

Computer Simulation of Staged Motorcycle-Vehicle Collisions Using EDSMAC4

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ABSTRACT

The use of computer simulation to analyze motorcycle-into-vehicle collisions is examined and presented. The software program EDSMAC4 within the HVE-2D suite, developed for the simulation of vehicle-to-vehicle collisions, is extended in this study to the analysis of collisions between motorcycles and other vehicles. Simulation results are compared to the results of the series of full-scale staged collisions between motorcycles and passenger vehicles previously published in SAE paper 2002-01-0551, "Seventeen Motorcycle Crash Tests Into Vehicles and a Barrier" by Adamson, et. al.

The rest positions, damage ranges, and speed changes of the test vehicles in the simulations and those in the full-scale tests are presented in numerical and graphical formats. This effort achieved good to excellent correlation between the simulated and test results, thereby providing support for the use of this simulation technique for the type of motorcycle-vehicle collisions examined in this study. In the set of 10 crash tests analyzed, 10 motorcycles moving at speeds between 25 and 49 miles per hour were guided into 2 stopped passenger vehicles. The simulations of these full-scale tests calculated the rest locations of the test automobiles to within approximately 1 foot or less in 7 out of the 10 tests, the changes in the automobile headings to within 4 degrees in all 10 of the tests, the automobiles' speed changes to within 2 ½ miles per hour in 8 of the 10 tests, the motorcycle speed changes to within 3 miles per hour in 7 out of the 10 tests, and the average automobile damage depths to within 2 inches in 7 out of the 10 tests.

INTRODUCTION

Accident reconstructionists are sometimes called upon to investigate an accident in which a motorcycle collided with a passenger car or other vehicle. Reconstructing such an accident can involve evaluating the interaction

of the two-wheeled vehicle and its unrestrained rider with an enclosed passenger or commercial vehicle. This type of accident may involve a motorcycle which is upright or sliding on its side at the moment of impact, and may involve the separation of the rider from the motorcycle prior to or during the collision between the vehicles.

In this type of accident, traditional accident reconstruction techniques such as momentum and energy analyses are subject to the above factors, as well as the challenge in quantifying separation angles, the disparity in weight between the two vehicles, and data regarding vehicle-to-ground friction coefficients.

In order to better enable the reconstruction of motorcycle versus vehicle accidents, a class of such accidents involving the documented post-impact motion of a vehicle impacted by a moving motorcycle is examined with regard to viability for reconstruction via computer simulation. Ideal candidates for simulation would include those accidents where the impact and rest locations of the struck vehicle, the struck vehicle's post-impact path of travel, and the location and depth of damage to the struck vehicle are documented. Accidents involving lesser documentation may also benefit from such a technique.

In this paper, the reconstruction of such types of accidents via computer simulation is examined via simulation of published crash tests.

SIMULATION STUDY

A series of staged motorcycle collisions was presented in the 2002 paper "Seventeen Motorcycle Crash Tests into Vehicles and a Barrier" by Adamson, et. al. (1). Seven of these tests involved a moving motorcycle being guided into a concrete barrier and ten of these tests involved motorcycles colliding with a stopped passenger vehicle. The impact speeds of the motorcycles and the impact and rest positions of the

barriers, cars, and motorcycles were well-documented, and all of the vehicles were equipped with data acquisition equipment. The reader is invited to review reference (1) for further details regarding these tests. The vehicle configurations for each of the 10 motorcycle-into-vehicle tests are provided later in this paper.

In the current study, the computer program EDSMAC4 v6.40, developed by Engineering Dynamics Corporation (2), was used to simulate these full-scale collisions. EDSMAC4, developed from the public domain program SMAC produced by Calspan for NHTSA, includes the ability to model collisions between multiple multi-axle and articulated vehicles each having zones of varying crush stiffness around their periphery (3).

EDSMAC4 is a yaw-plane analysis in which the vertical translation, roll, and pitch degrees of freedom are not considered, although weight transfer among the vehicles' wheels is included. Such a model is valid for a large class of vehicular accidents in which simulating vehicle rollover is not required. EDSMAC4 has the ability to model the motion of individual vehicles having two or three axles and four to twelve wheels, as well as combination vehicles with articulated connections and multiple axles and wheels. EDSMAC4 is a planar analysis which does not explicitly model a two-wheeled vehicle, and so does not simulate the tipover regime of motorcycle motion. Much has been published on the SMAC programs and its iterations, including EDSMAC4, and the reader is invited to refer to previously published literature (3),(4),(5).

VEHICLE MODELS

For this study, a two-wheeled vehicle was modeled in EDSMAC4 by generating a four-wheeled vehicle in which the left side and right side tire-ground contact points are a very short distance apart. It was hypothesized that such a narrow-trackwidth vehicle model would not significantly affect the simulation of the collision, since the impact forces between the motorcycle and the other vehicle will be very much larger than expected tire-ground forces. Further, because the parameter of interest in analyzing many motorcycle-versus-vehicle accidents is the impact speed of the motorcycle, and because the post-impact motion of a motorcycle is usually three-dimensional in nature, a refined simulation of the post-impact motion of the motorcycles is not considered in this study.

In the Adamson motorcycle crash tests, the test motorcycles were guided into the barriers and target vehicles in an upright attitude and in a direction approximately perpendicular to these targets. Accordingly, no pre-impact maneuvering was considered in this simulation study. Where quantifying the pre-impact maneuvering of the motorcycle is of interest, such a narrow trackwidth motorcycle model may not be appropriate, as weight transfer between the left and right tires during a turning maneuver may result

in large vertical tire forces as a result of the large ratio between the height of the simulated motorcycle center of gravity and its half-trackwidth.

Dimensions and Inertial Properties

The motorcycles involved in the Adamson tests were all Kawasaki KZ 1000 Police models of model years ranging from 1989 to 1993. The weight of each individual motorcycle was documented and presented in the Adamson paper. The motorcycles were guided into various locations along a concrete barrier and along two stationary target vehicles – both 1989 Ford Thunderbirds which were also weighed by the researchers.

Published dimensional data (6) were used to create computer models of the two Ford Thunderbirds for use in EDSMAC4. Yaw inertias for the simulated Fords were set as the average of two values calculated from the methodologies described in references (7) and (8).

For the motorcycles, four-wheeled vehicles with the same weights and wheelbases as the full-scale motorcycles were created (9). A trackwidth of 0.02 inches was selected to model the two-wheeled nature of the full-scale motorcycles. An overall width of 18 inches was used as a representation of the motorcycles' physical width at their midsection and fairings. Such a width would also reasonably approximate the mechanics of specific motorcycle-into-vehicle collisions in which the front wheel of the motorcycle articulates during the collision sequence and brings a greater dimension of the motorcycle's structure to bear against the struck vehicle than just the width of the motorcycle's front tire. Computationally, the selection of this width dimension also avoided the simulation of excess penetration into the test cars by the motorcycles in the computer runs. As is presented in the remainder of this paper, such an estimate resulted in simulated vehicle motions, damages, and speed changes which were consistent with those measured in the full-scale tests.

Yaw inertias for the motorcycles were calculated based on the measured weights of the motorcycles and the presumption of a yaw inertia similar to a parallelepiped of width and length the same as that of the test motorcycles via the equation

$$I_{yaw} = \frac{1}{12} \times m \times (OAW^2 + OAL^2) \quad [1]$$

where

- m = mass of test motorcycle
- OAW = overall width of test motorcycle
- OAL = overall length of test motorcycle

The EDSMAC4 Vehicle Data page in Figure 36 provides a listing of the dimensional data of the vehicles for a

typical simulation run, in this case for Test 8. Figures 1 and 2 depict the exterior geometries of the simulated Fords and motorcycles.

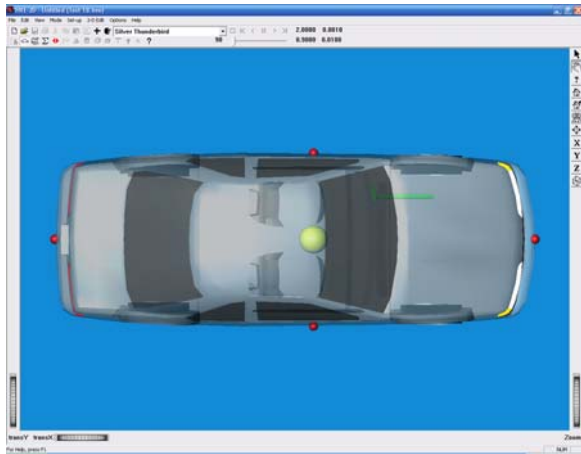


Figure 1 - Geometric model of Ford Thunderbird.

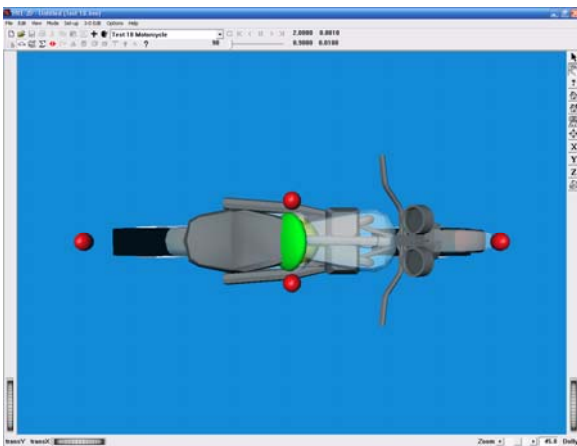


Figure 2 - Geometric model of motorcycle.

