain some of these collision parameters to non-technical individuals. The change in velocity (ΔV) sustained by a vehicle during a collision has become an indicator of the relative severity of a collision. Change in velocity is generally described as the near instantaneous difference between a vehicle's pre-impact and post-impact speeds. As ΔV increases with increasing impact severity and gives an indication of the impact forces and accelerations, it has become the standard measure of collision severity in the reconstruction of real world low speed collisions.

In order to practically assess the severity (ΔV) of a real world collision, the physical evidence remaining after the impact must be reviewed. Limited vehicle speeds in low speed impacts mean impacting vehicles sustain little or no visible damage. Due to limited test data, it is often difficult to quantify collision severity when a vehicle's bumper system exhibits very little damage or shows no evidence of contact at all. This paper presents an analytical method that can be used to assess the change in velocity of real world low speed collisions involving modern vehicles. The paper will demonstrate that observations of vehicle damage in collisions can be compared with the results of staged vehicle-barrier impact tests.

Vehicle-barrier tests are frequently staged rather than vehicle-vehicle collisions due to the cost and the ability to control specific collision variables. Therefore, there is a large database of staged slow speed vehicle-barrier tests that can be referenced for assessing the severity of real world low speed collisions. In order to validate this approach of using the results of barrier tests for assessing the severity of vehicle-vehicle collisions, several researchers have compared collision parameters resulting from staged vehicle-vehicle and vehicle-barrier collisions. However, the majority of these studies have focused on collisions involving vehicles with bumper isolators. There are limited data from modern vehicles with foam/plastic impact absorbers or rigid bumper components. Thus, a series of vehicle-barrier and vehicle-vehicle tests were conducted with modern vehicles in order to validate the analysis method and determine its accuracy in predicting collision severity.

BACKGROUND

VEHICLE BUMPER CONSTRUCTION

There are three common types of vehicle bumper construction:

1. Reinforcement beam with isolators:

   A piston and cylinder assembly is used to mount the bumper assembly to the vehicle's frame. Isolators are designed to behave as a spring-dashpot system. Either real springs or compressed gas is used to create the spring characteristics. A viscous oil and piston is used to achieve damping properties.

2. Reinforcement beam with a polymer absorber:

   High-density polyurethane foam, polystyrene foam or an open-cell lattice (honeycomb) structure is situated between a reinforcement beam and plastic cover.

3. Rigid bumpers:

   These bumpers do not have any energy dissipating elements. Typically, a steel reinforcement beam or face bar is directly connected to the vehicle's frame.

MER METHOD

A common method for assessing the severity of a collinear frontal or rear collision uses conservation of momentum, conservation of energy and restitution principles. This Momentum Energy Restitution (MER) method has been discussed by several other researchers[2-5;17;18;20;22] and can be used to assess the change in velocities sustained by two impacting vehicles. The following principles and formulae provide the foundation for this analysis method.

Conservation of Momentum

Momentum prior to a collision is equal to the momentum after the collision.

$$M_1 \Delta V_1 = M_2 \Delta V_2 \quad (1)$$

Conservation of Energy

The initial energy of a system is equal to the energy after a collision.

$$KE_i = KE_f + E_a \quad (2)$$

$$\tfrac{1}{2} M_1 V_{1i}^{\;2} + \tfrac{1}{2} M_2 V_{2i}^{\;2} = \tfrac{1}{2} M_1 V_{1f}^{\;2} + \tfrac{1}{2} M_2 V_{2f}^{\;2} + E_a \quad (3)$$

Restitution

Restitution is defined as:

$$e = \frac{V_{2f} - V_{1f}}{V_{1i} - V_{2i}} = \frac{V_{Cf}}{V_{Ci}} \quad (4)$$

These equations apply to an aligned collision between two vehicles where external forces are negligible (i.e. the vehicles' wheels are free-rolling and tire/road friction is negligible). The variables include vehicle mass (M), change in velocity (ΔV), kinetic energy (KE), absorbed energy (E_a), speed (V), co-efficient of restitution (e) and closing speed (V_c). The subscripts denote the involved vehicle and either a pre- or post-impact parameter (e.g. "initial" or "final"). E_a represents energy that is not converted back into post-impact kinetic energy, but is absorbed by the two involved vehicles.

The following relationships can be derived from the MER theory:

$$V_{Ci} = V_{1i} - V_{2i} = \sqrt{\frac{2E_a (M_1 + M_2)}{M_1 M_2 (1 - e^2)}} \quad (5)$$

$$\Delta V_1 = \frac{M_2 (1 + e)(V_{Ci})}{(M_1 + M_2)} \quad (6)$$

Thus, the collision severity (ΔV) of an aligned low speed collision can be determined with specific knowledge of the energy absorbed by the involved vehicles and the impact restitution.

IMPACT ENERGY

At the time of maximum engagement when two impacting vehicles achieve a common speed, the maximum amount of kinetic energy has been transferred to the vehicles' structures. This "lost" energy is shown in Figure A1 (in Appendix A). The difference between the initial kinetic energy and the kinetic energy at maximum engagement (i.e. when the vehicles reach a common speed) is the sum of energy that has been stored as potential energy in the vehicles' structures (E_{stored}) and energy that has been absorbed by the vehicles' structures (E_a). Stored energy is converted back into kinetic energy in the latter portion of the impact as the vehicles rebound, whereas the absorbed energy (E_a) is lost to:

1. Plastic deformation – Yielding of structures and distortion of components.

2. Viscous losses – Heat generation during compression of oil/gas in bumper isolators or tiny air pockets within foam impact absorbers, released sound energy, frictional/heat losses between interacting vehicle surfaces and other frictional/heat losses in a vehicle's suspension or frame.

At lower impact speeds where there is no deformation of vehicle components, the impact forces remain below the yielding points of bumper materials and the materials react to the impact forces within their elastic ranges. Thus, the energy absorbed by a vehicle in a low speed impact is primarily due to viscous losses. However, at moderate impact speeds involving the onset of permanent deformation of vehicle components, energy is absorbed due to both plastic deformation and viscous losses. As the impact severity increases and significant permanent deformation results, the energy absorbed by a vehicle is primarily due to plastic deformation with a negligible amount of energy distributed by viscous losses.

The structural characteristics of a vehicle affect the amount of energy that is absorbed and stored during the collision. The post-impact vehicle speeds are dependent on the amount of stored energy that is converted back into kinetic energy. Thus, a vehicle's structural characteristics will affect the extent of rebound of a collision. A fully plastic collision where no kinetic energy is stored will result in no vehicle rebound; whereas, a fully elastic impact will result in vehicles absorbing no energy (i.e. kinetic energy is identical before and after the collision).

COLLISION RESTITUTION

Bumpers respond differently depending upon their construction; however, most bumpers typically respond in a viscoelastic manner. For example, a bumper will deflect with an increase in applied force, but rebound with less force due to viscous damping properties. A hysteresis loop is generated in the force vs. deflection relationship. Both bumpers with isolators and polymer absorbers have the same slow rebound properties. Figure A2 shows a plot of force vs. deflection for a barrier impact with a vehicle bumper within its elastic range (i.e. no permanent deformation). As this example did not result in the generation of plastic crush energy, all of the absorbed energy (the shaded area within the curve) corresponds to viscous energy absorbed by the vehicle. The shaded area below the rebound line corresponds to the stored energy or post-impact kinetic energy. Thus, an increase in the amount of absorbed energy will decrease the amount of energy available for post-impact vehicle motion (i.e. the restitution).

Howard[8] provided a good discussion of the viscous energy losses in low speed collisions that can reduce the restitution of an impact. Other structural components within a vehicle can shift and move during a collision that cause frictional energy losses with each movement. In addition, wheel and transaxle assemblies interact with the vehicle frame through the suspension system. The viscous energy losses attributed to these other factors ultimately reduce the amount of energy that can be transformed back into post-impact kinetic energy. This outcome reduces the magnitude of the coefficient of restitution. Although the independent effects of each of these energy sinks are difficult to quantify, the overall effect can be practically quantified by the coefficient of restitution.

As collision restitution is directly dependent on a vehicle's structural characteristics, it will vary depending upon the colliding vehicles, the vehicles' impact orientation and the collision severity. Past research has shown that restitution decreases with increasing closing speeds in motor vehicle collisions. Howard presented a relationship for assessing the restitution of a vehicle-vehicle impact from individual restitution values for separate barrier impacts involving the same two vehicles:

$$e_{12} = \sqrt{\frac{M_2 e_1^{\,2} + M_1 e_2^{\,2}}{(M_1 + M_2)}} \qquad (7)$$

The theory used to derive this equation assumes that the masses of the vehicles in the barrier tests are equivalent to the masses of the respective vehicles in the vehicle-vehicle impact. Furthermore, the theory assumes that the sum of energy absorbed in each barrier impact sums up to the energy absorbed in the vehicle-vehicle impact. Thus, barrier impacts resulting in a similar amount of vehicle damage (i.e. a similar amount of absorbed energy) can be compared to a specific vehicle-vehicle collision for assessing the collision restitution.

REPEATED IMPACT TESTS

Several researchers have staged repeated impact tests where a vehicle receives multiple impacts at increasing severities. The test vehicles in these studies were not repaired between the multiple tests. Thus, subsequent tests may have resulted in different damage to what would have resulted from an impact of identical severity on a similar vehicle that was not previously damaged. A study conducted by Warner[21] presented the results of likely one of the first repeated impact test series. Warner described the fundamental underlying assumption of this type of test series: a vehicle deforms under repeated impacts in a manner similar to that in a test at a higher speed having the same equivalent impact energy. Thus, the total crush energy absorbed in one high severity impact should be equal to the sum of energies absorbed in previous lower severity impacts where the accumulated crush is equivalent to that in the one high severity impact.

Prasad[16] successfully demonstrated that the repeated test technique was useful in assessing the severity of a high speed impact based upon accumulating the vehicle permanent crush and approach energies in repeated impacts at lower speeds. His repeated test technique gave acceptable results for impact speeds greater than 16 km/h. At higher impact speeds, the plastic deformation energy is the dominant form of energy absorbed by a vehicle (as opposed to viscous energy losses). When repeated tests are conducted at lower impact speeds, viscous energy losses become more predominant. As viscous losses do not contribute to the extent of permanent deformation, the viscous energy losses should not be summed when applying the repeated test technique. Prasad's paper discussed this and other potential sources of error in applying the repeated test method. In addition to the influence of including viscous energy losses during each successive impact, differences in vehicle crushing behaviour and collision restitution over different impact velocities will influence the outcome of the repeated test technique. As the potential sources of error are negligible at higher impact speeds, the results of Prasad's study were favourable in demonstrating that a higher severity impact can be modeled using the repeated test technique with several lower speed impacts.

A recent publication by Evans[6] modeled the viscoelastic behaviour of thermoplastic energy absorbers mounted to steel reinforcement beams. The study discussed the effects of multiple impacts on two different types of bumper absorbers (expanded Polypropylene foam and injection molded Polycarbonate/Polybutylene Terephthalate). Each absorber was mounted to a rigid beam and then impacted by a 1590 kg moving barrier at 8 km/h. Although both bumper absorbers were allowed time to recover before being impacted a second time, they still sustained 8 mm of permanent deformation after the first set of tests. The Polypropylene foam absorber's ability to absorb energy in the second impact was reduced whereas the injection molded bumper absorbed a similar amount of energy in both impacts. The results of this testing indicated that the material properties of a specific impact absorber affect its ability to absorb energy in subsequent collisions.

EXISTING DATA

There is an extensive database of literature that has analyzed the interaction of two motor vehicles during a collision of a minor severity. Several researchers have staged vehicle-barrier and vehicle-vehicle tests and then compared the resulting collision parameters. Although the majority of these studies focused on tests involving vehicles equipped with bumper isolators[2;3;10;12-14;19;20], some of these references have documented data that can be used in the reconstruction of real world collisions with the practical analytical method presented in this paper. These useful studies provide limited data for vehicles with modern bumpers that were involved in both vehicle-vehicle and vehicle-barrier tests:

- Bailey[2] – 1980 Toyota Corolla polyurethane foam bumper and 1988 Mazda 323 polystyrene foam bumper.
- Bailey[3] – 1980 Toyota Corolla foam bumper.
- King[10] – 1989 Chevrolet Sprint foam bumper.
- Siegmund[20] – 1985 Hyundai Stellar foam bumper.

The data in these publications include co-efficients of restitution, absorbed energy, change in velocity and impact force. Unfortunately, these studies do not describe the damage exhibited by the vehicles.

Bailey[3] demonstrated the effectiveness of utilizing the MER method for low speed collisions involving two vehicles equipped with bumper isolators. The paper indicated that comparison of isolator compression to observed speed change (ΔV) in barrier impacts couldn't be accurately correlated to vehicle-vehicle collisions in all cases. Thus, he recommended that the MER method of analysis be used for calculating vehicle speed changes. In this method, the energy absorbed in the vehicle-vehicle impact was determined from the energy absorbed in barrier impacts resulting in similar isolator compression. The appropriate collision restitution was assessed by applying Howard's formula with the corresponding co-efficients of restitution from each vehicle's separate barrier impact. The author also identified that there were a limited amount of data pertaining to foam impact absorber and rigid bumper systems.

