HVE-WP-2018-3

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Reprinted From: 2018 HVE Forum White Paper Session

ENGINEERING DYNAMICS CORPORATION

2018 HVE Forum
Charleston, SC
February 12 – 16, 2018

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ABSTRACT

A staged collision between a 2002 Toyota Camry and an adult pedestrian dummy was modeled via the GATB physics module within the HVE software suite to evaluate the performance of GATB in modeling such an impact configuration. During the test, the upright and stationary dummy was struck by the front of the Toyota, which was traveling at approximately 20 miles per hour while undergoing hard braking. During the collision sequence the dummy experienced a typical wrap trajectory, rotating onto the hood of the vehicle while being accelerated in the direction of travel of the vehicle. As the vehicle continued to brake, the dummy separated from the car, landing on the pavement with its center of gravity approximately 24 feet ahead of the point of impact. The GATB computer model was used to simulate the collision and its output was visually compared against high speed video of the staged test. It was found that, to model the motion of the dummy accurately, the default slope for the unloading portion of the force-deflection relation for the dummy's segments needed to be increased by a factor of approximately two. The resulting simulated motion of the test dummy matched that of the test dummy well, including its trajectory, limb movement, as well as its contact locations and point of rest. No other modifications to the dummy's default parameters were required.

LITERATURE REVIEW

Others have modeled pedestrian-vehicle collisions via computer simulation, and some have also examined force-deflection relationships for automobile exterior components. Several prior studies are identified and described here:

- Akiyama et. al. [1999] modified the Euro-SID dummy included in the MADYMO database to model the motion of a dummy struck by the front of a vehicle. The model was validated against the trajectories of selected dummy components established by Ishikawa [1993] during full-scale crash tests. From these simulations, a physical dummy was developed to better understand pedestrian kinematics in full-scale crash tests. Component testing was undertaken to quantify force-deflection characteristics of the dummy components.

- Moser et. el. [1999] described the PC-crash pedestrian model and attempted to validate it against several crash tests. A single test was presented in this paper and the authors described good correlation between simulation and test, although values of and sources of pedestrian-vehicle force-deflection properties were not identified.

- Moser et. al. [2000] once again used the PC-crash pedestrian model to simulate the general trajectories of pedestrians struck by vehicles, and to compare the simulated pedestrian throw distances against various relations previously published in the literature. The detailed motions of the simulated dummies were not evaluated or presented. However, geometric and force-deflection properties for the simulated dummy's body segments were provided.

- Mizuno and Kajzer [2000] modeled vehicle-pedestrian collisions using a proprietary simulation model developed by Yang and Kajzer in 1992. The force-deflection properties of various regions of a Toyota Corolla sedan were established via load testing using a headform impactor. Pedestrian kinematics and head injury potential were evaluated via simulation of generic collisions.

- van Rooij [2003] et. el. used the MADYMO human pedestrian model and a finite element mesh model of the striking vehicle. They noted that the MADYMO contact algorithm did not allow for a combined stiffness model for contact between the pedestrian and vehicle, which they reasoned was valid for very stiff portions of the human model, such as the head and knee, but would require caution in interpretation for softer areas of the pedestrian.

Only the force-deflection properties of the vehicle are included in the model, and these relations were developed for various regions of the vehicle via load testing with rigid impactors. MADYMO was then used to iteratively model two real-world pedestrian crashes until the predicted pedestrian contact points matched the observed vehicle damages and pedestrian injuries well.

- Becker et. al. [2015] used Virtual CRASH 3 to model the overall throw distance of staged pedestrian collisions, which it was found to model well. Additionally, the simulated dummy's inertial, stiffness, and friction parameters were tuned to model the detailed motion of a single crash test. The values for these parameters were not presented in this paper.

CURRENT STUDY

The current study was intended to use the GATB physics model within the HVE software suite to model the detailed motion of a pedestrian dummy during a single well-documented full-scale crash test. The intent was to determine what adjustments needed be made to dummy-vehicle force-deflection parameters to accurately model the collision sequence.

TEST CONDITIONS

The crash test was conducted on September 25, 2014 at approximately 1:40 PM as part of the Southwestern Association of Technical Accident Investigators (SATAI) fall conference. The test location was the Glendale Regional Public Safety Training Center located in Glendale, Arizona. The test surface was comprised of asphalt and the weather was dry and sunny, with a reported air temperature of approximately 97 degrees Fahrenheit. (Figure 1)