Tire Data

Tire-road friction data was measured by the researchers in the Adamson study as being 0.72 and this value was employed in the computer simulations.

Tire cornering stiffness data for the Fords was based on that provided in the HVE database, which is based upon automobile tire test data. For the motorcycles, front and rear cornering stiffnesses were derived from motorcycle tire test data presented in reference (10).

Crush Stiffnesses

The Fords' resistances to deformation were based on published crash test data (11), which suggested the crush stiffness values given in Table 1 for the front, sides, and rear of the Ford Thunderbirds. The reader is referred to references (12) and (13) for the source and derivation of these stiffness values.

These baseline stiffness coefficients for the Ford Thunderbird were developed from fixed and moving

barrier crash tests which involve barrier contact with broad regions of the car's structure, such as body panels. The motorcycle impacts in this study often involved motorcycle contact with narrower and in some cases expectedly stiffer regions of the cars, including the regions near the axles, door sills, roof pillars and bumper attachment points.

Vehicle Surface	A (lb/in)	B (lb/in/in)
Front	252	79
Side	97	55
Rear	257	82

Table 1 - Baseline values of Ford Thunderbird stiffness coefficients

During the simulation runs, the stiffness values of the Fords were thus increased from their baseline values to levels 1 ¼ to 3 times their baseline values in order to better match the damage patterns documented on the test vehicles and to reflect the nature of the contact between the narrow motorcycles and the impact locations on the test automobiles.

Table 2 provides a listing of the locations on the test Fords which were impacted by the test motorcycles and the factors by which the stiffness coefficients of each of the test cars were increased in the simulations. The adjustments to the Ford stiffnesses did not significantly affect the trajectories of the simulated Fords.

Test Number	Vehicle Surface Contacted	Stiffness Multiplier
8	Ahead of left rear wheel well	2 ½
9	Aft of left rear wheel well	2
10	Rear bumper; right of centerline	1 ¼
11	Right front wheel	2 ½
12	Right front wheel	3
13	Middle of right door	2 ½
14	Front bumper; right of centerline	1 ¼
16	Ahead of right front wheel well	2 ½
18	Front bumper; right of centerline	1 ¼
19	Aft of left rear wheel well	3

Table 2 - Multiplication factors used for Ford Thunderbird stiffness coefficients

The crush resistances for the front ends of the simulated motorcycles were determined by analyzing the results of the seven motorcycle-into-barrier tests in the Adamson

paper. As depicted in Figure 3, the relationship between barrier impact speed and reduction in wheelbase of the test motorcycles is reasonably linear in nature.

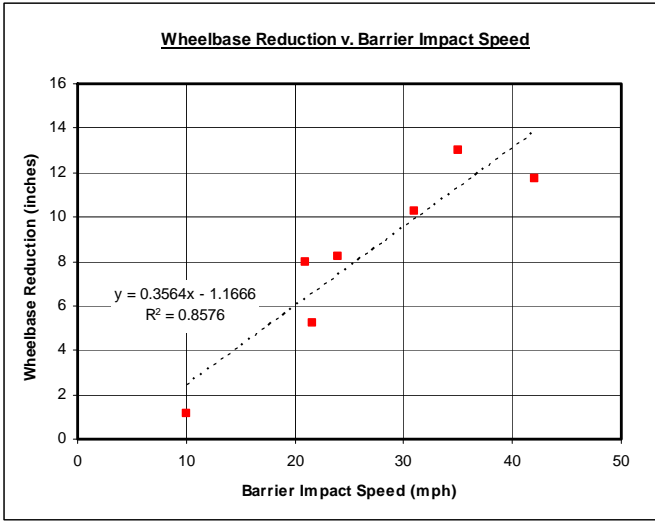


Figure 3 - Reduction in motorcycle wheelbase versus barrier impact speed (Adamson).

Treating the reduction in wheelbase in these frontal collisions as being equivalent to the motorcycles' average frontal crush depth, and assuming a linear force-deflection relation for the motorcycles' front structures such as in the model used in the CRASH family of computer programs (14) as well as in EDSMAC4, the crush energy versus damage depth relation for the test motorcycles was developed using the standard relation described in references such as (14), (15) and (16):

$$\sqrt{\frac{2 \times CE}{L}} = \sqrt{B} \times X_c + \frac{A}{\sqrt{B}} \quad [2]$$

where

- CE = crush energy absorbed by motorcycle during barrier test
- L = effective contact width of motorcycle
- B = slope of force-versus-crush curve ("B" stiffness coefficient)
- X_c = residual crush depth of motorcycle (presumed equivalent to reduction in wheelbase)
- A = force at zero crush depth ("A" stiffness coefficient)

The crush energies absorbed by the motorcycles' front structures in the barrier tests were calculated by determining the kinetic energies of the motorcycles at impact and subtracting the frictional energy dissipated by the concrete barriers (almost all of which slid a small but measured distance during the tests) and then subtracting the motorcycles' kinetic energies after separating from the barriers, and which was

documented by the Adamson researchers via the measurement of the motorcycles' change in speed during the barrier collisions.

Thus,

$$CE = KE_{initial} - FE_{barrier} - KE_{separation} \quad [3]$$

where

$$KE_{initial} = \frac{1}{2} \times \frac{W_{mc}}{g} \times V_{impact}^2 \quad [4]$$

$$FE_{barrier} = W_{barrier} \times \mu \times d \quad [5]$$

$$KE_{separation} = \frac{1}{2} \times \frac{W_{mc}}{g} \times V_{separation}^2 \quad [6]$$

$$V_{separation} = V_{impact} - \Delta V \quad [7]$$

and where

- $KE_{initial}$ = initial kinetic energy of motorcycle
- $FE_{barrier}$ = frictional energy dissipated during barrier sliding
- $KE_{separation}$ = kinetic energy of motorcycle at moment of separation from barrier
- W_{mc} = motorcycle weight
- V_{impact} = speed of motorcycle at time of impact with barrier
- $W_{barrier}$ = weight of concrete block barrier (measured to be 11,080 lb)
- μ = friction between barrier and pavement (measured to be 0.40)
- d = post-impact slide distance of concrete barrier at CG (presumed to be average of barrier displacement measured at either end of barrier)
- ΔV = motorcycle change in speed during barrier impact

Equation [2] is plotted in Figure 4 for the results of the 7 motorcycle-into barrier tests, where the entity

$$\sqrt{\frac{2 \times CE}{L}}$$

is termed the "Energy of Crush Factor" (ECF). The stiffness coefficients "A" and "B" for the fronts of the motorcycles were then determined from a linear regression of the experimental data plotted in Figure 4. The mathematical equation defining the trend line is indicated on the plot. From equation [2], it can be seen that the stiffness coefficients "A" and "B" can be derived by equating equation [2] to the mathematical relation that defines the trend line. This analysis results in an "A"

coefficient of 333 lb/in and a “B” coefficient of 155 lb/in/in. These values of stiffness were used for the front of the motorcycle in the simulation runs.

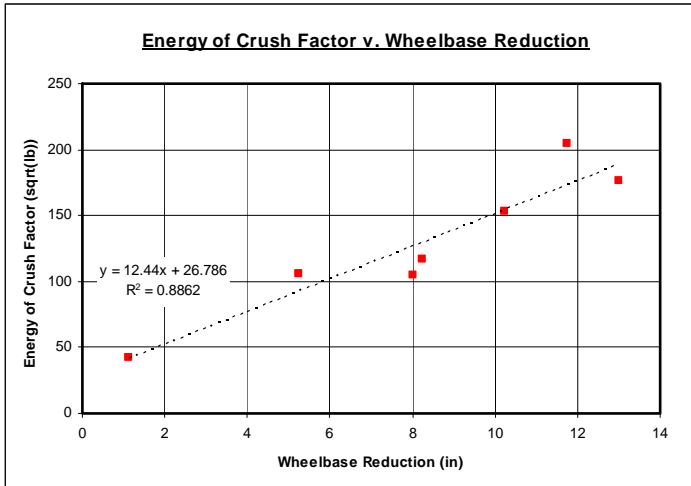


Figure 4 - Plot of Energy of Crush Factor for motorcycles in barrier impact tests.

For reference, these stiffness values are compared with the suggested frontal stiffness values for the generic vehicle classes suggested in reference (17). The above values for the front of the motorcycles are most similar to the values suggested for the front of a generic Class 2 passenger van, A = 359 lb/in and B = 155 lb/in/in, which are the stiffest of the suggested values for all of the non-commercial vehicle classes presented in that paper. This finding would indicate that the stiffness of the front structure of a motorcycle can approach that of a much stiffer, heavier vehicle. Such a finding may be indicative of the mechanics of many motorcycle-into-vehicle collisions in which the collision force is rapidly transmitted to the stiffer main structure of the motorcycle upon initiation of contact between the front tire and the motorcycle’s engine block during a frontal collision.

The same stiffness values were also employed for the left and right sides of the simulated motorcycles, the structures of which are dominated by the engine and transmission case, and which are hypothesized to be at least as stiff as the front wheel and fork assemblies of the test motorcycles.

Driver Control Inputs

Driver control inputs for the cars and motorcycles were generally similar in all of the simulation runs.

For the Fords, the rear wheels were locked and the front wheels given a rolling resistance value of 1% of available friction to reflect the conditions of the rear-wheel-drive test vehicles, which had their automatic transmissions in “Park” and the parking brakes released. A small steering input was provided for the Fords in Tests 10 and 18 in order to simulate the heading angle change experienced by the Fords during these collisions. As discussed in the Adamson paper, the

Fords’ front wheels were unconstrained against changes in steering angle during the tests.