Bailey[2] also presented a unique approach for estimating the energy absorbed by a foam impact absorber from elastic strain energy theory for centric axial loading. In order to apply this method of analysis, the magnitude of the impact force, elastic modulus and physical dimensions of the impact absorber must be known.

Typically, these parameters cannot be determined in the routine reconstruction of real world collisions. In order to obtain the physical dimensions and elastic properties of an impact absorber, one would have to measure and compress an exemplar absorber. The impact force is typically not known unless it can be determined from analysis of the other impacting vehicle's damage (e.g. from bumper isolator compression). Thus, utilizing elastic strain energy theory for assessing collision severity is not practical for the majority of low speed collisions involving modern vehicles.

Nielsen[15] applied the MER analysis technique to a series of repeated low speed impacts with utility vehicles. The study presented absorbed energy, speed changes and restitution for each collision. Representative parameters for each successive impact were also presented; these values for restitution and change in velocity were used to calculate an equivalent severity (ΔV_{rep}) for a representative single impact. However, the target vehicle driver had his foot lightly applied to the brake pedal, which influenced the results of this test series. The absorbed energy (ΔKE) values were overestimates of the energy absorbed by the vehicles, as the effects of the tire/road interaction from vehicle braking were also included. Therefore, care must be used when using Nielsen's values for subsequent analysis of real world collisions.

Several other authors have addressed the effects of vehicle braking on the resulting post-impact vehicle speeds. One particular study by Schmidt[18] addressed the effect on the calculated energy loss by colliding a braking bullet vehicle into the rear of a stationary target vehicle. This braking activity affected the post-impact kinetic energy and the final speeds of the vehicles. Thus, the calculation of the absorbed energy (i.e. ΔKE) was influenced by including energy lost to tire/road friction and resulted in a gross overestimate of the energy absorbed by vehicle crush.

A study recently completed by Heinrichs[7] tested five pick-up trucks with rigid bumpers (i.e. bumpers without energy dissipating elements). The front and rear bumpers of these vehicles were impacted into both a barrier and a passenger vehicle. All impacts resulted in the pick-up trucks sustaining speed changes of about 8 km/h. The resulting damage sustained in the vehicle-barrier tests was compared with the damage resulting from the vehicle-vehicle tests. The paper concluded that the shape of bumper deformation depended upon the shape of the impactor. Thus, it was recommended that more tests involving vehicles with rigid bumpers be conducted in order to assess the use of barrier impact test data for analyzing rigid bumper damage.

A recent publication by Cipriani[4] identified that there were a limited amount of data on the performance of foam core bumpers in low speed impacts so 30 vehicle-vehicle impact tests were staged with four vehicles. As only two import models with foam impact absorbers were used in this study (the other two domestic models had bumper isolators), only 18 of the 30 tests involved a vehicle with a foam impact absorber. The paper presented the MER method of analysis and used the CRASH 3 damage algorithm to assess the energy sustained by the involved vehicles. Appropriate co-efficients of restitution were derived from logarithmic relationships that Cipriani developed from both his and Antonetti's[1] collision restitution data. Predicted ΔV values were then compared to the actual measured values.

Cipriani's energy estimates were based upon the assumption of crush and most of his test vehicles did not sustain significant crush. Thus, the analysis method consistently overestimated the change in velocity sustained by each of the test vehicles. The uncertainty (error) was more predominant for lower speed impacts and ranged up to 540%. This analysis method is limited in its applicability for low speed collisions as crush calculations/co-efficients assume a threshold at which crush is observed (typically around 8 km/h). A quick scan of the MER calculated ΔV's in Cipriani's publication indicates the minimum presented value was 2.4 m/s (8.6 km/h). Although application of this method to real world low speed impacts would consistently provide overestimates of the collision severity, forensic engineers are typically required to assess low speed collision severity (ΔV) more precisely for predicting the potential for occupant injury.

The Insurance Institute for Highway Safety (IIHS) regularly conducts low-speed tests on new model vehicles and reports the sustained damage and required repairs. The tests are typically conducted at about 8 km/h (5 mph) closing speeds into a rigid barrier. These tests provide a useful benchmark for assessing damage sustained at a specific impact speed.

DATA SUMMARY

Currently, there is a lack of test data and the existing data have limited relevance to real world collisions involving non-isolator bumper systems. The method presented here can, when combined with existing test data and results of future impact tests, be used to analyze real world low speed collisions involving vehicles with modern bumper systems.

ANALYSIS METHOD

A practical analysis technique has been developed to assess the collision severity (ΔV) sustained by two vehicles in an aligned low speed collision (where tire forces are negligible or considered separately). The method incorporates MER theory and compares the observed vehicle damage to damage exhibited in barrier tests with the same vehicles. The technique can be used for the analysis of real world motor vehicle collisions by the following procedure:

1. Review the physical evidence remaining after the collision and assess the extent of damage sustained by each vehicle.

2. Compare the damage sustained by each vehicle to barrier tests involving similar vehicles.

3. Estimate the magnitude of energy absorbed by each vehicle during the collision using the barrier test results as a guide. Sum the energies to determine the total E_a.

4. Assess each vehicle's mass (M) by considering curb weights, occupants and cargo.

5. Assess an appropriate co-efficient of restitution (*e*) for the collision by accounting for vehicle bumper types, impact orientation and closing velocity. This initial estimate can be somewhat arbitrary as it will be refined through an iterative process.

6. Calculate an approximate initial closing velocity (V_c) from Equation (5) based upon the estimated co-efficient of restitution.

7. Using an empirical model, ensure that the estimated co-efficient of restitution is consistent with the calculated initial closing velocity. If not, then iterate the co-efficient of restitution (repeat Steps #5 to 7) until it is consistent with the initial closing velocity.

8. Calculate the change in velocity (ΔV) sustained by one of the involved vehicles using Equation (6) and based upon the applicable restitution and closing velocity.

9. Calculate the other vehicle's change in velocity by applying Equation (1).

The key to the application of this analysis technique to real world collisions is quantification of the energy absorbed by the impacting vehicles and the coefficient of restitution. Existing literature has suggested that the absorbed energy and restitution can be determined by comparing the vehicle damage in a real world collision with the damage sustained in staged vehicle-barrier impact tests. Despite this suggestion, little testing has been performed on vehicles with more modern composite bumper systems. Thus, in order to validate this methodology, a series of vehicle-vehicle and vehicle-barrier tests were performed.

STAGED IMPACT TESTS

In order to validate the method presented in this paper and obtain additional impact data pertaining to vehicles with modern bumper systems, a series of staged impact tests were conducted.

TEST PROCEDURE

A series of 69 low speed collisions were staged using five different late model test vehicles. There were 49 vehicle-to-barrier tests and 20 vehicle-to-vehicle collisions conducted over a three-day period in June 2002 in Edmonton, Alberta, Canada.

TEST VEHICLES

The modern test vehicles were chosen based upon their varying bumper construction: plastic covers, foam impact absorbers, plastic lattice impact absorbers, aluminum reinforcement beams, steel reinforcement beams, plastic reinforcement beams and steel face bars (Figures C1 to C10 – from Mitchell PartsPoint). Table B1 in Appendix B provides descriptions of the test vehicles and their respective bumper systems. The vehicles were loaned from the Northern Alberta Institute of Technology (NAIT) fleet of vehicles that are used for their automotive technology programs. With the exception of a few scratches and areas of chipped paint, the vehicle bumper systems were intact and in excellent condition.

The test vehicles were weighed, photographed and bumper geometries were measured prior to impact testing. Table B2 gives a breakdown of the collision series and the maximum closing speed reached for each set of vehicle-barrier and vehicle-vehicle tests. The tests were staged with each vehicle being pushed into a rigid barrier or another vehicle in an aligned orientation. No occupants were within the vehicles during the testing. Transmissions were placed in neutral and parking brakes were disengaged for all collisions.

Repeated testing was initially conducted by colliding vehicles into a rigid barrier and increasing the closing speed with each successive impact. The testing of each vehicle was terminated when either damage was starting to appear at the bumper mounts, or the vehicle reached the maximum desired impact speed. As a result of the vehicle-barrier tests, the test vehicles sustained damage to bumper system components, bumper mounting brackets and some adjoining areas in the vicinity of the bumper. Thus, all five vehicles were repaired and bumper components were replaced before the vehicle-vehicle impacts were conducted.

The vehicles were grouped into pairs such that their contacting bumpers were at consistent elevations. The vehicle-vehicle tests were then staged with the initial closing speeds increasing with each successive impact. The testing of each vehicle pair was finished when either significant damage was observed or the maximum desired closing speed was reached.

INSTRUMENTATION

Two Sintra Engineering Inc. 5th wheels were utilized in the testing and mounted to the side of the test vehicles (Figure 1). Each 5th wheel was composed of a bicycle wheel and aluminum frame assembly that was firmly attached to the test vehicles. A shaft encoder was mounted to each bicycle wheel axle that read pulses into a laptop data acquisition card. The encoder generated 1000 pulses per rotation of the bicycle wheel and produced a resolution of about 2 mm. These pulse counts were analyzed by customized software that calculated instantaneous vehicle velocity at a frequency of 50 Hz.

A PCB Piezotronics 200G capacitive accelerometer was also mounted to a rigid horizontal surface within each vehicle as close as possible to the center of gravity (e.g. on the transmission tunnel or floor pan). The accelerometers measured positive longitudinal vehicle acceleration towards the front of each vehicle. The accelerometer signals were output to a data acquisition system that was calibrated as per the accelerometers' calibration certificates and collected at a frequency of 200 Hz. A Butterworth digital filter was applied to the raw accelerometer data to remove high frequency noise and vibrations.

Figure 1 – Sintra Engineering 5th Wheel Mounted to Buick Park Avenue for Vehicle-Vehicle Test

A contact switch was designed and mounted on the surface of the barrier for the barrier tests and to one of the vehicle's bumpers for the vehicle-vehicle tests; the signal voltage from the switch was inputted to the data acquisition system in order to indicate the initiation of bumper contact. Figure A3 shows a sample of the accelerometer and contact switch output voltages for a specific test.

Each impact test was documented by video and 35 mm camera photography. In addition, the extent of damage sustained by the involved vehicles was recorded. A customized measurement jig (Figure 2) was utilized to measure the pre-testing bumper geometries. After each test, the jig was used to measure the extent of bumper displacement with respect to the initial undamaged position; the distance of bumper displacement was measured in millimeters. This jig was used in all barrier tests but only for some of the vehicles during the vehicle-vehicle testing. After the barrier impact series, it was discovered that some vehicles did not exhibit noticeable bumper displacement. In addition, the asphalt road surface used for conducting the vehicle-vehicle tests had several surface imperfections that made accurate alignment of the measurement jig difficult. The barrier tests were conducted on smooth polished concrete. Thus, the jig was only used for a limited number of vehicles during the vehicle-vehicle testing.

Figure 2 - Measurement Jig Aligned with Pontiac Sunfire's Front Bumper

Other quantitative measurements and qualitative visual observations were made after each impact test:

- Contact marks on the bumper's exterior surfaces and other vehicle components.
- Distance between the bumper reinforcement beam/face bar and the vehicle body.
- Air gap between the bumper cover and impact absorber.
- Bumper shift on the mounting bolts.
- Misalignment of bumper and body components.
- Reduced functionality of hoods and trunk lids.
- Localized damage to bumper components, bumper mounts and other body components.

DATA ANALYSIS

The data collected during the testing period were used to calculate the following parameters for each vehicle: velocity, change in velocity (ΔV), peak acceleration, average acceleration, peak impact force and average impact force. For each impact, the collision duration, co-efficient of restitution, kinetic energies and absorbed energy were also assessed.

DATA UNCERTAINTY

The uncertainty in velocity data was dependent upon the method in which it was tracked. Vehicle velocity was generated two different ways: from the 5th wheel and from accelerometer data. In order to assess vehicle speed from the accelerometer data, mathematical integration of the data was completed. The instantaneous speed was dependent on previously calculated values. Thus, small errors in the data could propagate through the integration. These errors could be attributed to electrical noise, vehicle body pitching and vibration. As the velocity was also calculated from the 5th wheel and was independent of previously calculated values, it provided a more robust measure of vehicle speed. Figure A4 illustrates velocity data for a specific vehicle-vehicle test.

The velocity curve generated by the 5th wheel typically included a section of pulses immediately after the impact. In addition, the velocity curve generated by integrating the accelerometer data revealed a sinusoidal wave that pulsated after the impact. This non-steady output was likely related to the vehicle rocking on its suspension and impact vibrations. The method described in a paper by King[11] was used to assess the vehicle's post-impact speed from the fluctuating post-impact 5th wheel and accelerometer generated speed curves. Thus, the uncertainty in vehicle velocity measurements was assessed to be ±0.02 m/s.

The collision duration was determined from analysis of both the 5th wheel and accelerometer velocity data. Although the contact switch indicated the beginning of bumper contact, it did not provide an accurate indicator of the end of bumper contact due to the nature of its design. The collisions revealed that a test vehicle's center of gravity experienced a change in velocity or acceleration after the initiation of bumper contact. Thus, the initiation of each collision was taken to be at the beginning of the acceleration pulse. The end of the impact was determined to be when the acceleration became zero and the velocity change leveled out. In most cases, this point was difficult to assess due to the cyclic nature of the 5th wheel and accelerometer output after the impact (as discussed earlier). King[11] described this problem in determining collision duration from these types of sensors. The measured collision durations had an associated uncertainty of ±0.02 s.