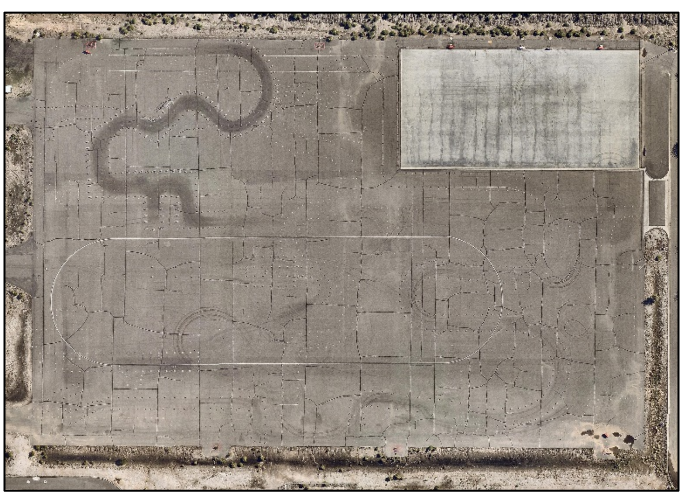

Figure 1 – Crash test location, Glendale Regional Public Safety Training Center (Nearmap US, Inc.)

The test vehicle was a 2002 Toyota Camry SE four-door sedan, loaded with a 280-pound human driver and data acquisition equipment consisting of on-board video cameras, a VBOX Video Lite GPS system and a Vericom VC4000DAQ brake meter. (Figure 2) During the test, the vehicle was accelerated to a maximum speed of approximately 25 miles per hour at which point the vehicle was braked firmly by the driver prior to the front of the vehicle striking the standing dummy at a speed of approximately 20 miles per hour. Figure 3 presents data traces of the vehicle's speed and acceleration as recorded during the test.

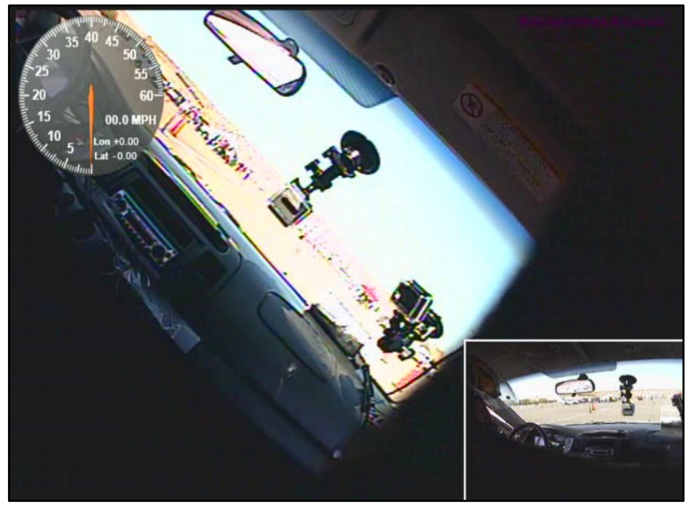

Figure 2 –Interior of test vehicle, depicting instrumentation

The clothed test dummy approximated a 50th percentile adult male. It featured a jointed metal skeleton, weighed 170 pounds and stood 5'10" tall. Prior to the collision, the dummy was suspended in a standing position with legs astride via a breakaway wire attached to its head, and was hung from a wooden frame surrounding the area of impact. At the moment of impact, the dummy was facing away from the driver's side of the car and toward the passenger side. The point of contact on the vehicle was near the center of the vehicle's left headlight assembly. (Figure 4)

SIMULATION ANALYSIS OF TEST VEHICLE MOTION

The motion of the test vehicle was modeled via the EDSMAC4 physics model within the HVE software suite developed by Engineering Dynamics Corporation. Vehicle inertial and dimensional parameters were based on published data, and the vehicle's exterior geometry was comprised of the mesh of a 2003 Camry, the geometry of which is the same as that of the test vehicle. To enable the HVE "Human" dummy to interact with the exterior of the vehicle during the crash, a series of contact planes were created which generally followed the contours of the front of the test vehicle. The number of planes generated were enough to adequately mimic the structure of the vehicle while moderating construction effort. The arrangement of the contact planes for the simulated vehicle is depicted in Figure 5.