No driver inputs were given to the motorcycles. Although it was initially hypothesized that brief application of the front brakes of the motorcycles might be required to simulate the cessation of rotation of the front tires of the test motorcycles in these frontal collision tests, during initial simulation runs, it was found that significant application of the front brakes of the simulated motorcycles during the collision reduced the force transmitted to the target vehicles, resulting in post-impact travel distances for the target vehicles which were smaller than those measured during the full-scale tests.

The EDSMAC4 Driver Control Tables page in Figure 37 provides a listing of the driver control input data for the vehicles in a typical simulation run, in this case, Test 8.

Vehicle Initial Positions and Velocities

At the start of the simulation runs, the vehicles were positioned to attain the approximate impact configurations and test speeds as documented in the Adamson study. Small adjustments (within +/- 3 inches) to the motorcycles’ impact locations along the Fords were made until the resulting post-collision rest locations of the simulated cars closely matched those documented in the Adamson paper.

Other Simulation Parameters

With the exception of Test 19, the value for the intervehicle friction coefficient was held at the value suggested by EDSMAC4’s developers, 0.55. In Test 19, this value was reduced slightly to 0.40 to best match the post-impact travel of the test car.

Integration timesteps for the collision phase, separation phase, and trajectory phase were all set to be 0.001 seconds.

SIMULATION RESULTS

The results of the motorcycle-into-car simulations were compared to the test data presented in the Adamson paper with regard to several parameters: the post-impact motion of the Fords, the speed changes of both vehicles, and the damage patterns of both vehicles.

A comparison between the simulation results and the full-scale test measurements regarding vehicle speed changes and the Fords’ at-rest positions is provided in Table 3. Diagrams depicting the simulated and measured positions of the vehicles are provided in Figures 5 through 14, and charts comparing the numerical results of the tests and simulations are provided in Figures 15 through 20.

Test No.	Method	Motorcycle		Ford Thunderbird			Delta-V (mph)
		Impact Speed (mph)	Delta-V (mph)	At-Rest Position			
				X (ft)	Y (ft)	Heading (deg)	
8	Measured	46	38.0	-3.7	0.4	40.0	8.9
	EDSMAC4		43.4	-3.2	0.2	39.7	5.7
9	Measured	39	28.3	-4.6	0.6	54.0	8.3
	EDSMAC4		35.7	-5.2	0.0	58.1	5.9
10	Measured	34	35.0	-4.0	0.8	1.5	4.7
	EDSMAC4		36.7	-3.4	-0.1	1.0	5.1
11	Measured	25	23.1	-0.8	0.0	5.0	2.8
	EDSMAC4		26.6	-0.8	0.1	7.6	3.2
12	Measured	30	27.5	-1.9	0.1	19.0	3.6
	EDSMAC4		30.0	-1.7	0.3	18.1	4.4
13	Measured	42	41.0	-2.1	0.0	-5.0	9.1
	EDSMAC4		43.8	-1.8	0.1	-8.1	5.7
14	Measured	30	33.3	-1.2	0.0	0.0	4.3
	EDSMAC4		32.2	-3.2	-0.1	-1.1	5.5
16	Measured	41	40.0	-8.6*	-3.2*	37.0	4.3
	EDSMAC4		37.3	-2.9	0.8	35.5	5.7
18	Measured	45	42.0	-2.8	0.9	-3.0	7.7
	EDSMAC4		41.8	-4.9	-0.1	-2.6	7.7
19	Measured	49	39.0	-6.3	-0.3	70.0	8.9
	EDSMAC4		39.7	-6.5	0.0	66.2	6.4

Table 3 - Measured test data and results of simulation runs.

* = suspected incorrectly-reported test results.

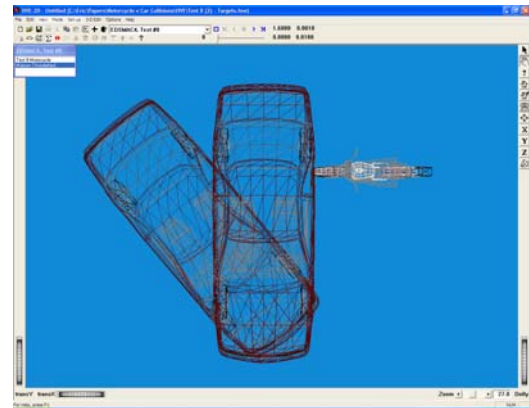
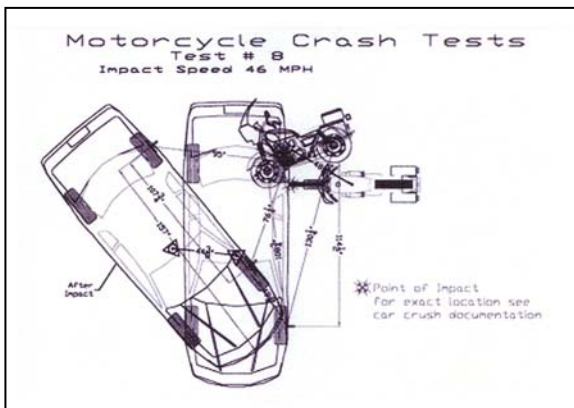


Figure 5 - Measured and simulated vehicle positions – Test 8

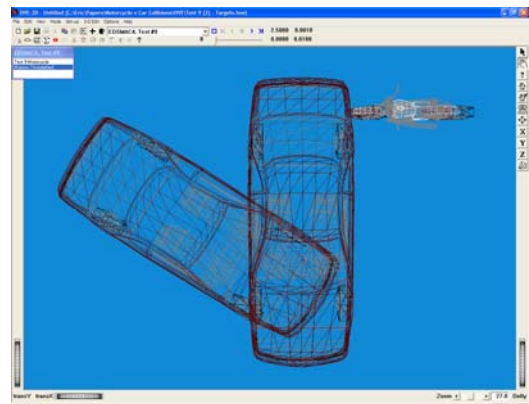
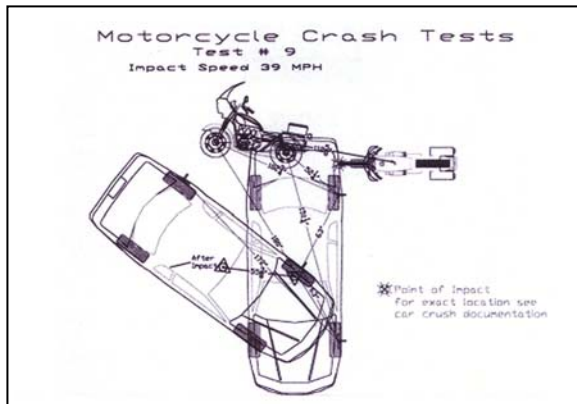


Figure 6 - Measured and simulated vehicle positions – Test 9

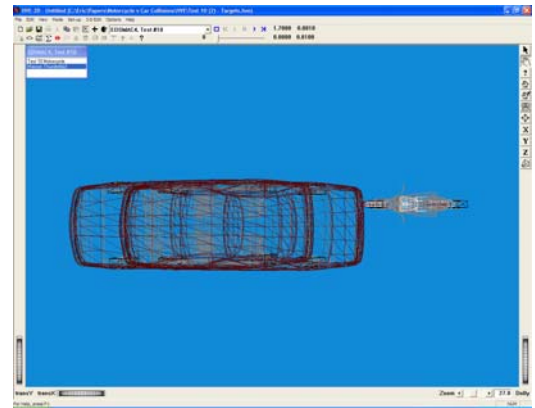
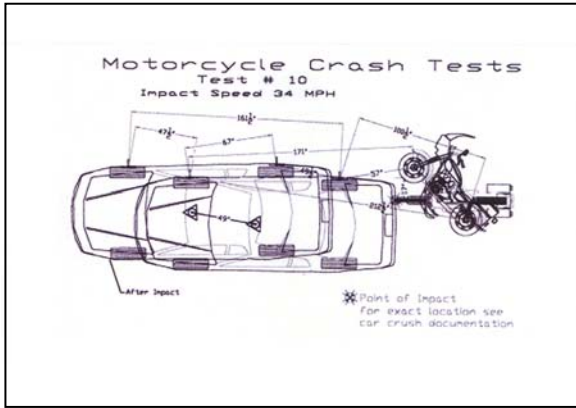


Figure 7 - Measured and simulated vehicle positions – Test 10

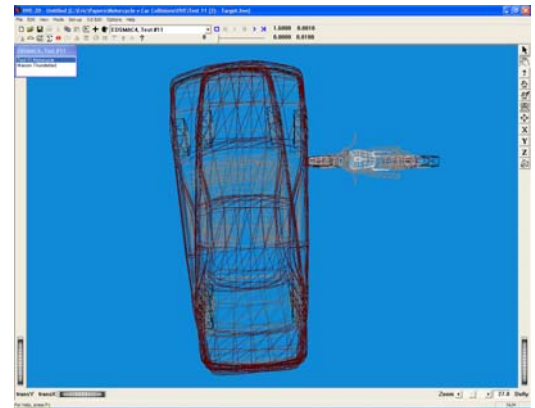
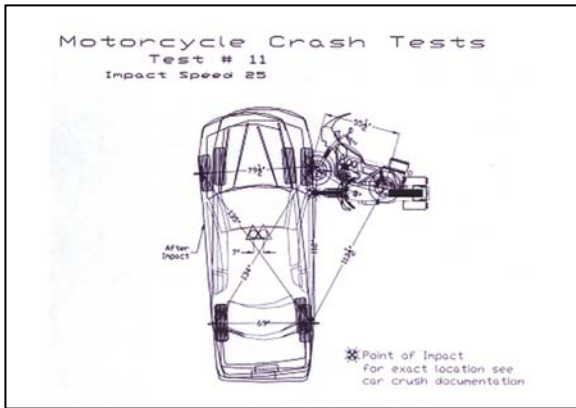