The co-efficient of restitution for each staged collision was calculated from the velocity data and had an associated uncertainty of ± 0.02. The energy absorbed by the vehicles was calculated for each vehicle-barrier and vehicle-vehicle test from Equation 3. The uncertainty of assessed energy values increased with higher impact severities. The absorbed energy uncertainty ranged from about ± 10 J (about 10% error) at lower speeds to about ± 100 J (about 1% error) for higher severity impacts. As the magnitude of the uncertainty increased at higher speeds, the percent error decreased.

DAMAGE COMPARISON

Although a series of repeated impacts was conducted in this study for each set of vehicle-barrier and vehicle-vehicle pairs, the analysis technique presented in this paper does not require the assessment of a ΔV_{rep} (such as in Nielsen's study). The damage sustained by test vehicles in the vehicle-vehicle impacts was directly compared with the damage and absorbed energy realized from the staged barrier impact tests. Due to the repeated test technique, absorbed energy from previous collisions of the same test group (e.g. a lower severity impact with the same vehicle) had to be considered in order to assess a reasonable range for the absorbed energy required to cause the observed extent of damage in the referenced collision.

As long as successive impacts were within the viscoelastic range of bumper components (below the onset of permanent damage), the energy absorbed from these impacts was primarily due to viscous losses (i.e. there was no plastic deformation energy). Thus, this viscous energy was not included in the summation process as it was transient and would not affect bumper performance in subsequent tests. However, for impacts with permanent damage, the "plastic" energy component of the absorbed energy had to be summed up to find an equivalent energy [22].

When a vehicle sustains some plastic crush in a low speed impact, it is difficult to quantify the magnitude of energy associated with this damage and the viscous energy losses. However, as vehicle crush increases, the plastic energy component dominates over the viscous energy component (although the viscous component also increases). Thus, summing of all absorbed energy in a series of successive low speed impact tests will provide an overestimate of energy required to cause the extent of observed damage in a single higher severity impact.

APPLICATION OF ANALYSIS METHOD

In order to demonstrate the application of the proposed analysis technique with the results of the vehicle-vehicle impact tests in this study, Test #51 (vehicle-vehicle) involving the Chevrolet Blazer and Buick Park Avenue will be used as an example. Data from vehicle-vehicle Tests #50 and 52 were included in the appended tables for clarity and completeness. Tables B3 and B4 summarize the results of the barrier and vehicle-vehicle tests involving the Chevrolet Blazer and Buick Park Avenue. Photographs D1 to D7 show the damage from the different vehicle-vehicle tests.

1. REVIEW THE PHYSICAL EVIDENCE

The damage sustained by both the Chevrolet Blazer and Buick Park Avenue in the vehicle-vehicle tests was documented after each impact. This damage included scuff marks on the bumpers, bumper displacement and shifting of the bumper mounting bolts (Table B4). The customized measurement jig was also used to measure the average bumper displacement on the Chevrolet Blazer.

2. DAMAGE COMPARISON

The damage sustained by both vehicles was compared to the damage sustained in their respective barrier tests (Table B3). As the collision severity increased, the Chevrolet Blazer's front bumper shifted further rearward on its mounting bolts and exhibited more localized deformation. The Buick Park Avenue's rear bumper exhibited larger displacement of its reinforcement beam and impact absorber as the collision severity increased.

3. ABSORBED ENERGY ESTIMATION

The energies absorbed by the Chevrolet Blazer and Buick Park Avenue during the vehicle-vehicle collisions were estimated from referencing the documented energies of the barrier tests. Table B5 summarizes the results of this analysis. The results of the barrier tests were analyzed in order to assess the magnitude of energy required for a specific amount of damage.

In vehicle-vehicle Test #51, the Chevrolet Blazer's front face bar was displaced rearward by 6 mm and a left bumper mounting bolt was shifted (Photo D4). Similarly, in barrier Test #2, the Chevrolet Blazer's face bar exhibited an average displacement of 6 mm and mounting bolts on both sides were shifted about 2 mm. The centre of the face bar showed localized deformation during the barrier impacts that was not observed in the vehicle-vehicle testing. This damage was not observed during the tests with the Buick Park Avenue as the impact force was distributed more evenly over the front surface of the face bar during the vehicle-vehicle tests. Nonetheless, the 450 J absorbed by the Chevrolet Blazer during barrier Test #2 likely provides a lower limit.

The extent of bumper displacement in barrier Test #3 exceeded that sustained by the Chevrolet in vehicle-vehicle Test #51. The equivalent energy required to cause the observed damage after barrier Test #3 provides an upper limit for the energy absorbed by the Chevrolet Blazer in vehicle-vehicle Test #51. The Chevrolet Blazer sustained plastic deformation and shifting of the bumper in barrier Tests #1 and #2. As a consequence, a portion of the absorbed energy in these barrier tests was not from viscous losses. Direct summation of the energies from barrier Tests #1 to 3 (i.e. 193 J + 450 J + 1070 J = 1713 J) provides an upper limit of the energy absorbed during vehicle-vehicle Test #51.

During vehicle-vehicle Test #51, the Buick Park Avenue exhibited two localized regions with scuff marks on the rear surface of its bumper cover (Photo D5). These marks were from contact with the Chevrolet Blazer's tow hooks and this damage was not observed during the Buick's barrier tests. The Buick Park Avenue also exhibited longitudinal scuff marks on the top surface of its bumper cover that extended 21 mm from the trunk lid. In its lowest severity barrier impact (Test #17), the Buick Park Avenue absorbed 407 J but did not exhibit any damage. Thus, this energy value provides a lower limit to that absorbed by the Buick during vehicle-vehicle Test #51.

In barrier Test #18, the Buick Park Avenue's rear bumper beam was displaced slightly and scuff marks were deposited on the bumper cover's upper surface. As this damage exceeded that sustained by the Buick in vehicle-vehicle Test #51, the energy absorbed by the Buick Park Avenue during Test #51 was likely less than 870 J. The 407 J absorbed during the previous barrier Test #17 was not summed with 870 J, as viscous losses were primarily responsible for absorbing the energy in Test #17 (i.e. there was no energy absorbed due to plastic deformation).

The range of total energy absorbed by both the Chevrolet Blazer and Buick Park Avenue in each vehicle-vehicle test was determined by summing the individual upper and lower energy limits. Table B5 lists the total estimated absorbed energies for vehicle-vehicle tests #50 to 52.

4. VEHICLE MASS ASSESSMENT

The Chevrolet Blazer and Buick Park Avenue were weighed prior to the impact testing. The Chevrolet Blazer weighed 1908 kg with instrumentation and the Buick Park Avenue weighed 1697 kg with instrumentation.

5. CO-EFFICIENT OF RESTITUTION ASSESSMENT

The restitution of a specific vehicle-vehicle collision is required to accurately assess the impact severity. As collision restitution is dependent upon several factors including bumper construction, impact orientation and collision severity, it would be ideal to stage a collision between the specific pair of vehicles in order to get the impact parameters directly. However, the cost of staging a collision with exemplar vehicles for modeling a real world collision typically precludes facilitation of exemplar vehicle testing and the ability to directly obtain the co-efficient of restitution. Therefore, empirical data from other staged collisions must be used to determine an appropriate restitution value for a specific case.

For this test series, the restitution was calculated for each staged vehicle-vehicle collision and vehicle-barrier collision. The restitution of vehicle-vehicle tests #50 to 52 was about 0.39 to 0.41 (Table B4). Ideally, these values could be used directly in the analysis. However, as this information is typically not measured during a real world collision, an empirical model is used to predict an appropriate co-efficient of restitution from other more readily available parameters. The recent publication by Cipriani provided logarithmic relationships from empirical restitution data. Cipriani's model calculated an average co-efficient of restitution for a specific closing speed. His study presented three models: one for vehicles with bumper isolators, one for vehicles with foam core bumpers and one all data composite.

The closing velocity is required before Cipriani's model can be applied to assess the collision restitution. Equation (5) can be used to assess the initial closing velocity of a vehicle-vehicle collision, but it is also dependent on restitution. In order to solve this circular relationship, an arbitrary initial co-efficient of restitution (*e*) was chosen for vehicle-vehicle Test #51 of 0.4. This initial arbitrary estimate will be further refined through an iterative process.

6. INITIAL CLOSING VELOCITY ASSESSMENT

Equation (5) was applied to calculate the closing velocity for vehicle-vehicle Test #51 from the estimated energy range, vehicle masses and the arbitrary co-efficient of restitution.

7. ITERATE TO REFINE RESTITUTION

The calculated closing velocity from Step #6 can be applied to one of Cipriani's empirical models. As the Chevrolet Blazer had a rigid bumper (i.e. no isolators or foam core), Cipriani's All Data Composite model was utilized to reassess the collision restitution from the calculated closing velocity. By using this method, the restitution calculated from Cipriani's model was not consistent with the original arbitrary restitution estimate.

A revised co-efficient of restitution was chosen for the test and Steps #5 to 7 were repeated until the co-efficient of restitution from Cipriani's model was consistent with the calculated initial closing velocity. The final predicted co-efficient of restitution for vehicle-vehicle Test #51 is shown in Table B5.

8. AND 9. CHANGE IN VELOCITY ASSESSMENT

Equation (6) calculates the change in velocity sustained by the Chevrolet Blazer in the impact with the Buick Park Avenue. This calculation was performed for the lower and upper limits of absorbed energy and was based upon the applicable co-efficients of restitution and closing velocities. Equation (1) was then applied to assess the corresponding change in velocity sustained by the Buick Park Avenue. Table B5 lists the calculated lower and upper limits for the vehicles' change in velocity.

ANALYSIS METHOD SUMMARY

This analysis method was applied to the results of the vehicle-vehicle tests performed as part of this study. The predicted collision severity results were compared to the actual results from the instrumented tests of the vehicle-vehicle collisions.

OBSERVATIONS AND RESULTS

The primary purpose of the staged impact tests was to validate the analysis method presented in this paper. Figure A5 illustrates the 40 predicted ΔV ranges for the actual ΔV values obtained from the 20 vehicle-vehicle collisions in order of increasing severity. The following observations were made:

- The predicted change in velocity ranges bounded the actual change in velocity values in 80% (32/40) of the vehicle-vehicle collisions.
- In two cases, the predicted ranges slightly overestimate the actual severity values. These two ranges were within 0.1 m/s (0.3 km/h) of the actual ΔV value and occurred in vehicle-vehicle tests #63 and 64.
- There were six cases where the predicted values underestimated the actual values. All six of these predicted ranges were within 0.3 m/s (1.1 km/h) of the actual ΔV value and occurred in vehicle-vehicle tests #56, 57 (x2), 58 and 60 (x2).

The inconsistent results in eight of the tests were likely related to the predicted collision restitution.

COLLISION RESTITUTION

In order to calculate ΔV values for the vehicle-vehicle collisions, a co-efficient of restitution for each vehicle-vehicle impact was assessed. Empirical models derived by Cipriani were used to predict co-efficient of restitution. An alternative approach was to calculate the co-efficient of restitution from the formula presented by Howard and shown as Equation (7). This method provides a theoretical methodology for predicting collision restitution from the results of barrier impact tests.

Howard's restitution formula was used to predict restitution values from the observed coefficients of restitution in the vehicle-barrier tests performed as part of this study. When Howard's formula was used, it was found that the predicted restitution values and ΔV ranges tended to be above the actual observed restitution and ΔV values from the instrumented vehicle-vehicle tests. The primary reason for this inconsistency appears to have been due to differences in bumper engagement between the vehicle-barrier tests and vehicle-vehicle tests.

During the barrier tests, each vehicle's bumper made flush contact with the surface of the barrier. The vehicle-vehicle tests were planned so that bumper elevations would be consistent. However, there were a few vehicle-vehicle pairs where bumper engagement varied due to the geometry and elevation of the impacting vehicles' bumpers. The greatest discrepancies between barrier restitution values and vehicle-vehicle restitution values were noted in the vehicle-vehicle tests involving slight under-ride (Tests #63-65) and localized contact with the Chevrolet Blazer's rigid bumpers (Tests #50-52, 66-69). In these unique collisions, vehicles experienced collision forces through more unsupported areas and absorbed more plastic energy that ultimately reduced the post-impact kinetic energy and the magnitude of restitution.

In vehicle-vehicle Tests #63 to 65, the top of the Pontiac Sunfire's rear bumper was situated slightly higher than the top of the Honda Accord's front bumper. As a consequence, the Sunfire's bumper made contact with the Honda's headlights and hood at higher impact severities. The slight elevation difference yielded lower collision restitution values in the vehicle-vehicle tests than in each of the vehicles' respective barrier tests.

In vehicle-vehicle Tests #50 to 52 and #66 to 69 involving the Chevrolet Blazer, the front and rear face bars interacted differently with other vehicles than it did with the barrier. The Chevrolet Blazer's front face bar had a pointed profile (Figure C3) that caused the impact forces to be primarily transmitted to the center of the face bar during the rigid barrier impacts. However, with the Buick Park Avenue, the compliant Buick bumper distributed the impact forces across a larger contact area on the Chevrolet Blazer's face bar. The rear face bar on the Chevrolet Blazer had a thin step at its center (Figure C4) that made contact with the pointed profile of the Pontiac Sunfire's front bumper cover. This localized bumper-bumper contact applied the impact forces to a small section of the Pontiac Sunfire's bumper. The interaction with the Chevrolet Blazer's rigid face bars resulted in slightly lower collision restitution values in the vehicle-vehicle tests than in the vehicles' respective barrier tests.