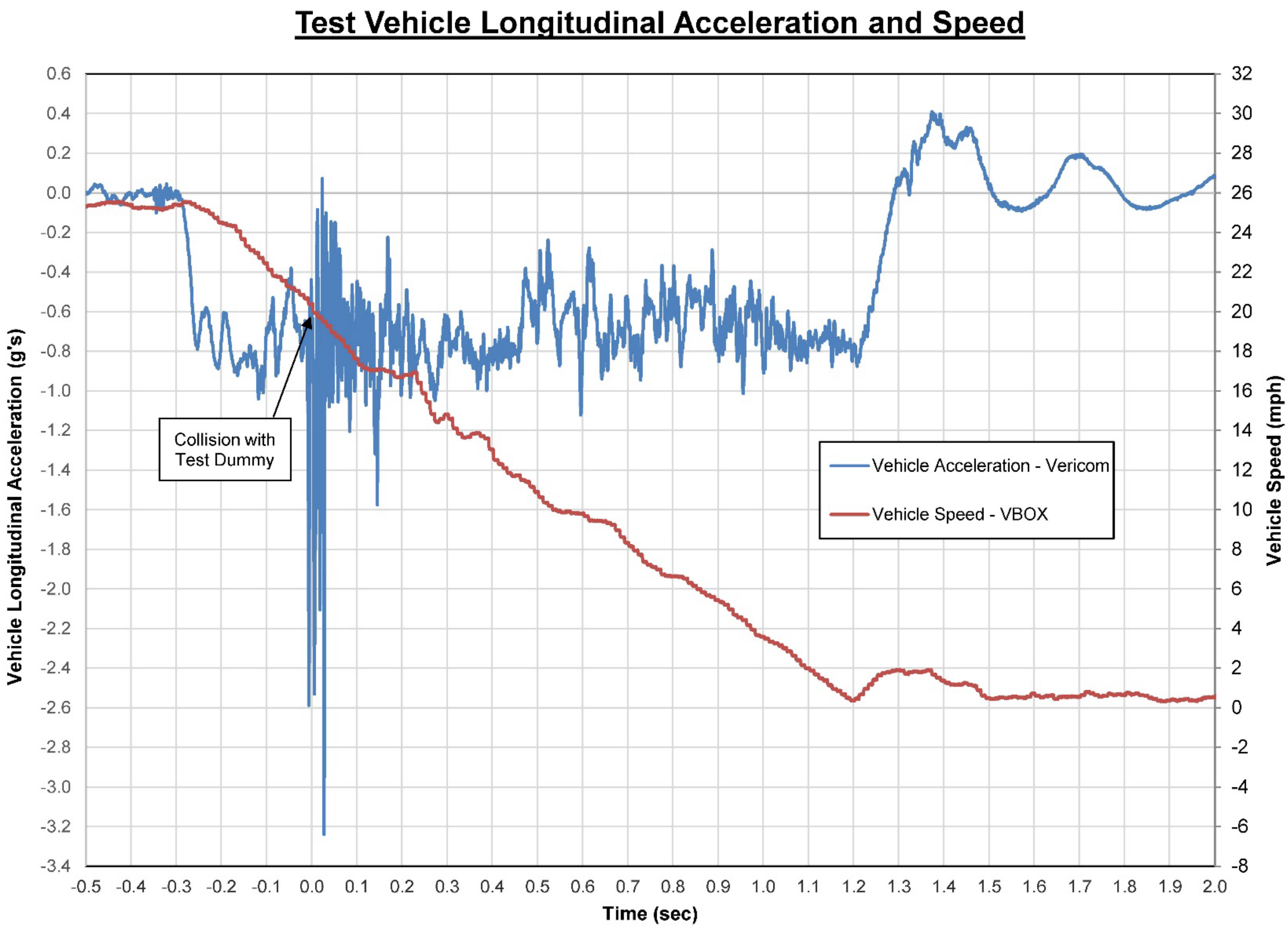

Figure 3 – Test vehicle acceleration and speed traces

Figure 4 – Test vehicle and dummy at moment of impact

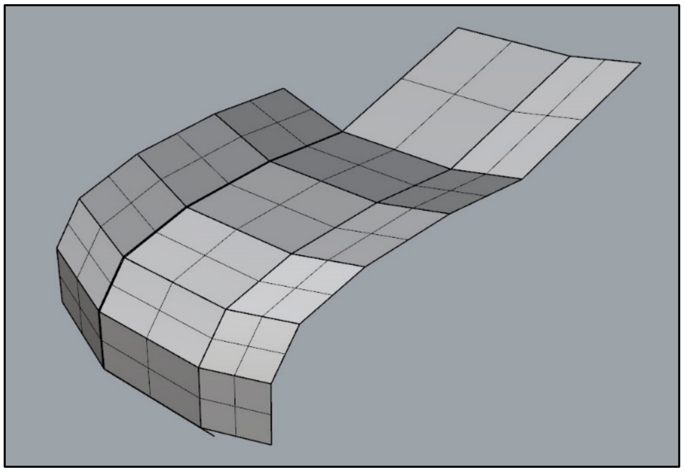

Figure 5 – HVE vehicle mesh (top) and contact planes used to model dummy motion (bottom)

The simulated vehicle was braked maximally such that the calculated vehicle speed history matched that measured on the test vehicle. This required that the simulated vehicle decelerate at a constant rate of 0.76 g's during the braking phase of motion. The resulting vehicle acceleration history was used as a "Collision Pulse" for the subsequent GATB simulation. Figure 6 is a plot of the test vehicle's speed versus time as compared to that calculated by the simulation model.