Figure 8 - Measured and simulated vehicle positions – Test 11

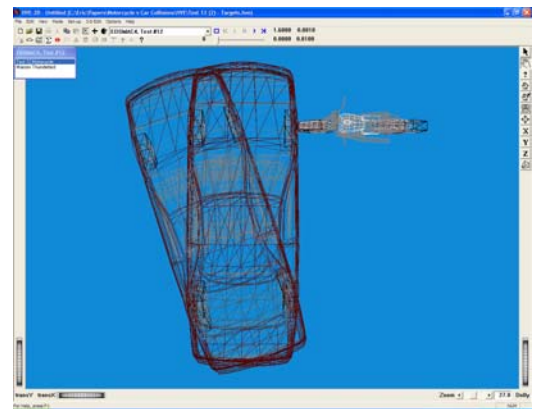
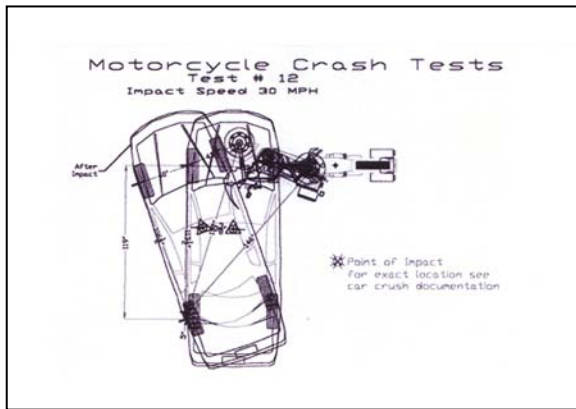


Figure 9 - Measured and simulated vehicle positions – Test 12

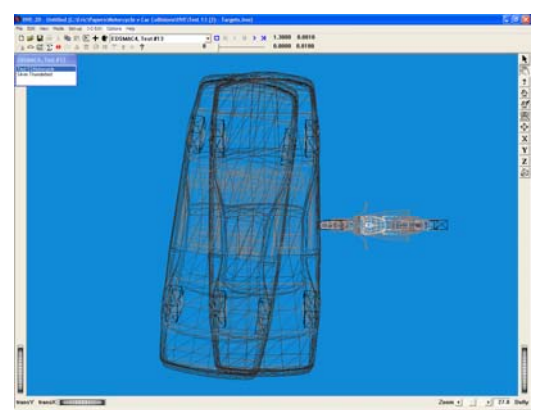
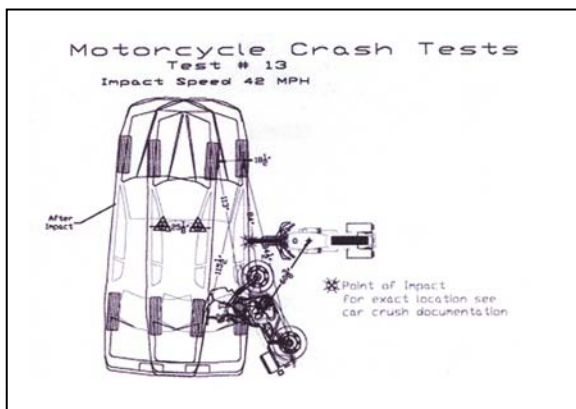


Figure 10 - Measured and simulated vehicle positions – Test 13

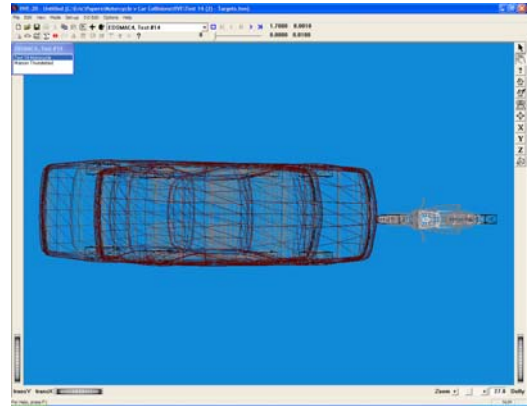
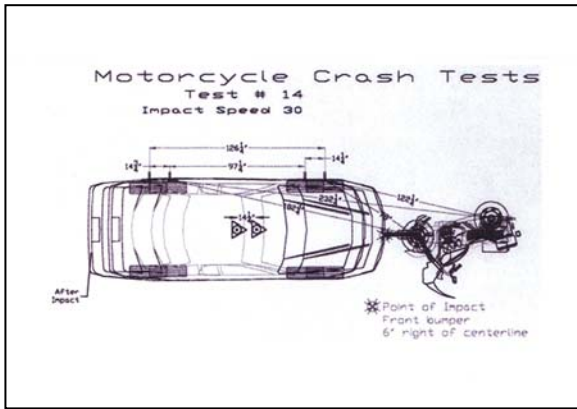


Figure 11 - Measured and simulated vehicle positions – Test 14

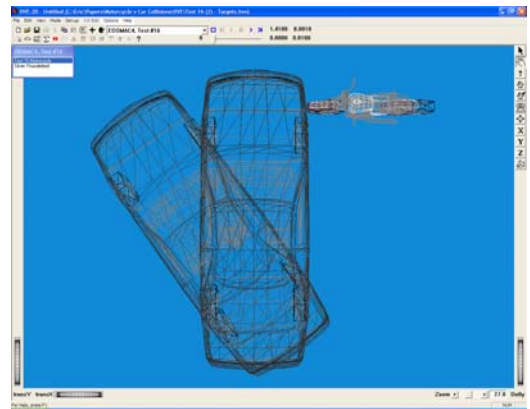
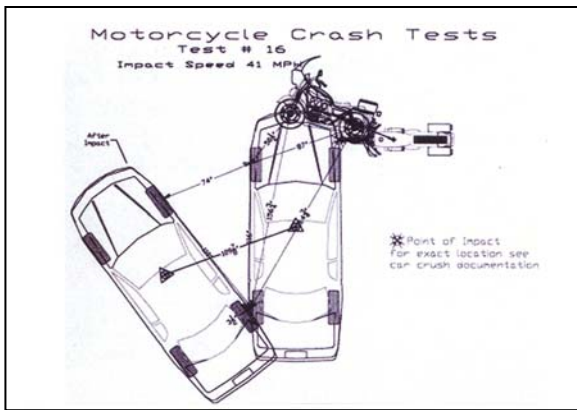


Figure 12 - Measured and simulated vehicle positions – Test 16

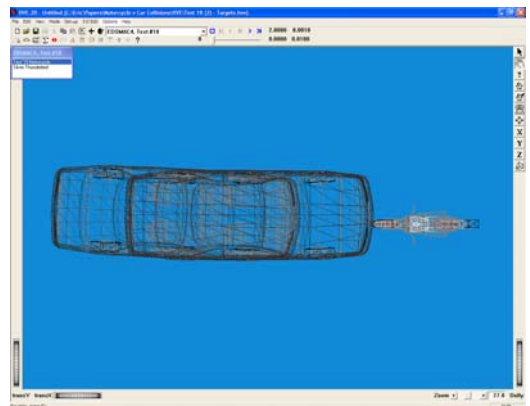
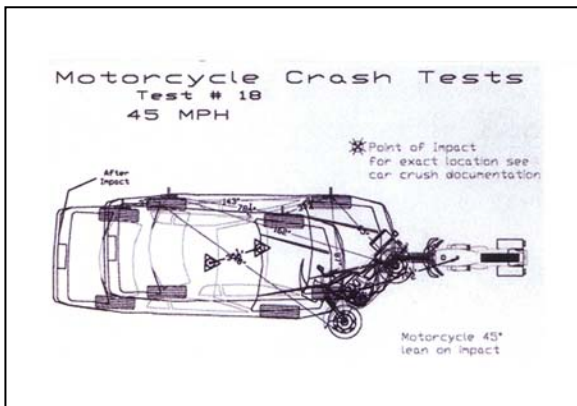


Figure 13 - Measured and simulated vehicle positions – Test 18

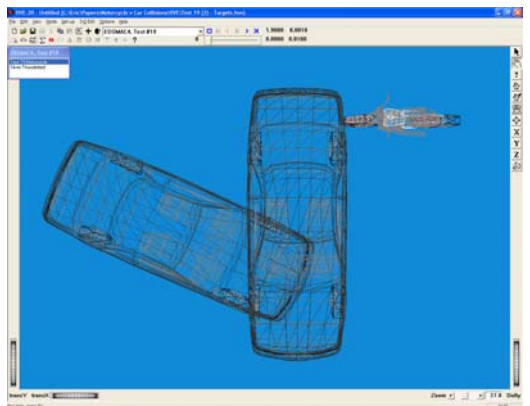
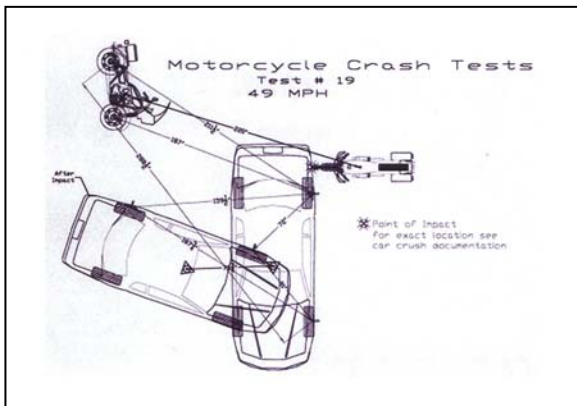


Figure 14 - Measured and simulated vehicle positions – Test 19

AUTOMOBILE POST-IMPACT MOTION

The accuracy of the post-impact motion of the simulated Fords as compared to the test vehicles was evaluated by examining the translation of the target vehicle in world coordinates and the change in heading of the target vehicle between impact and rest. In each simulation run, the Ford's initial location was with its center of gravity at the origin of the world coordinate system and its longitudinal axis aligned along either the X or Y-axis, where the positive X-axis points to the right and the positive Y-axis points down in Figures 5 through 14.