Application of Cipriani's restitution models worked well in predicting the change in velocity of the vehicle-vehicle impacts. There were eight cases where the predicted ΔV values did not bound the measured ΔV values from the test series:

- The non-conformance in vehicle-vehicle tests #63 and 64 can be attributed to Cipriani's model predicting a higher restitution than what was realized in the collisions between the Honda Accord and Pontiac Sunfire. These tests had unique bumper interaction where there was partial bumper over-ride.

- The underestimates resulting from vehicle-vehicle tests #56, 57 (x2), 58 and 60 (x2) occurred because Cipriani's model predicted co-efficients of restitution that were much lower than the actual vehicle-vehicle restitution. It was discovered that the calculated ΔV ranges could be corrected to bound the actual ΔV values when larger more appropriate co-efficients of restitution were applied to these tests.

The collision restitution is a factor of vehicle bumper structural characteristics, bumper impact orientation and closing speed. Thus, care must be used when applying a general empirical model to assess the restitution for a specific vehicle-vehicle collision. The restitution value must be carefully selected for the proposed analysis method in order to ensure useful results.

DAMAGE ASSESSMENT

The damage sustained by the test vehicles in the vehicle-vehicle collisions was compared with the damage sustained in the vehicle-barrier tests. This process of comparing damage was both subjective and objective. In most cases, direct measurements of bumper displacement were made and these measurements could be compared. However, in some cases, the damage was subjectively assessed in order to compare observations that were not measurable.

The bumper elevations of some of the vehicle pairs did not match exactly and this geometry differed from the impacts with the barrier. In vehicle-vehicle tests #66 to 69, the thin bottom step of the Chevrolet Blazer's rear bumper concentrated the impact force to the center of the Pontiac Sunfire's front bumper cover resulting in localized damage to the Pontiac's bumper cover. Furthermore, in vehicle-vehicle tests #63 to 65, the Honda Accord's front bumper was situated slightly lower than the Pontiac Sunfire's rear bumper. This bumper geometry allowed these impacts to focus on the upper portion of the Honda Accord's front bumper, its grille and the leading edge of its hood. The impacts resulted in the Honda sustaining more override damage to the headlights, hood and radiator:

- For example, in vehicle-vehicle test #65, the Honda Accord's hood was buckled, its right headlight was broken, the radiator was displaced rearward and the bumper cover bulged around the headlights. Due to the slight over-ride of this impact, the Honda's bumper beam remained undamaged. In the Honda's barrier tests, the bumper made flush contact with the barrier and the vehicle sustained damage only to its bumper components. Barrier Test #34 resulted in the bumper beam being displaced rearward 28 mm, both bumper mounting flanges starting to deform and the air gap between the bumper cover and impact absorber increasing by 3 mm. In the more severe barrier Test #35, the Honda Accord sustained more significant damage: the bumper beam buckled and was displaced rearward 62 mm, both bumper mounting brackets deformed and the bumper cover sides bulged outward.

As the damaged areas on the Honda Accord differed between the vehicle-vehicle tests and the barrier tests, subjective comparisons were made in order to assess equivalent damage. The damage sustained by the Honda Accord in vehicle-vehicle Test #65 was assumed to be comparable to that sustained by the Honda Accord in barrier Test #34. The equivalent energy of the damage that resulted from barrier Test #35 was likely much greater than that in vehicle-vehicle Test #65.

Vehicles with rigid bumper systems tend to sustain localized face bar damage in barrier tests but no localized damage in impacts with other vehicles. For example, in barrier tests, the Chevrolet Blazer sustained localized face bar damage due to the barrier's rigid surface concentrating the impact force at the center of the front and rear V-profile bumpers. However, the Blazer did not exhibit similar face bar damage in the vehicle-vehicle tests as the impact force was distributed over a larger contact area (due to compliance of the other vehicles' bumpers). Thus, in order to compare the Blazer's vehicle-vehicle impacts with its barrier impacts, other factors were considered: the extent of overall bumper shift, bumper misalignment, mounting bolt shift and localized mount damage. The example presented in this paper illustrates this technique.

The Honda Accord's rear bumper was observed to absorb a significant amount of energy without showing evidence of any damage or displacement. In other words, it was able to absorb a significant amount of viscous energy.

ENERGY ESTIMATES

The energy absorbed by each of the test vehicles in the vehicle-vehicle collisions was estimated from observations of the vehicle damage and compared to the results of the previously staged barrier impacts. The sum of the estimated energy absorbed by each vehicle in the vehicle-vehicle collisions was consistent with the actual total energy absorbed by the pair of vehicles in each impact. Figure A6 shows the actual energy values bordered by the minimum and maximum energy range estimates in order of increasing magnitude. This observation confirms the theory used by Howard that the sum of energies from two independent vehicle-barrier impacts equates to the total energy absorbed by the same two vehicles in a vehicle-vehicle collision involving the same amount of vehicle damage.

Vehicle-vehicle Test #56 was the only staged test where the magnitude of energy absorbed by the impacting vehicles was less than the previous test. Typically, the absorbed energy increased with increasing impact severity. Although vehicle-vehicle Test #56 was conducted with a slightly higher closing speed than vehicle-vehicle Test #55, the restitution increased slightly and caused the absorbed energy to decrease. Thus, an accurate estimate of E_a could not be made for this particular test.

The large maximum energy estimates shown in Figure A6 were primarily derived from referencing barrier tests where the absorbed energies of previous impacts were included. This method included large sums of viscous energy from previous impacts that could not be quantified. The availability of more thorough barrier test data would refine these large energy estimates and provide values closer to the actual vehicle-vehicle values.

The absorbed energy in a vehicle-vehicle impact was not shared proportionately between two vehicles, but rather was dependent on each vehicle's structural characteristics. For example, during the Buick Park Avenue and Hyundai Sonata tests, the Buick absorbed very little of the impact energy. The Hyundai Sonata bumper components had a much lower threshold for sustaining permanent damage. Thus, the Hyundai absorbed most of the impact energy in the form of plastic crush energy.

RESULTS SUMMARY

Application of the proposed analysis method to the results of the impact tests staged for this study indicates that the analytical technique is useful in predicting collision severity of an aligned real world low speed collision. However, an appropriate co-efficient of restitution must be selected bearing in mind the details of the specific collision being considered.

Further low speed barrier testing with modern vehicles should facilitate more precise predictions of real world collision severity.

USING IIHS DATA FOR ANALYSIS

Currently, there are limited sources of low speed barrier test data for vehicles with modern bumper systems. It would be unusual to find data from a series of staged barrier tests with a particular vehicle model. This lack of barrier impact data provides a challenge to any individual who wants to apply the proposed analysis technique to a real world collision.

The majority of available barrier test data are from private testing series and the Insurance Institute for Highway Safety (IIHS). Most of this testing is completed at a single closing speed with damage appraisals indicating required repairs and repair costs. The testing results typically do not include any restitution values, absorbed energy magnitudes or multiple testing results. Provided the extent of damage observed from a real world collision is less than the damage resulting from a single barrier test, the use of this limited data will provide the maximum collision severity for the real world impact.

The results of IIHS low speed barrier tests are readily available for several modern vehicles. As there is generally only one barrier test for each vehicle, analysis of an IIHS test will provide a much larger range for a predicted impact severity. Nonetheless, analysis of IIHS data with the proposed analysis method is an effective means for determining a limit of a real world collision's severity.

The energy absorbed by a vehicle during a barrier impact test can be assessed by combining Equations (3) and (4) and noting that the barrier is stationary before and after the impact:

$$E_a = \tfrac{1}{2} M_1 V_{1i}^{\,2} \left(1 - e^2\right) \tag{8}$$

Equation (8) indicates that the energy absorbed during a barrier test is determinable from the vehicle's mass, the barrier impact speed and the corresponding co-efficient of restitution. The IIHS tests are conducted at a nominal 2.2 m/s (8 km/h) impact speed. The mass of the test vehicle can be determined from the IIHS test report or by assuming an unloaded curb weight. The co-efficient of restitution is not reported by the IIHS, but a reasonable range for this co-efficient can be assumed. Several researchers have documented the restitution resulting from barrier tests. Review of the data in Antonetti's paper suggests that a range of 0.3 to 0.6 is reasonable for a barrier impact involving a vehicle with a modern bumper and a 2.2 m/s closing speed.

Thus, analysis of a single IIHS barrier test can provide a range of the energy absorbed by the test vehicle. This energy range can be compared to the damage sustained by the test vehicle in order to provide a reference for the energy absorbed by a similar vehicle model in a real world collision.

CONCLUSIONS

The following conclusions were drawn:

1. The staged tests in this research indicate that applying energy estimates from referenced vehicle-barrier impact tests and estimating an appropriate co-efficient of restitution can predict the collision severity (ΔV) of real world low speed motor vehicle collisions.

2. Howard's theoretical restitution equation slightly overestimated vehicle-vehicle restitution values from corresponding barrier impacts. The difference between Howard's predicted value and the actual restitution is dependent upon the vehicle-vehicle bumper interaction. In cases where vehicle bumper elevations do not match properly (e.g. over-ride collisions), the resulting vehicle-vehicle restitution will differ from that predicted by Howard's formula.

3. Using Cipriani's empirical restitution relationships with the practical analysis method presented in this paper yielded a better prediction of vehicle-vehicle collision severity.

4. Care must be exercised in selection of an appropriate co-efficient of restitution when applying the analysis method. Vehicle type, bumper impact orientation and closing speed all affect the choice of the collision restitution.

5. The bumper elevations of some of the vehicle pairs did not match exactly and this bumper interaction differed from the impacts with the barrier causing the type of damage resulting from the barrier tests to differ from the vehicle-vehicle damage. In these cases, subjective comparisons were made in order to assess equivalent damage.

6. Vehicles with rigid bumper systems tend to sustain localized face bar damage in barrier tests but no localized damage in impacts with other vehicles. Therefore, other factors must be considered when comparing damage sustained in vehicle-vehicle impacts with corresponding barrier impacts (e.g. extent of overall bumper shift, bumper misalignment, mounting bolt shift and localized mount damage).

7. Energy absorbed by two vehicles in their separate barrier impacts sums to the energy absorbed by the same two vehicles in a vehicle-vehicle impact involving the same extent of vehicular damage.

8. The absorbed energy in a vehicle-vehicle impact is not shared proportionately between the two impacting vehicles. The amount of energy absorbed by each vehicle is dependent on each vehicle's structural characteristics.

9. Provided the observed damage from a real world motor vehicle collision is less than the damage resulting from a single low speed barrier test, use of the practical analysis method with reference to the single barrier test will yield the maximum collision severity for the real world impact.

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CONTACT

The staged vehicle impact tests were fully documented, instrumented, photographed and video recorded. If the results of any of the tests in this study are desired, then please feel free to contact our office.

Mr. Andrew Happer, P.Eng.
Sintra Engineering Inc.
10620 – 105 Avenue
Edmonton, AB
Canada T5H 0L2
Tel: (780) 420-1551
Toll-free: 1-877-244-6251
Web: http://www.sintraeng.com
E-mail: ahapper@sintraeng.com