Note that EDSMAC4 is a yaw plane model, meaning that the vehicle's motion in the pitch degree of freedom is not modeled. Thus, the "nose dive" experienced by the test vehicle would not be replicated by the simulated vehicle. Given that the test vehicle was braked for a brief period of time prior to the collision, it was hypothesized that the pitch angle of the vehicle at impact would not play a large role in determining the trajectory of either the test dummy or a simulated pedestrian. This hypothesis was borne out by a comparison of the resulting simulated dummy trajectory against the video of the test dummy.

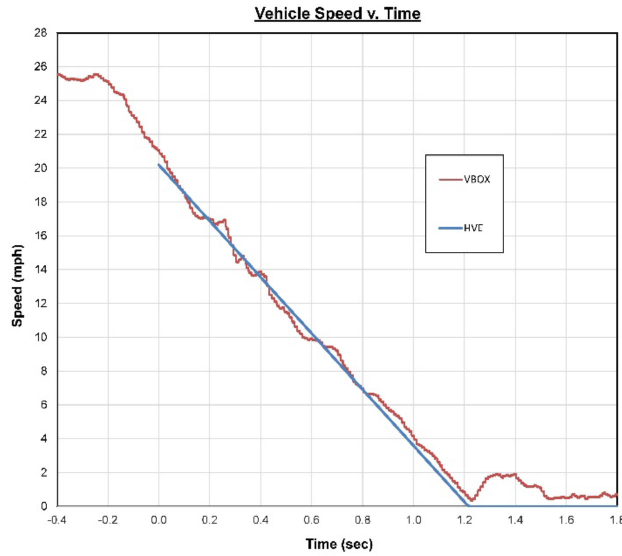

Figure 6 – Test vehicle speed trace (red) and HVE simulated vehicle speed trace (blue)

SIMULATION ANALYSIS OF CRASH TEST DUMMY

The test dummy was simulated using an HVE 50th percentile adult male "Human" with weight and height set to match the test dummy. The GATB human is comprised of 15 ellipsoids intended to represent the body and limbs of a typical dummy and/or human subject (Figure 7). In addition to dimensional and inertial properties of each limb, GATB also models the combined force-deflection properties between each ellipsoid and any contact planes based on a default force-deflection curve, as depicted in Figure 8.

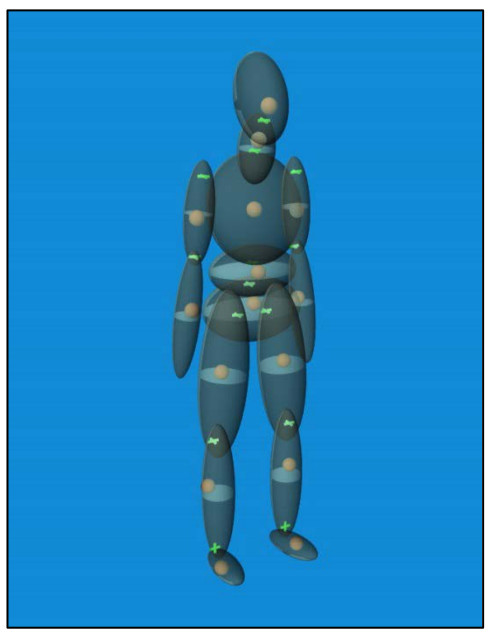

Figure 7 – HVE human model used in simulation

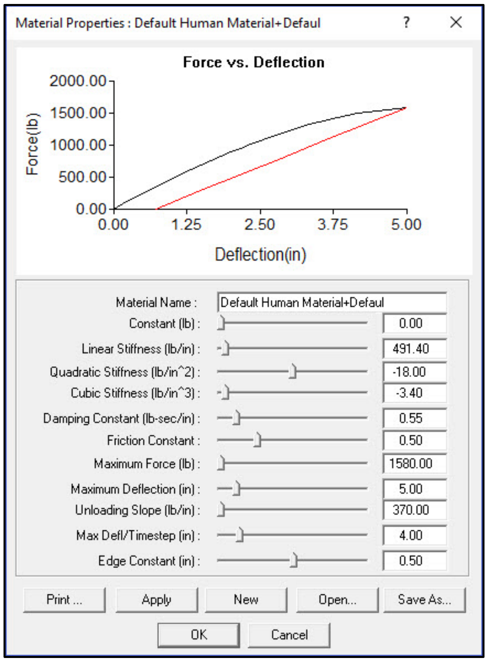

Figure 8 – Default material properties for interaction of human model ellipsoids with contact planes

During initial simulations of the subject crash test, the force-deflection properties of the simulated dummy's segments were left at the default values. During these simulations, it was noted that the motion of the dummy and its limbs appeared to be driven by an overly-resilient force-deflection relationship for the body ellipsoids. That is, the simulated dummy was observed to rebound or "bounce" too much when encountering either the test vehicle or the ground as compared to the motion of the test dummy depicted in the crash test video.