As observed in the tabulated data presented in Table 3 and in Figures 15 and 16, in the majority of the runs, the simulation results closely matched the test results, generally calculating the rest position of the Fords to within 2 feet in X and 1 foot in Y (2 ¼ feet in total travel distance) and to within 4 degrees of heading in all tests, with one notable exception, Test 16.

In Test 16, the Ford's post-impact heading was well-simulated, however, its simulated post-impact rest position was underestimated by almost exactly one car-width.

Given the reasonable fidelity of the simulated at-rest positions of the Fords in all of the other tests, it is suspected that the measured rest position of the Ford in Test 16 was inadvertently offset by one car width. Making such a correction in the reported at-rest position of the car in Test 16 would greatly reduce the difference between the simulated and measured rest position of the car. The suggestion that the rest position of the Ford in Test 16 was mis-measured is further supported via examination of the measured rest position of the Ford in Test 13, a test in which the right side of the Ford was struck at 42 miles per hour near the Ford's center of gravity. This impact resulted in a translation of the Ford's center of gravity by a measured value of only about 2 feet. Given these results, it would thus be unexpected that, in Test 16, upon the Ford being struck at the very right front corner of the car at a similar speed of 46 miles per hour, several feet away from the car's center of gravity (thus, a less central collision than Test 13), the Ford would have translated some 9 feet at its center of gravity, as indicated in the Adamson paper.

VEHICLE SPEED CHANGES

The total changes in speed during the simulated collisions were compared to those measured during the tests. As depicted in Table 3, the simulated delta-V's for the Fords matched the test results to within approximately 3 ½ miles per hour at the largest deviation. In 6 out of the 10 tests, the simulation calculated the Ford delta-V's to within less than 1 ½ miles per hour of the measured test results.

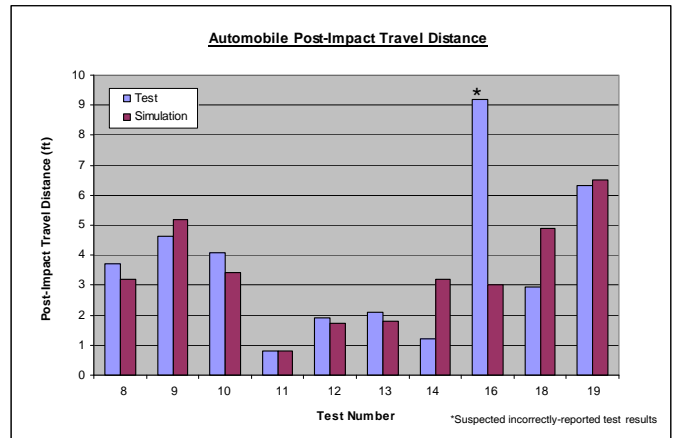


Figure 15

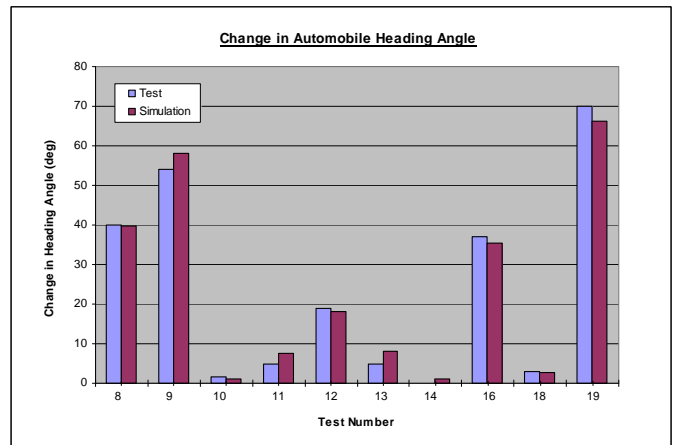


Figure 16

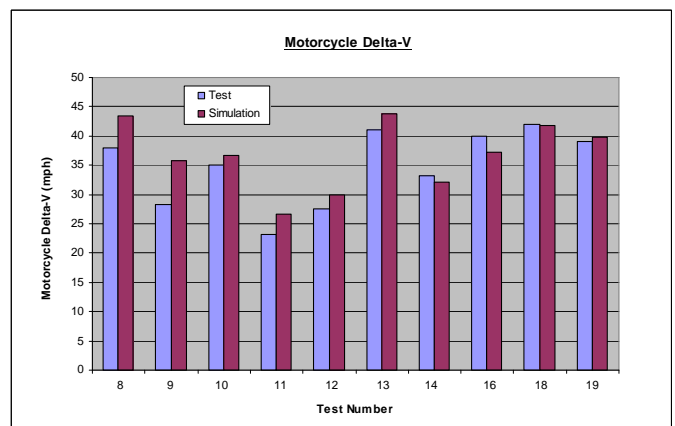


Figure 17

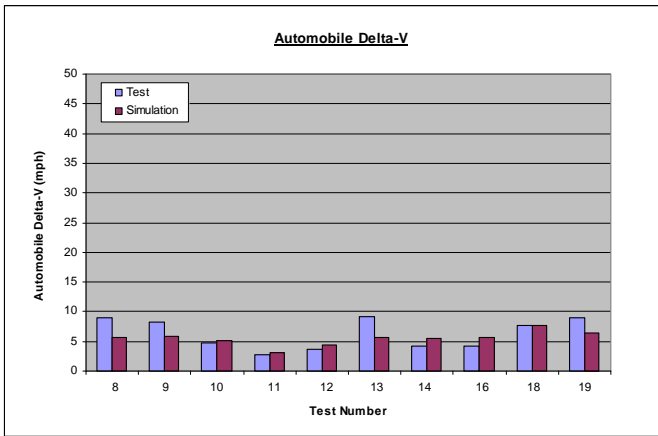


Figure 18

As reported by the original researchers, the measured acceleration data for the test motorcycles exceeded the limits of the on-board instrumentation in half of the tests, and in these cases, the motorcycle speed changes were determined by the Adamson group via a post-impact speed calculated from slide-to-stop energy methods. In spite of this, the simulation calculated the motorcycle speed changes to within 3 ½ miles per hour of the reported value in 9 out of the 10 tests. As expected, given the saturation of the accelerometers in the full-scale tests, the simulated results exceeded the measured delta-V's in 7 of the 10 tests.

Bar chart comparisons between the simulated results and the measured vehicle Delta-V's are provided in Figures 17 and 18.

VEHICLE DAMAGE PATTERNS

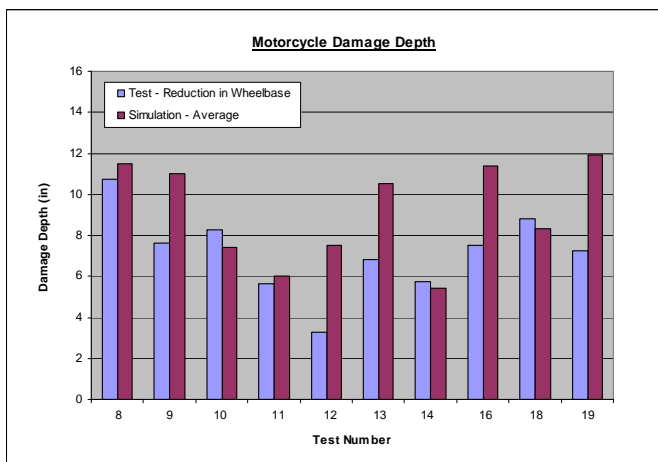


Figure 19

EDSMAC4 generates a damage pattern for a vehicle based upon the deflection of the perimeter of the vehicle's body resulting from the contact between the vehicles and the application of Newton's laws of motion. Although the precise simulation of vehicle damage patterns is less likely to be of interest in an actual accident reconstruction in which the post-impact motion of the struck vehicle is well-simulated, a comparison between the simulated and measured damage patterns for both vehicles was made for each test.

A plot comparing the simulated and test damage data for the Fords is provided in Figure 20. Diagrams comparing the exteriors of the simulated vehicles to the measured crush profiles are presented in Figures 21 through 29.