APPENDIX A - FIGURES

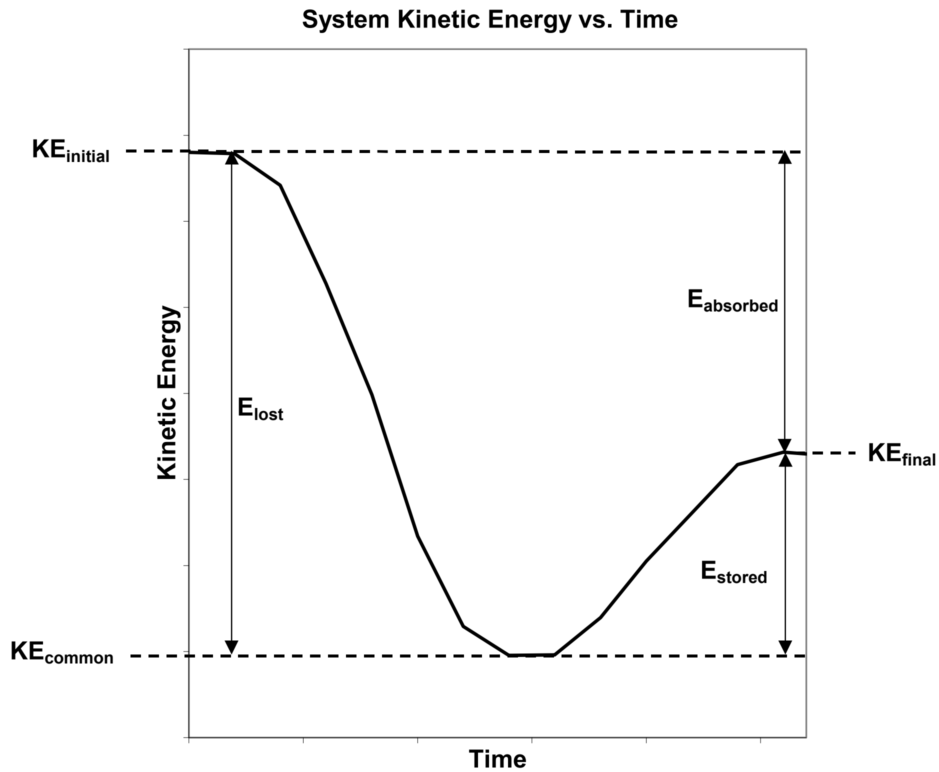


Figure A1 - Change in Kinetic Energy During a Collision

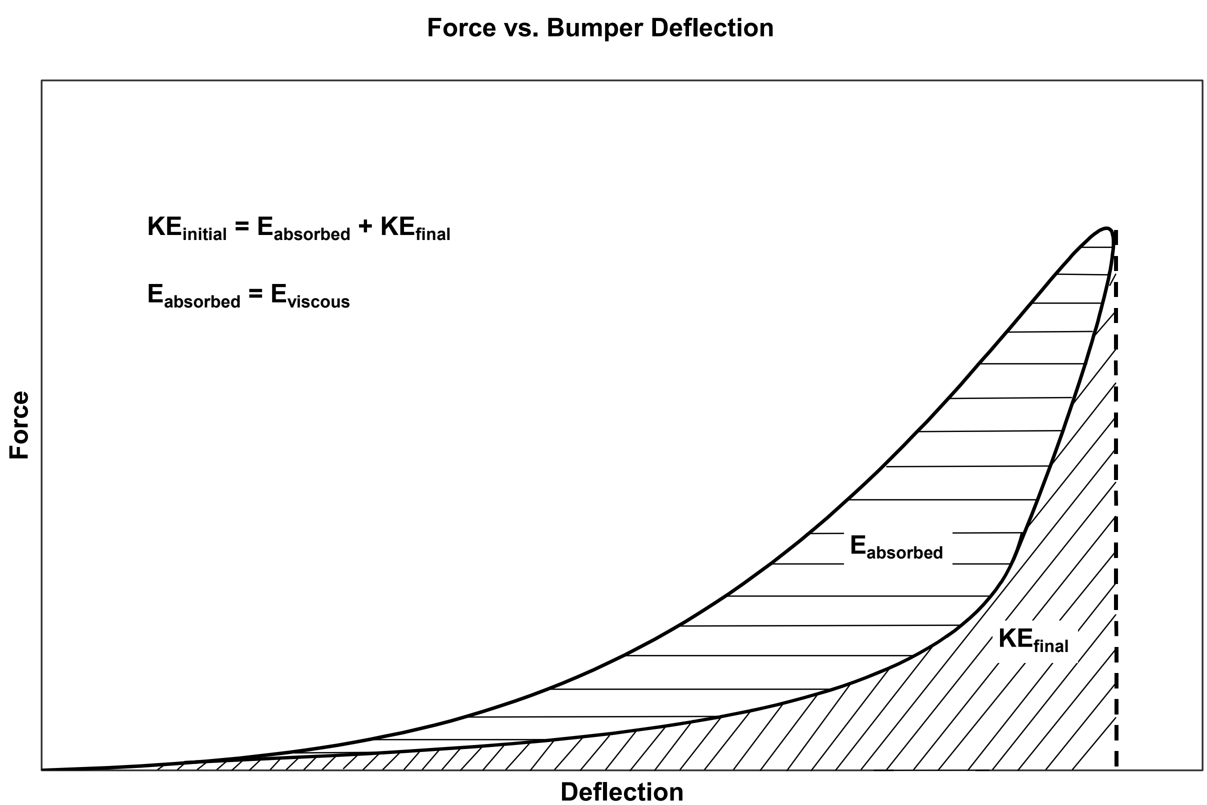


Figure A2 - Force vs. Deflection Relationship for a Barrier Impact within the Bumper's Viscoelastic Range

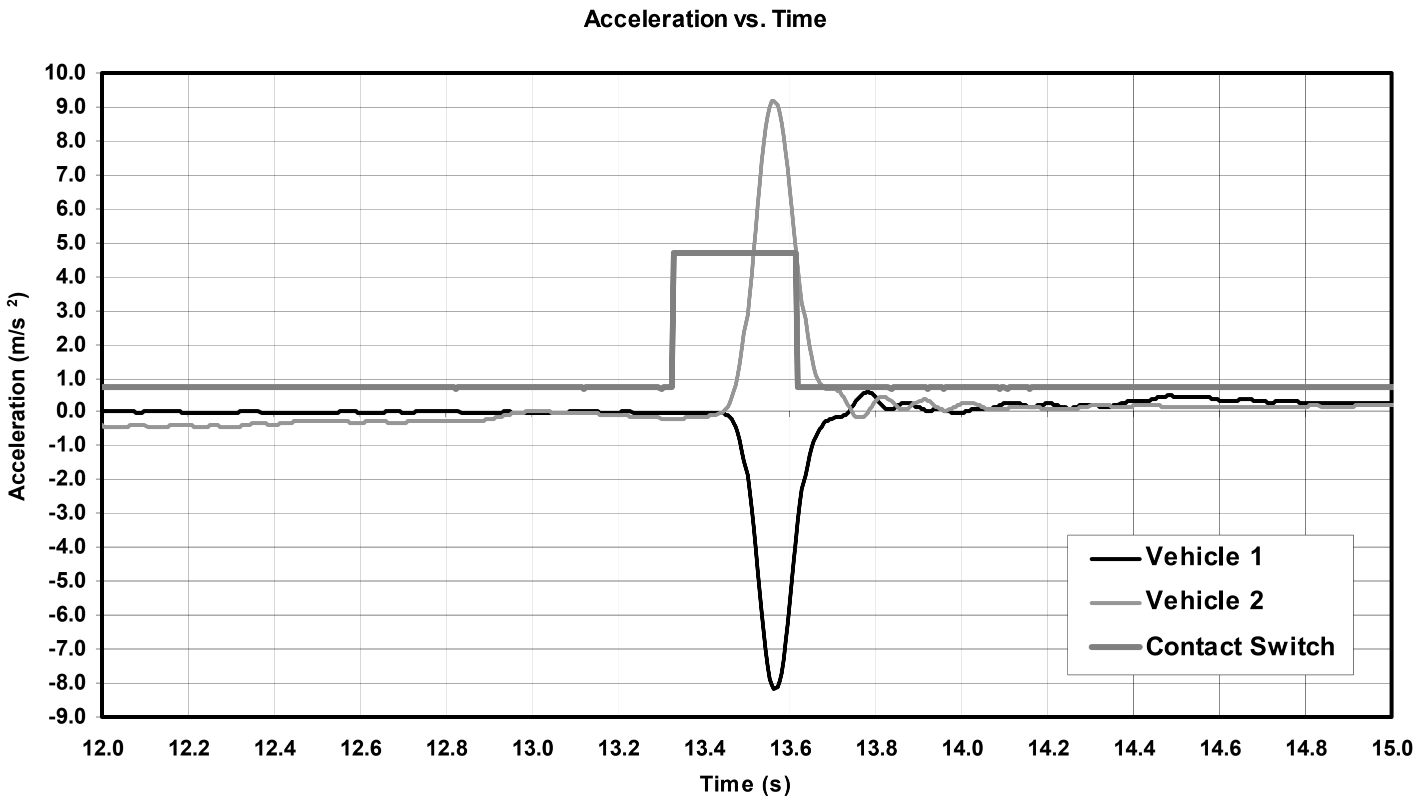


Figure A3 – Sample Accelerometer and Contact Switch Output Voltages

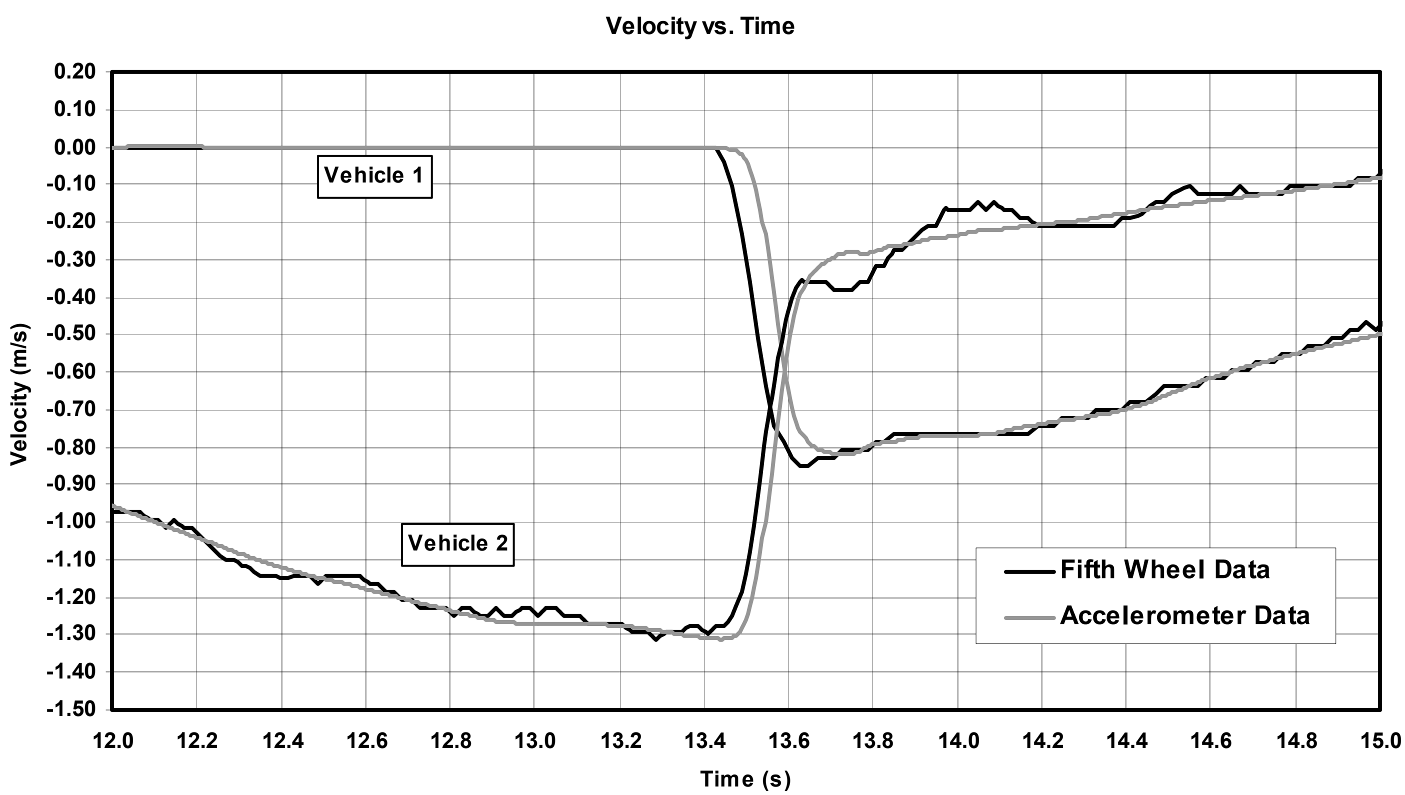


Figure A4 – Sample Velocity Graph Generated from Accelerometer and 5th Wheel Output

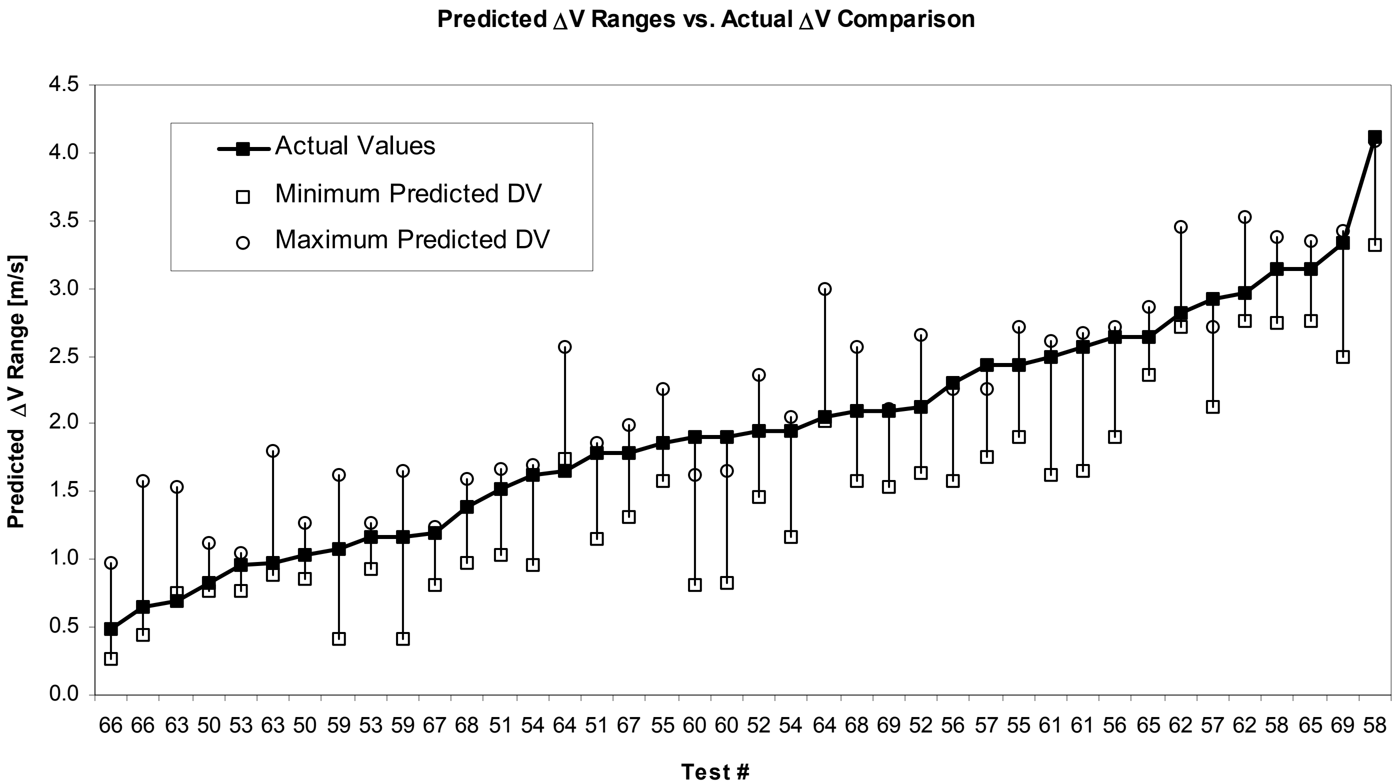


Figure A5 – Predicted ΔV Ranges Compared with Actual ΔV Values Measured in Vehicle-Vehicle Collisions