As the speed history of the test vehicle was known from instrumentation data, and the detailed motion of the test dummy was known from test videos and photographs, it remained to adjust the combined force-deflection properties of the simulated dummy and vehicle contact planes until the motion of the simulated dummy closely matched that of the test dummy.

The parameter identified by the authors as a prime candidate for adjustment was the slope of the unloading portion of the force-deflection relation shown in Figure 8. The difference between the areas under the loading curve and the unloading curve is the energy lost to deformation of the dummy ellipsoids. Increasing the slope of the unloading curve increases the difference in areas beneath these plots and hence increases the deformation energy, thereby returning less energy to the simulated dummy.

After several rounds of trial and error, the slope of the unloading portion of the force-deflection curve was increased from a value of 370 lb/in to 750 lb/in, as depicted in Figure 9. This had the effect of appropriately reducing the return of elastic energy stored within the ellipsoids when they made contact with the contact planes, thus reducing the "bounciness" of the simulated dummy.

SIMULATION RESULTS

Two simulation videos matching the perspective of two of the cameras used to document the full-scale test were generated in the HVE Video Creator, and these videos were placed next to the test videos for visual comparison of the motion of the vehicle and dummy.

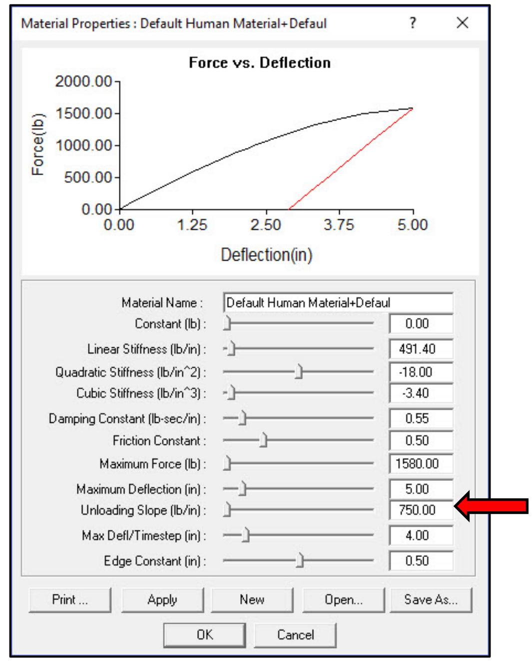

Figure 9 – Adjusted material properties for interaction of human model ellipsoids with other objects

Figure 10 (two pages) is comprised of still frames from a fixed-camera video of both the crash test (right column of images) and the computer simulation (left column of images) taken at the same moments in time, the values of which are indicated in the screen captures of the simulation.

Figure 11 (three pages) is comprised of still frames from a tracking-camera video of both the crash test (right column of images) and the computer simulation (left column of images) taken at the same moments in time, the values of which are indicated in the screen captures of the simulation.

As depicted in these qualitative comparisons, the trajectory of the simulated dummy closely matches that of the test dummy, including general orientation and vehicle contacts, throughout the travel path of the dummy from initial contact with the vehicle to the dummy's final rest position on the pavement, which is depicted as a dark gray oval on the simulated roadway surface.