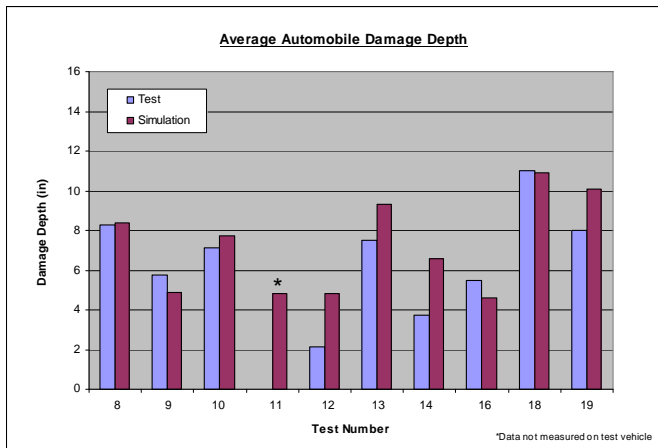
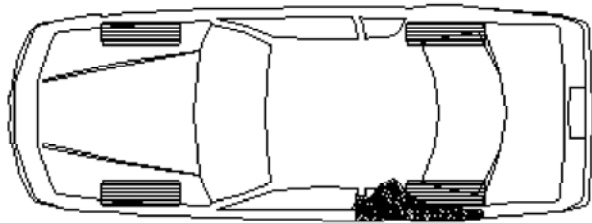


Figure 20

In the case of the test motorcycles, the measured frontal "crush depth" was considered to be equivalent to the reduction in wheelbase, consistent with the development of the frontal stiffness coefficients discussed earlier. In the case of the simulated motorcycles, the frontal crush depth was taken as the average of all reported values on the front of the simulated vehicle, excluding those within 1 inch of the left or right side of the vehicle.

As expected, given the more complex nature of the frontal structures of the full-scale motorcycles versus the homogenous exterior of the simulated motorcycles, the average frontal crush depths of the simulated motorcycles varied from the wheelbase reductions of the test motorcycles by several inches in some cases. Although, as provided in Table 4 and in Figure 19, the average frontal crush depths of the simulated motorcycles matched those of the test motorcycles to within 3 ½ inches in 6 out of the 10 tests.



TEST #08 46 MPH, LEFT REAR, FRONT OF WHEEL WELL

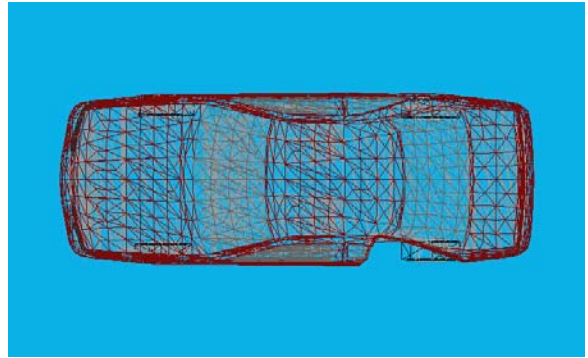
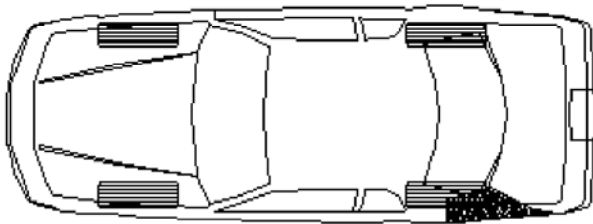


Figure 21 - Measured and simulated vehicle damage – Test 8



TEST # 9 39 MPH, LEFT REAR, BEHIND WHEEL WELL

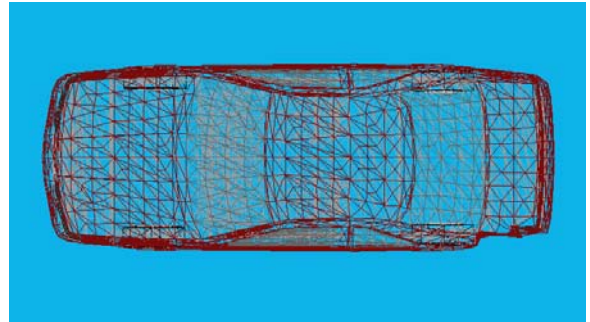
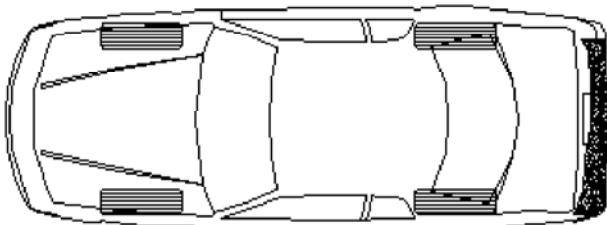


Figure 22 - Measured and simulated vehicle damage – Test 9



TEST #10 34 MPH, REAR, RIGHT OF C/L

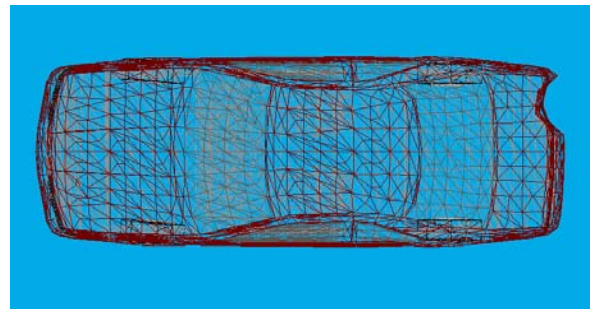
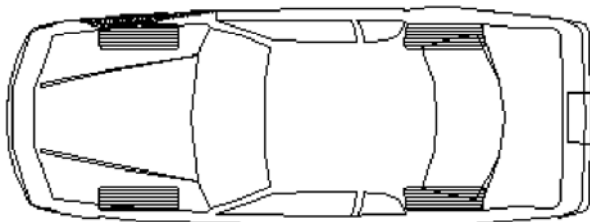


Figure 23 - Measured and simulated vehicle damage – Test 10



TEST #12 30 MPH, RIGHT SIDE, FRONT WHEEL

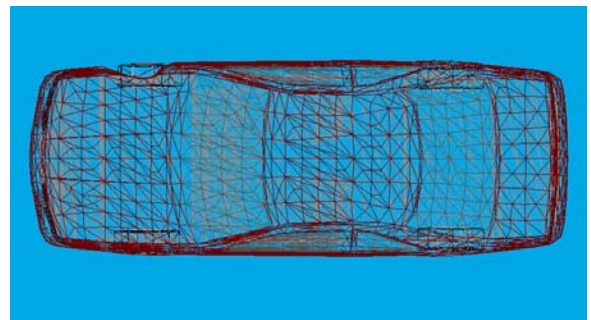
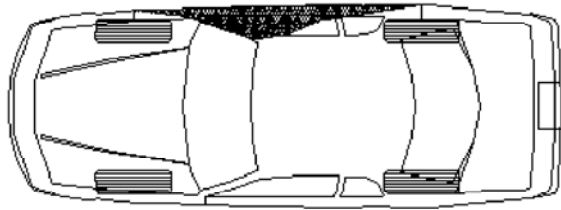


Figure 24 - Measured and simulated vehicle damage – Test 12



TEST #13 42 MPH, RIGHT SIDE

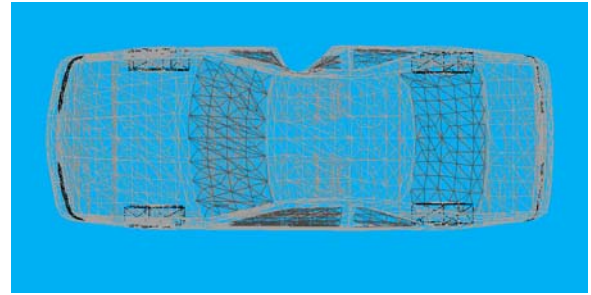
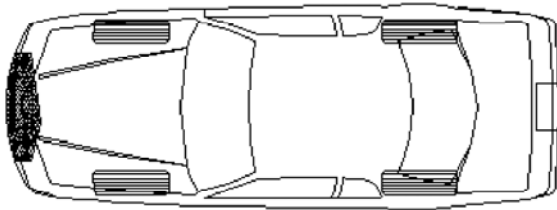


Figure 25 - Measured and simulated vehicle damage – Test 13



TEST #14 30 MPH, FRONTAL

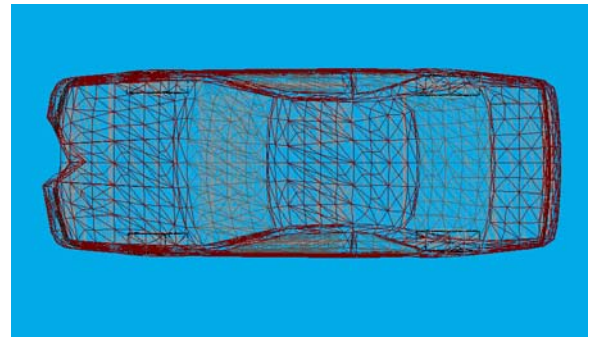
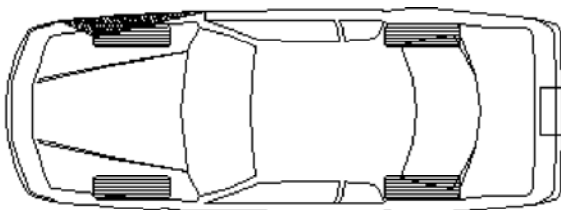


Figure 26 - Measured and simulated vehicle damage – Test 14



TEST #16 41 MPH, RIGHT FRONT WHEEL

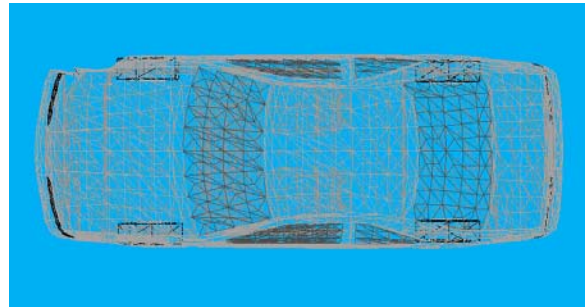
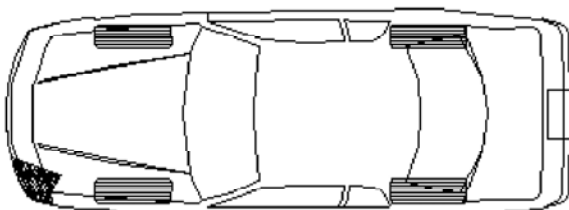
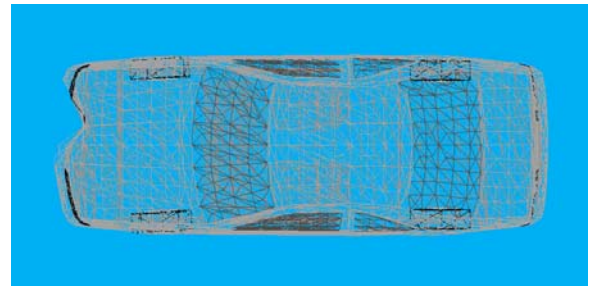