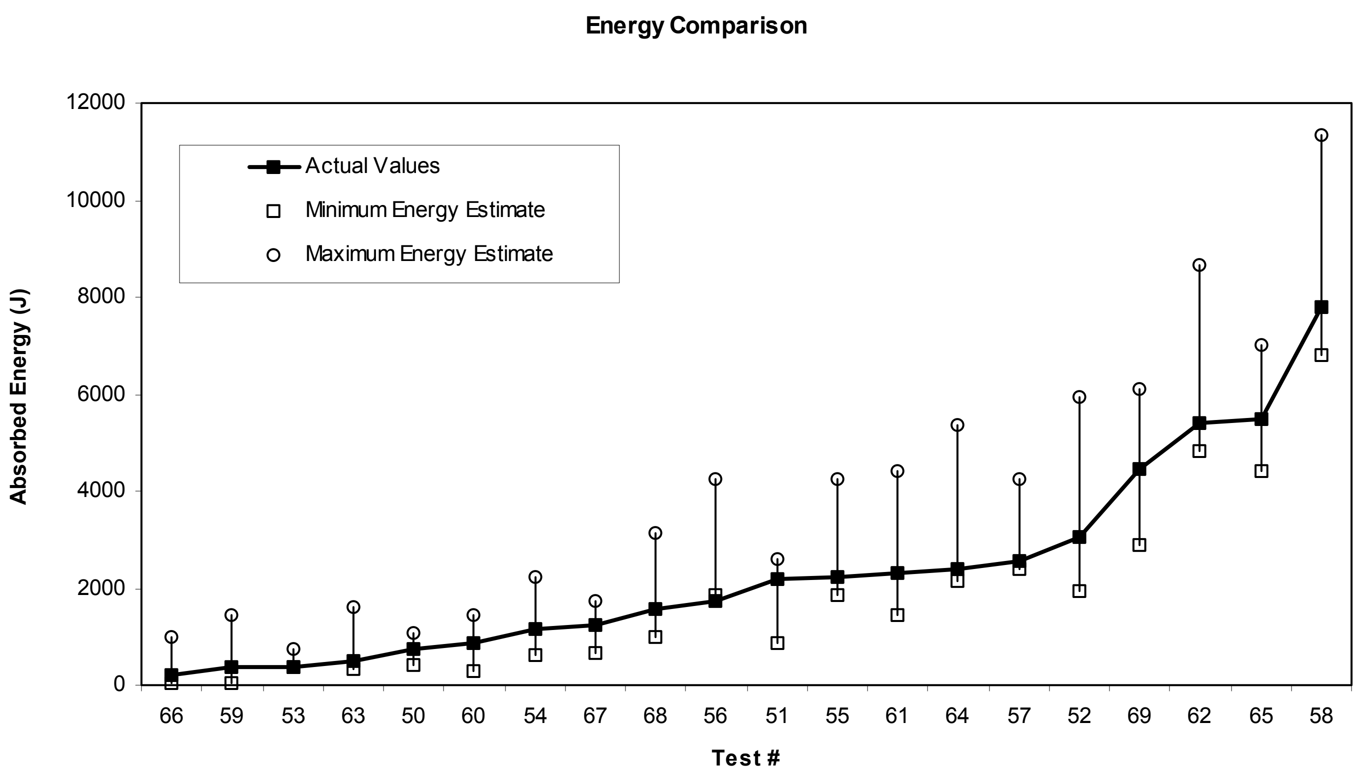


Figure A6 - Predicted Energy Ranges Compared with Actual Absorbed Energy in Vehicle-Vehicle Collisions

APPENDIX B - TABLES

Table B1 - Test Vehicle Data

Vehicle Identity	Year/ Make/ Model	Body Style	Mass (kg)	VIN	Bumper Construction
A	1998 Honda Accord LX	4-door Sedan	1372	1HGCG5649WA800011	Front: plastic cover, foam impact absorber, steel reinforcement beam
					Rear: plastic cover, foam impact absorber, steel reinforcement beam
B	1999 Chevrolet Blazer LT	4-door Utility	1901	1GNDT13W3X2129015	Front: steel face bar with plastic impact strip, lower plastic valence
					Rear: steel face bar with plastic step pad and end caps
C	1998 Buick Park Avenue	4-door Sedan	1690	1G4CW52K8W4628764	Front: plastic cover, foam impact absorber, aluminum reinforcement beam
					Rear: plastic cover, foam impact absorber, aluminum reinforcement beam
D	1999 Hyundai Sonata GL	4-door Sedan	1399	KMHWF25S5XA000400	Front: plastic cover, plastic reinforcement beam
					Rear: plastic cover, foam impact absorber, plastic reinforcement beam
E	2000 Pontiac Sunfire SE	2-door Coupe	1175	3G2JB1248YS251233	Front: plastic cover, plastic lattice impact absorber, steel reinforcement beam
					Rear: plastic cover, plastic lattice impact absorber, steel reinforcement beam

Table B2 - Test Collision Series

Test #	Vehicle 1		Vehicle 2		Maximum Closing Speeds (m/s)
	Identity	Surface Tested	Identity	Surface Tested	
1 - 5	Blazer	Front	Barrier	n/a	2.16
6 - 9	Blazer	Rear	Barrier	n/a	1.88
10 - 16	Park Avenue	Front	Barrier	n/a	2.44
17 - 21	Park Avenue	Rear	Barrier	n/a	2.40
22 - 25	Sonata	Front	Barrier	n/a	2.16
26 - 30	Sonata	Rear	Barrier	n/a	2.60
31 - 35	Accord	Front	Barrier	n/a	2.40
36 - 40	Accord	Rear	Barrier	n/a	2.60
41 - 44	Sunfire	Front	Barrier	n/a	2.92
45 - 49	Sunfire	Rear	Barrier	n/a	2.53
50 - 52	Blazer	Front	Park Avenue	Rear	2.76
53 - 58	Park Avenue	Front	Sonata	Rear	5.02
59 - 62	Sonata	Front	Accord	Rear	4.22
63 - 65	Accord	Front	Sunfire	Rear	4.38
66 - 69	Sunfire	Front	Blazer	Rear	3.83

Table B3 – Barrier Test Results for the 1999 Chevrolet Blazer and 1998 Buick Park Avenue

Test #	Vehicle Description	V_c [m/s]	Absorbed Energy [J]	Restitution (e)	Bumper Disp. [mm]	Damage Summary
1	Chevy Blazer – Front	0.52	193	0.50	0	Face bar deflected down by 10 mm.
2	Chevy Blazer – Front	0.78	450	0.47	6	Face bar minorly deformed. 2 mm of shift on both L & R mounting bolts.
3	Chevy Blazer – Front	1.18	1070	0.44	11	Face bar deformed by 10 mm at its center. 5 mm of shift on both L & R mounting bolts.
4	Chevy Blazer – Front	1.41	1597	0.40	21	Face bar deformed by 50 mm at its center. 10 mm of shift on both L & R mounting bolts (to end of slots).
5	Chevy Blazer – Front	2.16	3928	0.34	88	Face bar fractured & deformed by 150 mm at its center. Both bumper mounting flanges deformed.
17	Buick Park Ave – Rear	0.80	407	0.50	2	No notable damage.
18	Buick Park Ave – Rear	1.22	870	0.56	7	Gap between bumper beam & trunk panel reduced by 2 mm. Scuff marks on top surface of bumper cover (37 mm from trunk lid).
19	Buick Park Ave – Rear	1.90	2180	0.54	6	Gap between bumper beam & trunk panel reduced by total of 6 mm. Air gap between bumper cover & impact absorber increased by 5 mm.
20	Buick Park Ave – Rear	2.11	2824	0.50	12	Gap between bumper beam & trunk panel reduced by total of 11 mm. Air gap between bumper cover & impact absorber increased by total of 10 mm. Both sides of bumper cover flexed outward by 10 mm. Visible gaps between inside edges of frame rails & bumper mounting flanges.
21	Buick Park Ave – Rear	2.40	3224	0.58	11	Gap between bumper beam & trunk panel reduced by total of 13 mm. Air gap between bumper cover & impact absorber increased by total of 50 to 90 mm. Top surface of bumper cover bowed outward. Trunk lid misaligned. Larger gaps between inside edges of frame rails & bumper mounting flanges.

Table B4 – Test Results from 1999 Chevrolet Blazer and 1998 Buick Park Avenue Staged Impacts

Test #	V_c [m/s]	ΔV (Chevy) [m/s]	ΔV (Buick) [m/s]	Absorbed Energy [J]	Restitution (e)	Chevy Bumper Disp. [mm]	Damage Summary
50	1.31	0.82	1.03	748	0.41	0	Chevy – Minor scuff marks on impact strip. Buick – Scuff marks on top surface of bumper cover (16 mm from trunk lid).
51	2.34	1.52	1.78	2176	0.41	5	Chevy – Face bar displaced rearward by 6 mm. L bumper mounting bolt shifted. Buick – Tow hook imprints on bumper cover. Scuff marks on top surface of bumper cover (21 mm from trunk lid).
52	2.92	1.95	2.12	3064	0.39	12	Chevy – Lower face bar deformation. Face bar tilted downward & displaced rearward. Noticeable shift of both L & R bumper mounting bolts. Buick – Gap between bumper beam & trunk panel reduced by 2 mm. Air gap between bumper cover & impact absorber increased by 10 mm. More pronounced tow hook imprints on bumper cover. Top surface of bumper cover flexed upward. Scuff marks on top surface of bumper cover (28 mm from trunk lid).

Table B5 – Analysis Results from Tests #50 to 52

Test #		Referenced Barrier Energy Values			Predicted Values		
		Chevy E_a [J]	Buick E_a [J]	Total Estimated E_a [J]	Restitution (e)	Change in Velocity (ΔV)	
						Chevy [m/s]	Buick [m/s]
50	Min	25	407	432	0.46	0.76	0.86
	Max	193	870	1063	0.42	1.13	1.27
51	Min	450	407	857	0.43	1.03	1.15
	Max	1713	870	2583	0.37	1.66	1.86
52	Min	1070	870	1940	0.38	1.46	1.64
	Max	3310	2643	5953	0.31	2.36	2.66