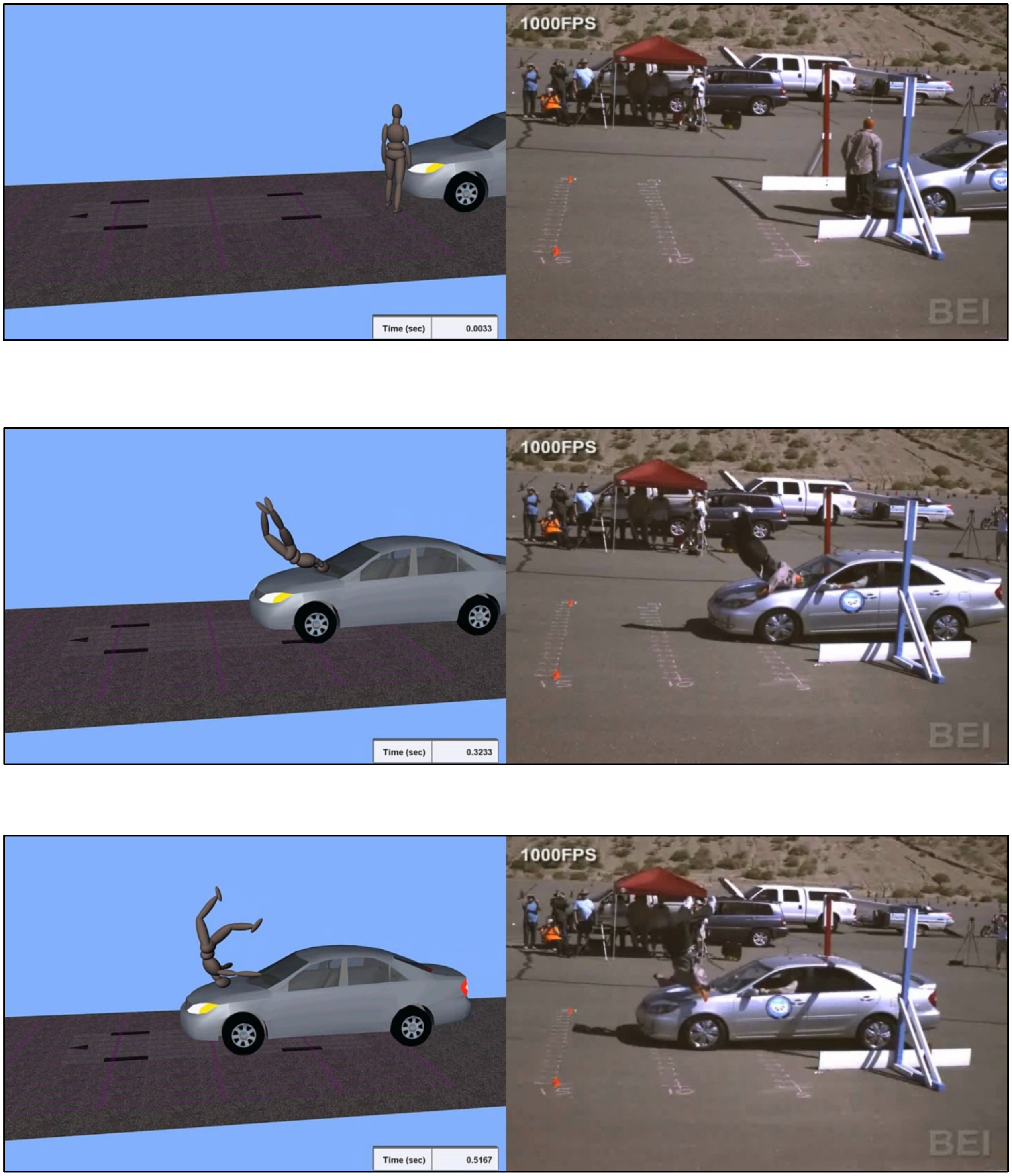

Figure 10 – Comparison of frames from stationary video

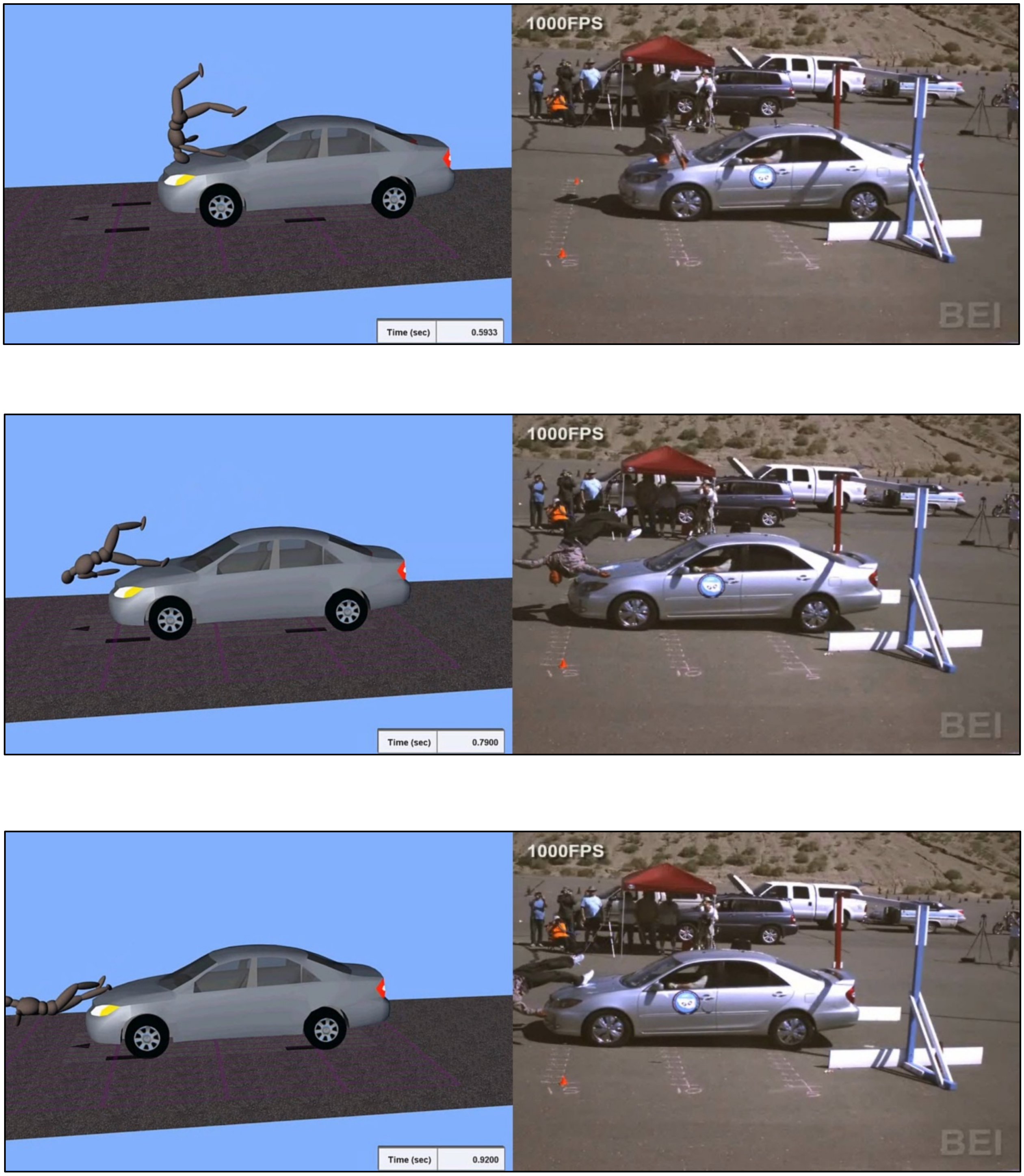