Figure 27 - Measured and simulated vehicle damage – Test 16



TEST #18 46 MPH, FRONT LEFT



Damage predicted based on test configuration in Figure 13

Figure 28 - Measured and simulated vehicle damage – Test 18

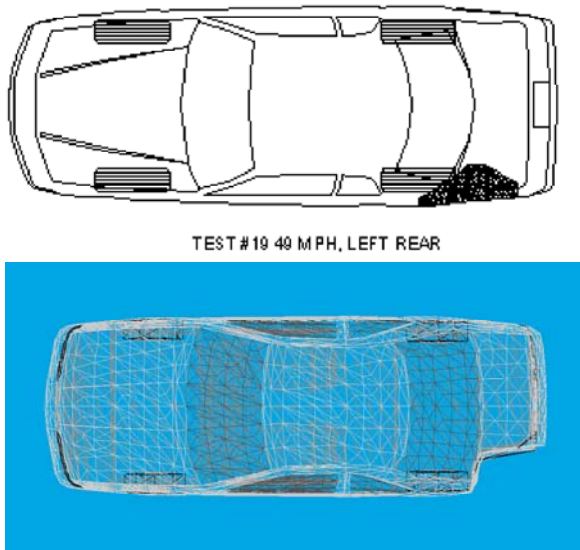


Figure 29 - Measured and simulated vehicle damage – Test 19

In the case of the Ford test vehicles, because damage depths were measured at non-regular intervals, the effective test vehicle crush depths were taken to be half of the sum of the largest and smallest reported crush depths for a particular vehicle. In the case of the simulated Fords, the crush depth was taken to be the average of all reported values. Perhaps due to the more uniform nature of the body panels of the test Fords, the average crush depth of the simulated Fords matched the crush depths of the test vehicles more closely than in the cases of the motorcycles, coming to within 2 inches of the test data in 8 out of the 9 total tests for which damage data was collected. The notable outlier is Test 14, in which the measured damage in this 30 mile per hour impact was given as a single value of only 3.75 inches, but for which the simulated average crush depth was 6.6 inches. A note by the Adamson researchers indicates that the crush measurement for this test was made after the front bumper of the Ford fell off, and thus this dimension may be affected by the absence of the front bumper.

Test No.	Method	Motorcycle		Ford Thunderbird
		Impact Speed (mph)	Crush Depth* (in)	Crush Depth** (in)
8	Measured	46	10.8	8.3
	EDSMAC4		11.5	8.4
9	Measured	39	7.6	6.1
	EDSMAC4		11	4.9
10	Measured	34	8.3	7.1
	EDSMAC4		7.4	7.7
11	Measured	25	5.6	N/A
	EDSMAC4		6.0	4.8
12	Measured	30	3.3	2.1
	EDSMAC4		7.5	4.8
13	Measured	42	6.8	7.5
	EDSMAC4		10.5	9.3
14	Measured	30	5.8	3.8***
	EDSMAC4		5.4	6.6
16	Measured	41	7.5	5.5
	EDSMAC4		11.4	4.6
18	Measured	45	8.8	11.0
	EDSMAC4		8.3	10.9
19	Measured	49	7.3	8.0
	EDSMAC4		11.9	10.1

*Presumed equivalent to reduction in wheelbase for test motorcycle
 **Equivalent to half of sum of largest and smallest reported depths for test vehicle and average of all calculated depths for simulated vehicle
 ***Measured from damaged components

Table 4 – Damage data comparison

PARAMETRIC STUDY

A parametric study was undertaken in order to quantify the effect of the variation of several parameters which might be considered specific to the simulation of a motorcycle-versus-automobile collision. The parameters selected for variation included:

Motorcycle overall width – allowed to vary from 12 inches to 24 inches

Motorcycle trackwidth – increased to 6 inches

Motorcycle stiffness – allowed to vary from 20% below to 20% above the baseline value

Automobile stiffness – allowed to vary from 20% below to 20% above the baseline value

The series of 10 crash tests was reviewed to select one such test for which to vary the above parameters. Test 8 was selected because the simulated at-rest position of the Thunderbird was among the closest to the measured test value of any of the simulation runs, and because this test involved a relatively substantial change in position of the Thunderbird, consisting of a 4-foot total travel distance and a 40-degree change in heading angle.

Each of the above parameters were allowed to vary individually, with all other parameters held constant, except for the cases in which the width of the simulated motorcycles were varied. As discussed earlier, because the stiffness of the motorcycle was based in part on the presumed width of the motorcycle, in the parametric runs where the motorcycle width was varied, the motorcycle's stiffness was also adjusted to reflect the change in width. Thus, in the case where the motorcycle width was reduced from the baseline value of 18 inches to a low value of 12 inches, the stiffness coefficients for the motorcycle were recalculated to be $A = 500 \text{ lb/in}$ and $B = 232 \text{ lb/in/in}$ as compared to their baseline values of $A = 333 \text{ lb/in}$ and $B = 155 \text{ lb/in/in}$. Similarly, when the motorcycle width was increased to a high of 24 inches, the resulting recalculated stiffness values were $A = 250 \text{ lb/in}$ and $B = 116 \text{ lb/in/in}$.

Comparative plots of each of the output parameters discussed previously in the validation study are presented in Figures 30 through 35 for each of the simulation runs in the parametric study.

As observed in these plots, the results of the simulations were not significantly affected by the variation of the above parameters within the ranges described. The minor differences in simulation results included variation of automobile post-impact travel distance of approximately 1 inch or less and a variation in heading

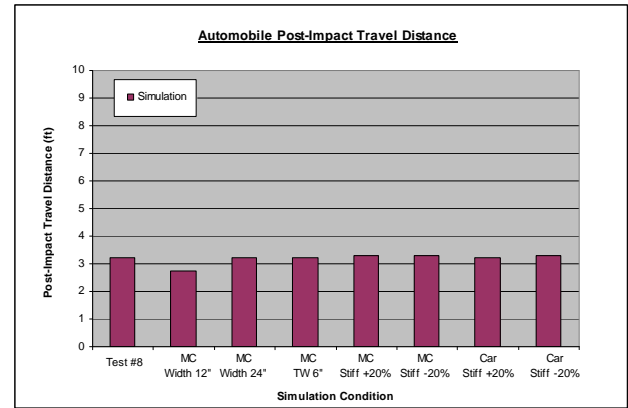


Figure 30

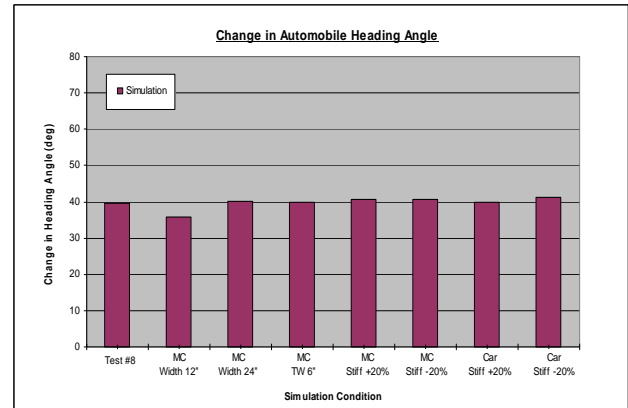


Figure 31

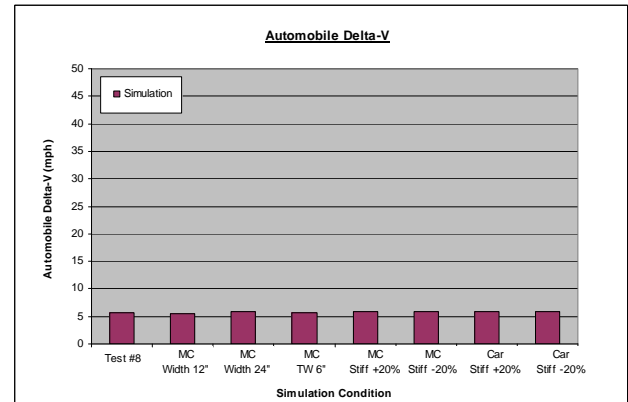


Figure 32

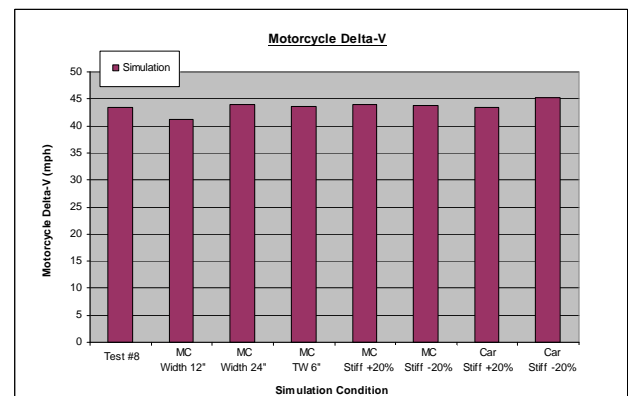


Figure 33

angle of 1 ½ degrees or less in 6 out of the 7 parametric runs, a variation of automobile delta-V of ¼ mile per hour or less and of motorcycle delta-V of approximately 2 miles per hour or less in all of the parametric runs, and variations in car and motorcycle damage depths of approximately 2 inches or less in all 7 of the parametric runs.