APPENDIX C – VEHICLE BUMPER CONSTRUCTION

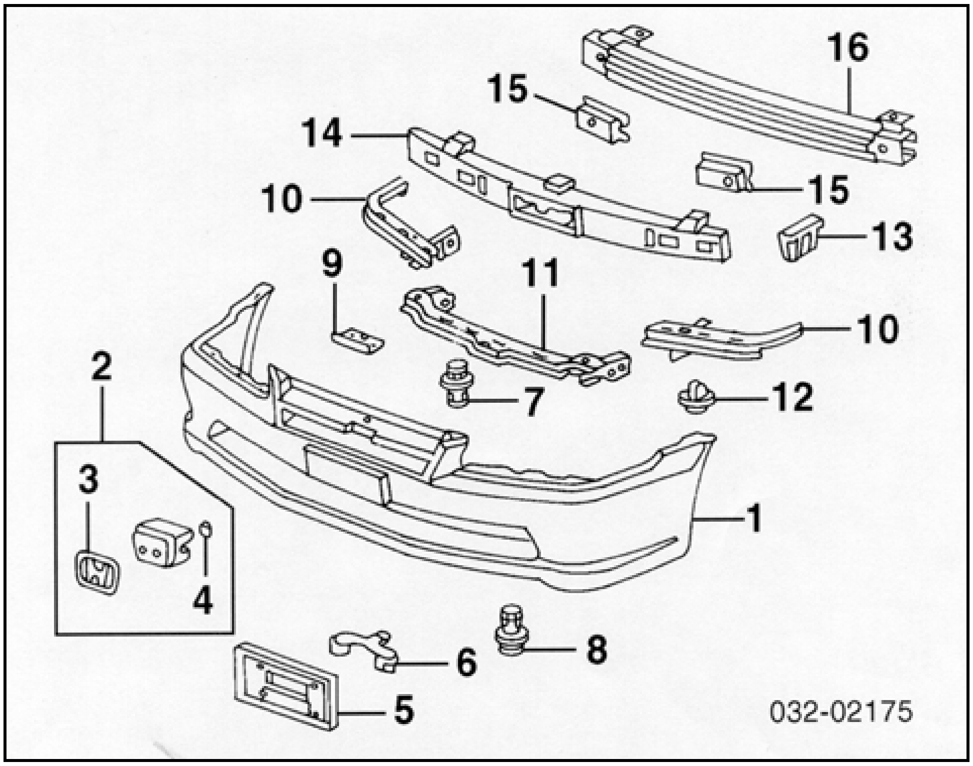


Figure C1 - 1998 Honda Accord LX Front Bumper Construction

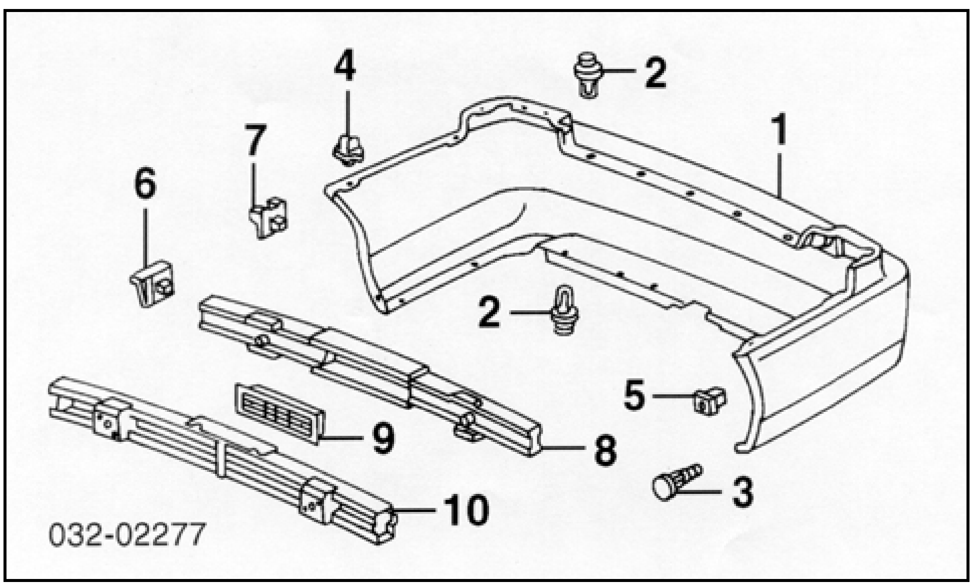


Figure C2 - 1998 Honda Accord LX Rear Bumper Construction

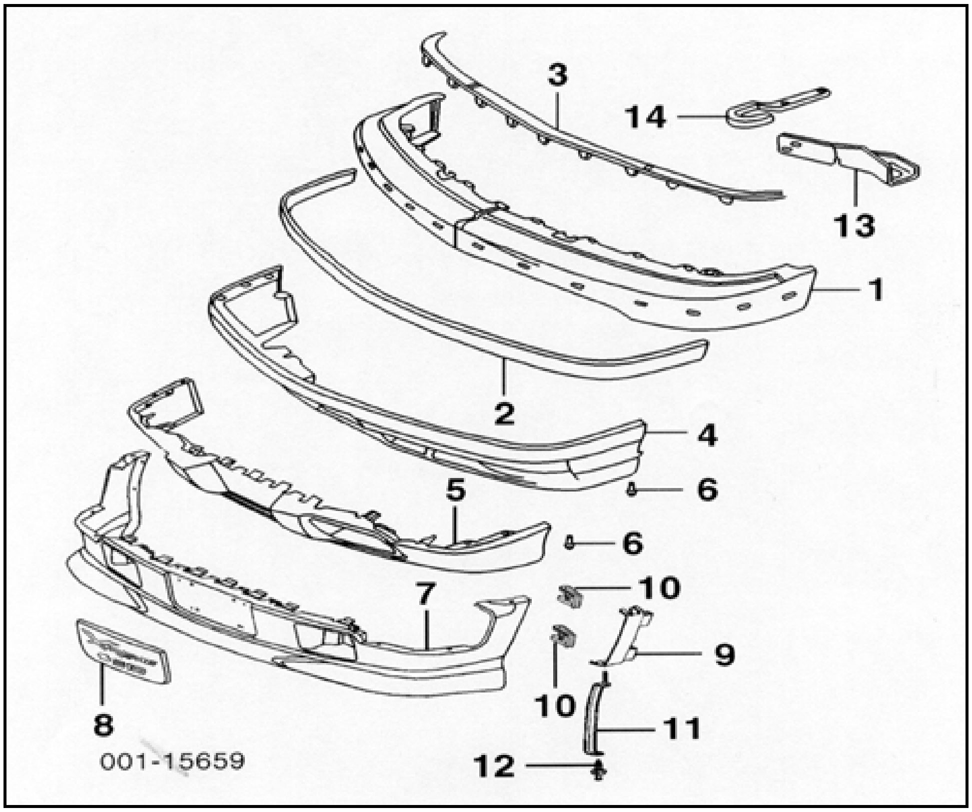


Figure C3 - 1999 Chevrolet Blazer LT Front Bumper Construction

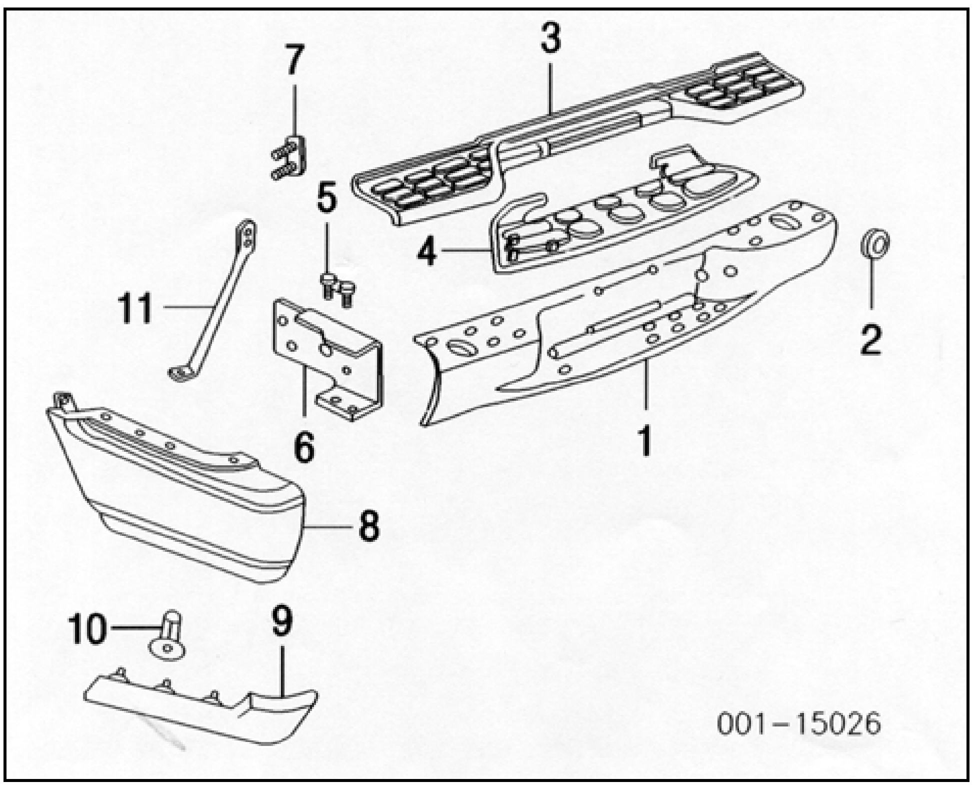


Figure C4 - 1999 Chevrolet Blazer LT Rear Bumper Construction

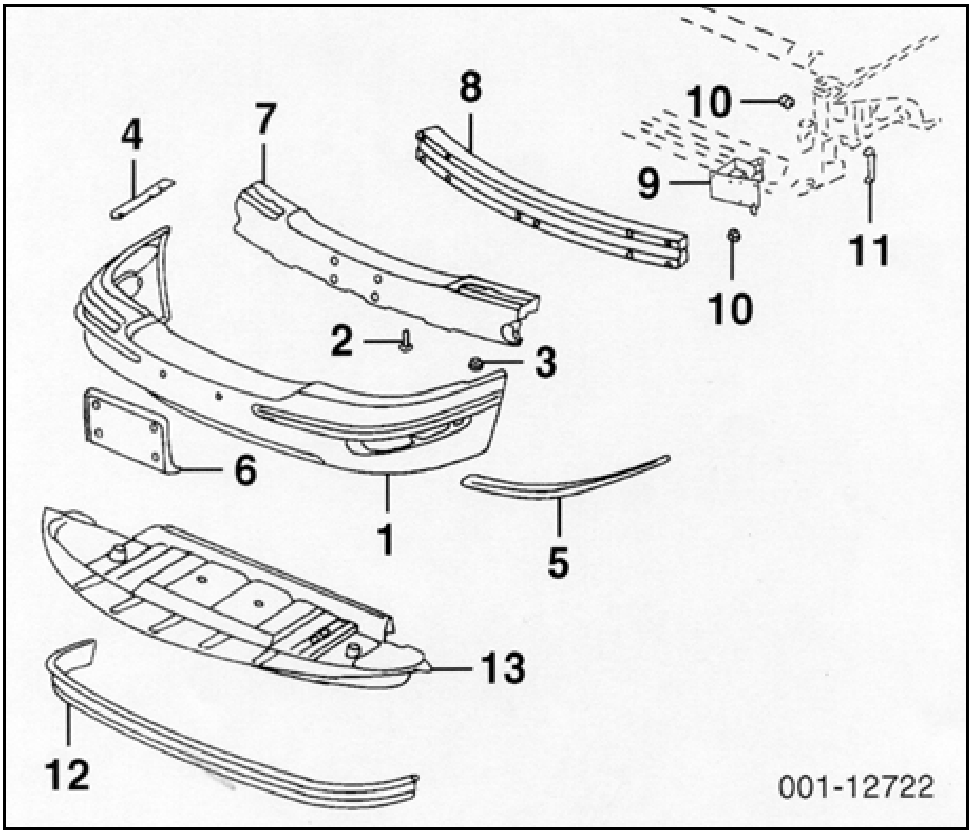


Figure C5 - 1998 Buick Park Avenue Front Bumper Construction

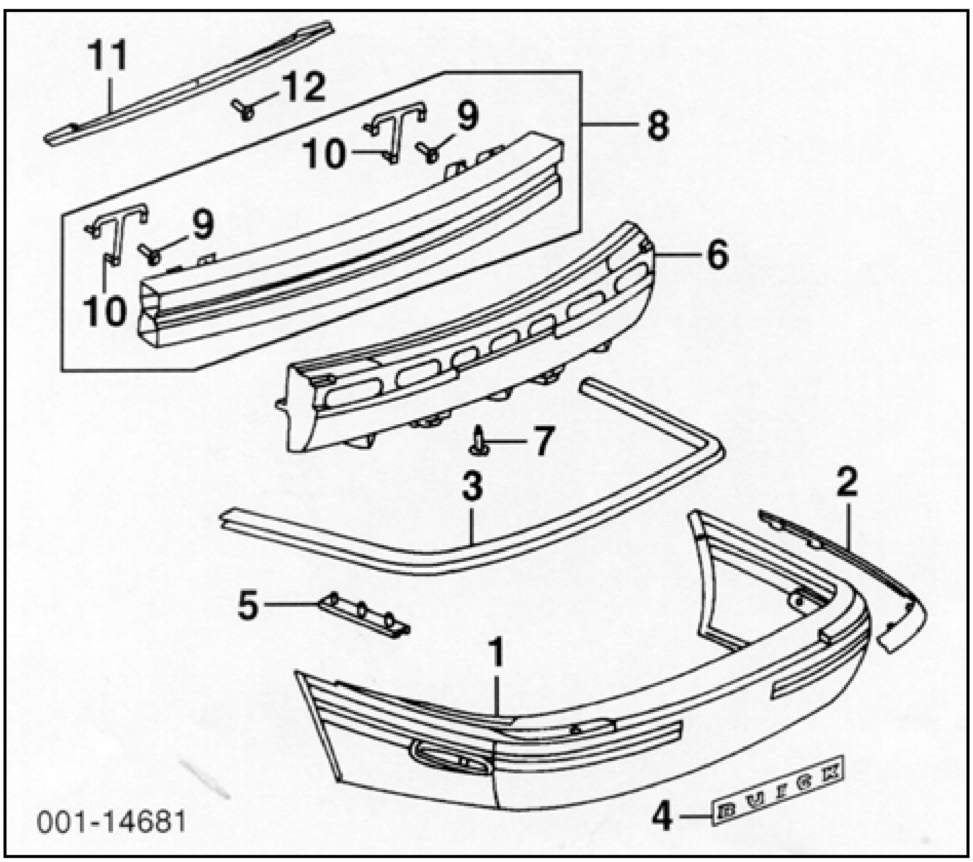


Figure C6 - 1998 Buick Park Avenue Rear Bumper Construction

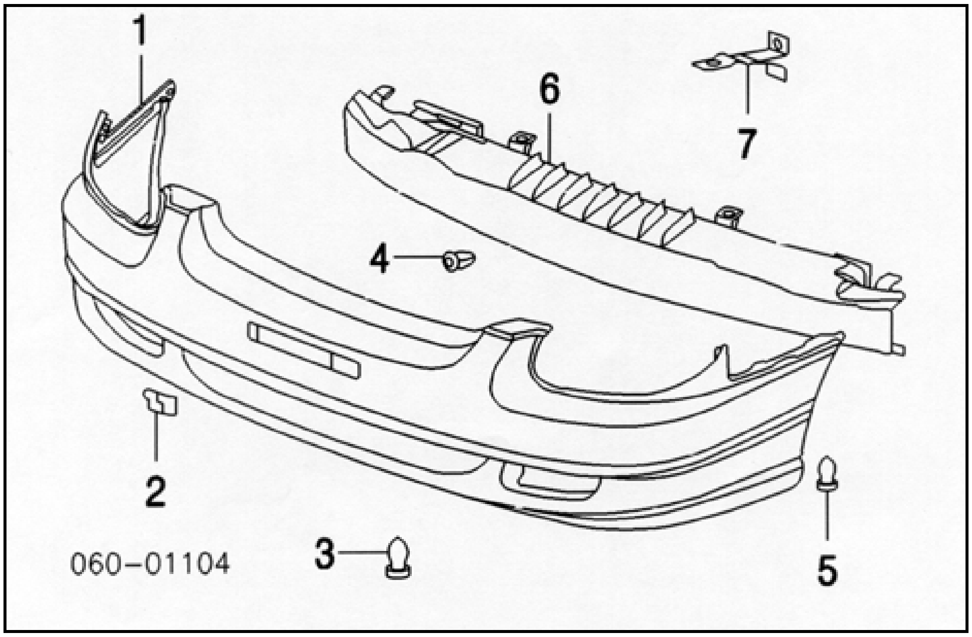


Figure C7 - 1999 Hyundai Sonata GL Front Bumper Construction

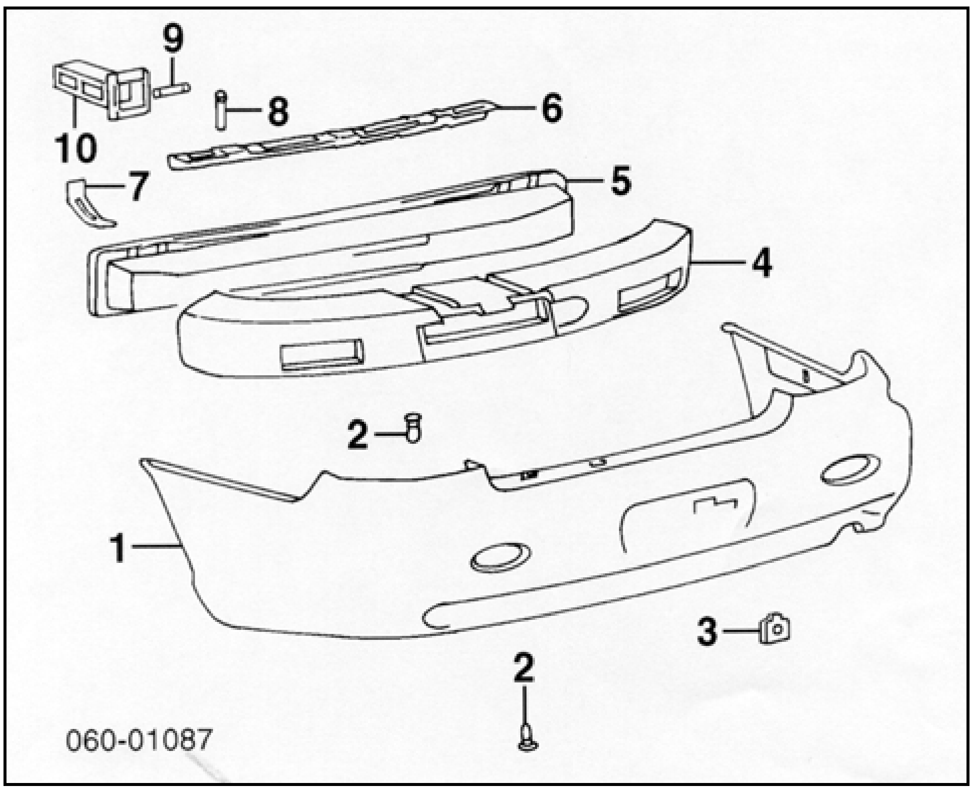


Figure C8 - 1999 Hyundai Sonata GL Rear Bumper Construction

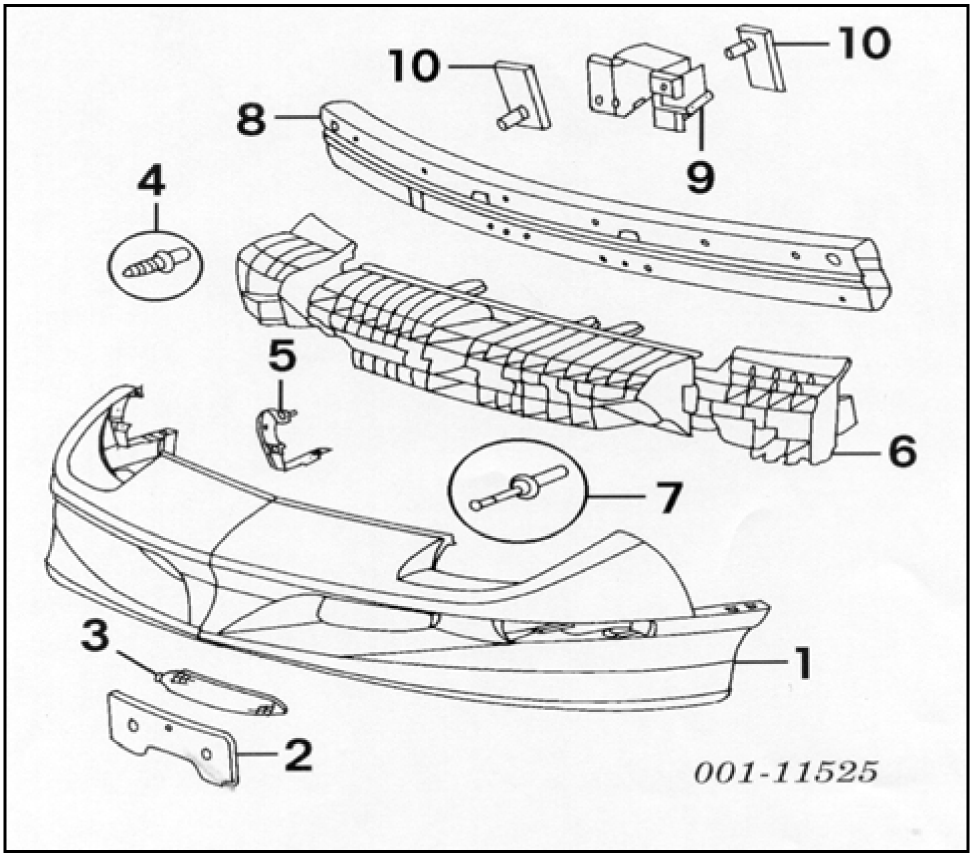


Figure C9 - 2000 Pontiac Sunfire SE Front Bumper Construction

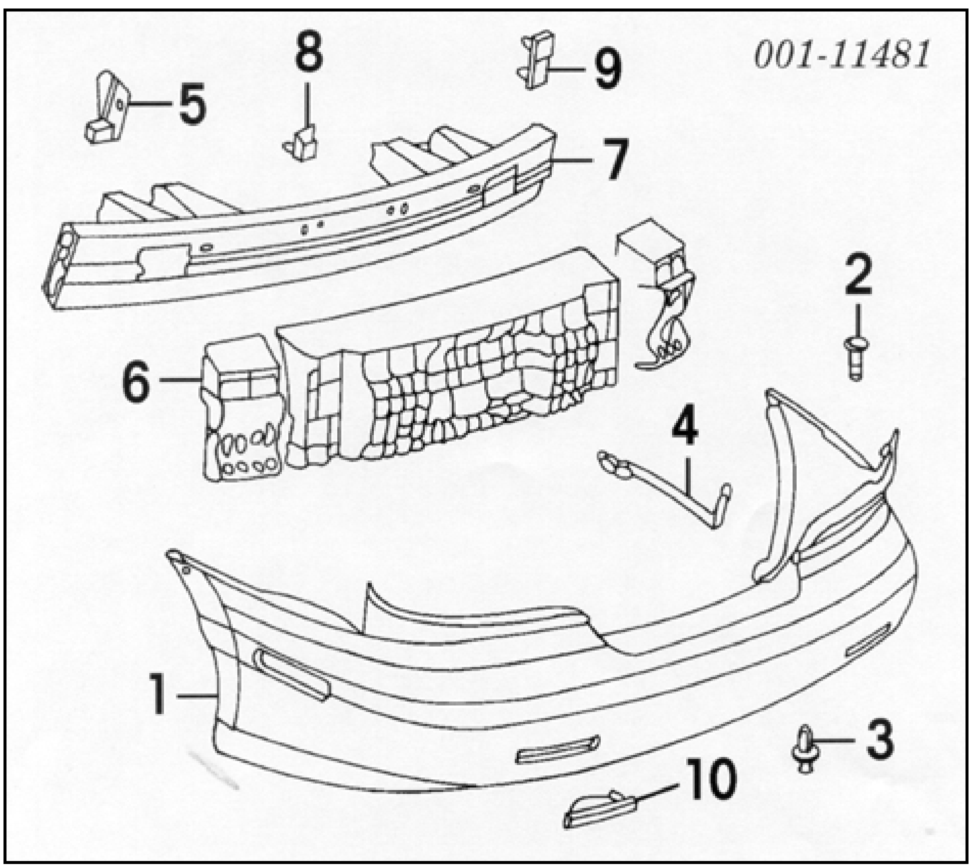