Figure 10 (continued) – Comparison of frames from stationary video

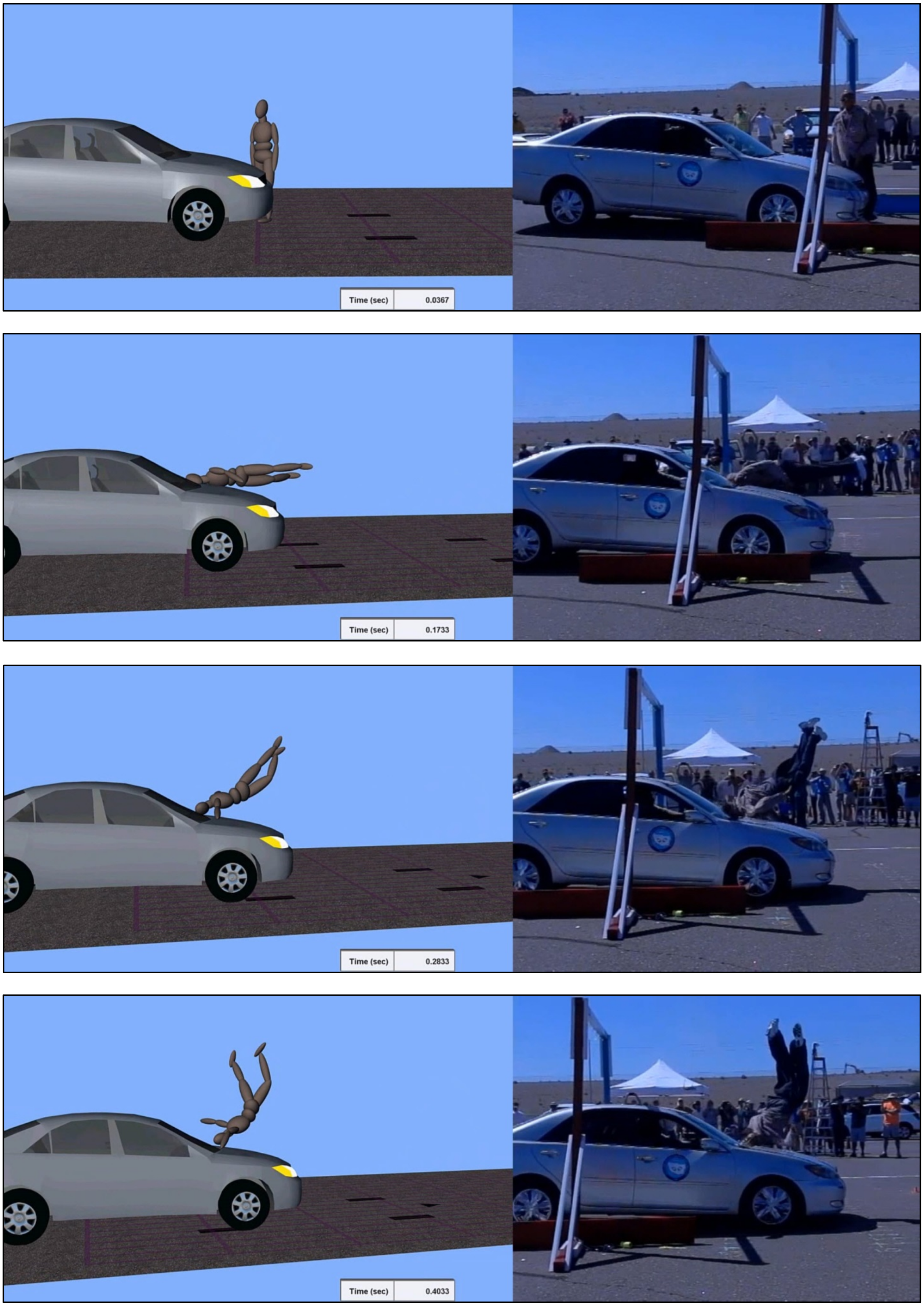

Figure 11 – Comparison of