There were some expected differences in the simulation results within the parametric study, such as an increase in vehicle damage depth with a decrease in the vehicle's stiffness. An interesting finding is an increase in automobile damage depth with a decrease in the width of the motorcycle, consistent with the narrower motorcycle more deeply penetrating the automobile's simulated structure.

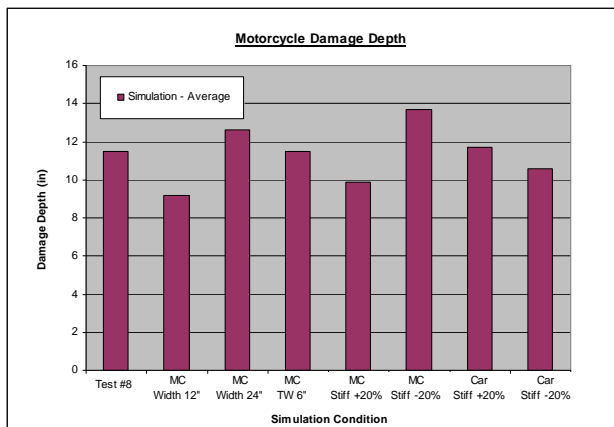


Figure 34

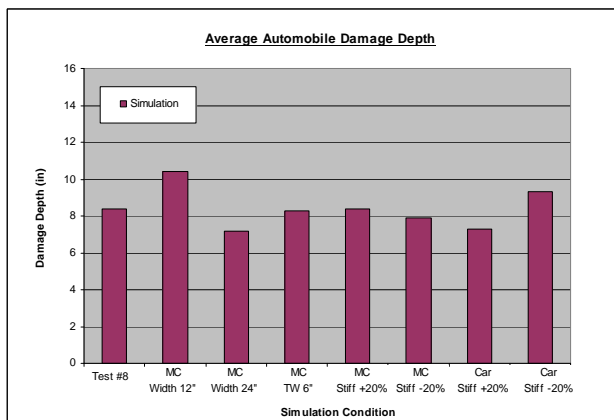


Figure 35

CONCLUSION

Based on the comparison of the results of the simulation of a series of motorcycle-into-automobile collisions against measured full-scale test data, it is concluded that the use of EDSMAC4 in the simulation of motorcycle-into-vehicle collisions provides a valid means for analyzing collisions with configurations similar to these crash tests, within the aspects discussed in this paper.

The simulation effort described resulted in good to excellent correlation of post-impact translations and heading angle changes of the vehicles struck by the motorcycles.

The damage profiles of the simulated vehicles matched those of the test vehicles reasonably well in depth, but were not as broad in extent as the test vehicles.

The simulations, in general, more closely predicted the Delta-V's of the motorcycles than the automobiles, although the measured and simulated Delta-V's of the automobiles were of comparably small values.

A parametric study demonstrates that the simulation model is not sensitive to a reasonable range of changes to motorcycle-collision-specific parameters such as motorcycle width, motorcycle trackwidth, or vehicle stiffnesses.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the efforts of the original researchers in the Adamson paper for the collection of test data against which the simulations in this effort were compared.

REFERENCES

1. Adamson, K.S., et. al., "Seventeen Motorcycle Crash Tests into Vehicles and a Barrier", SAE Paper No. 2002-01-0551
2. Engineering Dynamics Corporation, www.edccorp/products/edsmac42d.html
3. Day, T.D., "An Overview of the EDSMAC4 Collision Simulation Model", SAE Paper No. 1999-01-0102
4. Deyerl, E., et. al., "Presentation of HVE Validation Studies", HVE White Paper No. 2006-1
5. Day, T.D., "Validation of the Simon Model for Vehicle Handling and Collision Simulation – Comparison of Results with Experiments and Other Models", SAE Paper No. 2004-01-1207
6. Expert Autostats v4.3, 4N6XPRT Systems
7. MacInnis, D.D., "A Comparison of Moment of Inertia Estimation Techniques for Vehicle Dynamics Simulation", SAE Paper No. 970951
8. Alle, R.W., "Estimation of Passenger Vehicle Inertial Properties and Their Effect on Stability and Handling", SAE Paper No. 2003-01-0966
9. <http://Kawasaki-KZ900.tripod.com>

10. Pcejka, H.B., "Tire and Vehicle Dynamics", SAE Publication R-372
11. Neptune Engineering, Inc., www.neptuneeng.com
12. Neptune, J.A., "A Method for Determining Crush Stiffness Coefficients from Offset Frontal and Side Crash Tests", SAE Paper No. 980024
13. Neptune, J.A., et. al., "A Method for Quantifying Vehicle Crush Stiffness Coefficients", SAE Paper No. 920607
14. Strother, C.E., et. al., "Crush Energy in Accident Reconstruction", SAE Paper No. 860371
15. Nystrom, G.N., et. al., "Stiffness Parameters for Vehicle Collision Analysis", SAE Paper No. 910119
16. Kerkhoff, J.F., et. al., "An Investigation into Vehicle Frontal Impact Stiffness, BEV and Repeated Testing for Reconstruction", SAE Paper No. 930899
17. Siddall, D.E., "Updating the Vehicle Class Categories", SAE Paper No. 960897

CONTACT

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-----DRIVER CONTROL TABLES -----

Driver Controls for Test 8 Motorcycle

Steer Table:

Time (sec)	R/F (deg)	L/F (deg)	R/R (deg)	L/R (deg)
0.0000	0.00	0.00	0.00	0.00

Throttle Table:

Time (sec)	R/F (%/100)	L/F (%/100)	R/R (%/100)	L/R (%/100)
0.0000	0.00	0.00	0.00	0.00

Brake Table:

Time (sec)	R/F (%/100)	L/F (%/100)	R/R (%/100)	L/R (%/100)
0.0000	0.00	0.00	0.00	0.00

Driver Controls for Maroon Thunderbird

Steer Table:

Time (sec)	R/F (deg)	L/F (deg)	R/R (deg)	L/R (deg)
0.0000	0.00	0.00	0.00	0.00

Throttle Table:

Time (sec)	R/F (%/100)	L/F (%/100)	R/R (%/100)	L/R (%/100)
0.0000	0.00	0.00	0.00	0.00

Brake Table:

Time (sec)	R/F (%/100)	L/F (%/100)	R/R (%/100)	L/R (%/100)
0.0000	-0.01	-0.01	-1.00	-1.00

Figure 37 – Driver Control Tables for Test 8

----- VEHICLE DATA -----

Vehicle Name:	Test 8 Motorcycle	Maroon Thunderbird
Vehicle Type:	Passenger Car	Passenger Car
Vehicle Version Number:	V 5.00	V 5.00
Body Overall Length (in):	90.20	199.00
Body CG To Front (in):	45.10	91.40
Body CG To Rear (in):	-45.10	-107.60
Body Overall Width (in):	18.00	71.80
CG Elevation (in):	20.60	21.19
Roll Couple Dist:	0.55	0.55
Total Weight (lb):	615.00	3590.04
Total Mass (lb-sec ² /in):	1.59	9.29
Yaw Inertia Tot (lb-sec ² -in):	1123.00	29885.00
Yaw Inertia Sprg (lb-sec ² -in):	858.95	26520.49
3-D Geometry Filename:	MCYamaha650.h3d	PCFordThunderbird892Dr.h
Number of Vertices:	20	20
Number of Damaged Vertices:	0	0

	A Stiff (lb/in)	B Stiff (lb/in ²)	A Stiff (lb/in)	B Stiff (lb/in ²)
Front End:	333.0	155.0	252.0	79.0
Right Side:	333.0	155.0	97.0	55.0
Back End:	333.0	155.0	257.0	82.0
Left Side:	333.0	155.0	243.0	138.0

----- WHEEL AND TIRE DATA -----

Wheels _Tires, Front Axle --	Right	Left	Right	Left
Wheel Locn (in) - x:	30.20	30.20	48.40	48.40
y:	0.01	-0.01	31.00	-31.00
z:	9.22	9.22	8.32	8.32
Tire Name:	Generic	Generic	Generic	Generic
Tire Size:	P155/80R13	P155/80R13	P195/75R14	P195/75R14
Slide Mu (*):	0.72	0.72	0.72	0.72
Vel Dependence (sec/in):	0.00000	0.00000	0.00000	0.00000
Cornering Stiffness (lb/deg):	45.00	45.00	172.00	172.00

Second Axle --	Right	Left	Right	Left
Wheel Locn (in) - x:	-30.20	-30.20	-64.60	-64.60
y:	0.01	-0.01	30.00	-30.00
z:	9.22	9.22	8.32	8.32
Tire Name:	Generic	Generic	Generic	Generic
Tire Size:	P155/80R13	P155/80R13	P195/75R14	P195/75R14
Slide Mu (*):	0.72	0.72	0.72	0.72
Vel Dependence (sec/in):	0.00000	0.00000	0.00000	0.00000
Cornering Stiffness (lb/deg):	50.00	50.00	172.00	172.00

Figure 36 – Vehicle Data for Test 8