Figure C10 - 2000 Pontiac Sunfire SE Rear Bumper Construction

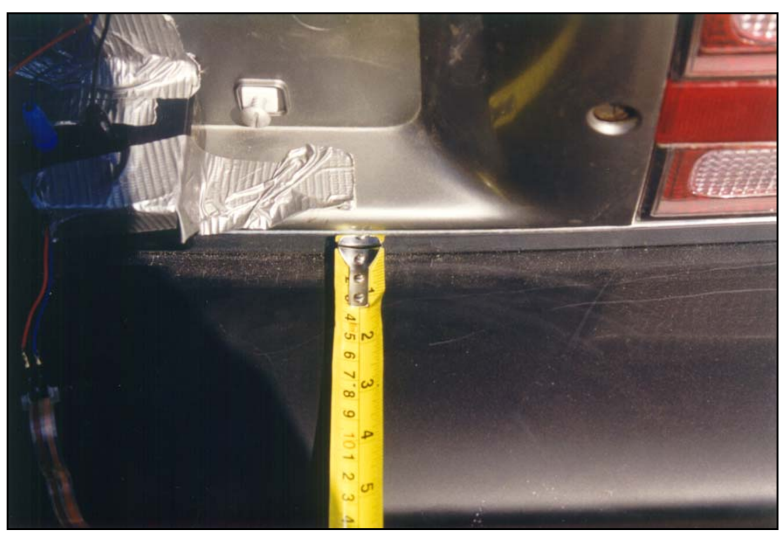
APPENDIX D – PHOTOGRAPHS

TEST #50: 1.31 M/S CLOSING SPEED

Photo D1 – Front of 1999 Chevrolet Blazer exhibits minor scuff marks on impact strip.

Photo D2 – Rear of 1998 Buick Park Avenue.

Photo D3 – Rear of 1998 Buick Park Avenue exhibits scuff marks on top surface of bumper cover.



TEST #51: 2.34 M/S CLOSING SPEED

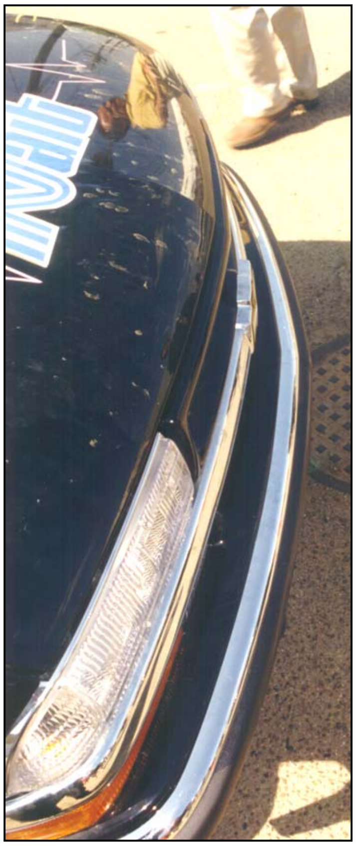


Photo D4 – Front face bar of 1999 Chevrolet Blazer displaced rearward by 6 mm.

Photo D5 – Rear of 1998 Buick Park Avenue exhibits scuff marks and tow hook imprints on bumper cover.

TEST #52: 2.92 M/S CLOSING SPEED

Photo D6 – Front face bar of 1999 Chevrolet Blazer tilted downward and displaced rearward by 12 mm. Lower portion of face bar is also locally deformed.

Photo D7 – Rear bumper cover of 1998 Buick Park Avenue exhibits more pronounced tow hook imprints and is flexed upward. Reinforcement beam and impact absorber displaced forward.