frames from tracking video

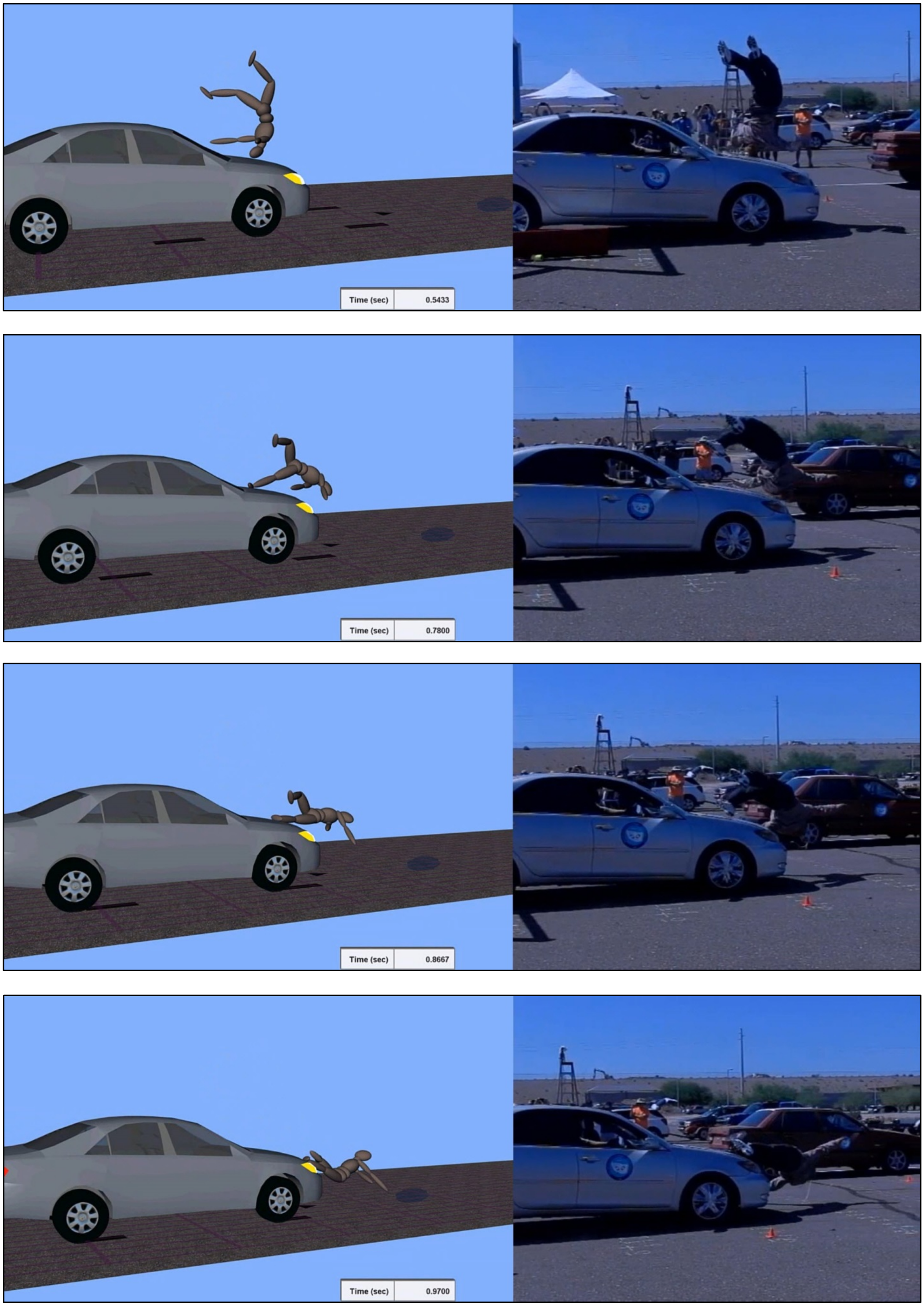

Figure 11 (continued) – Comparison of frames from tracking video

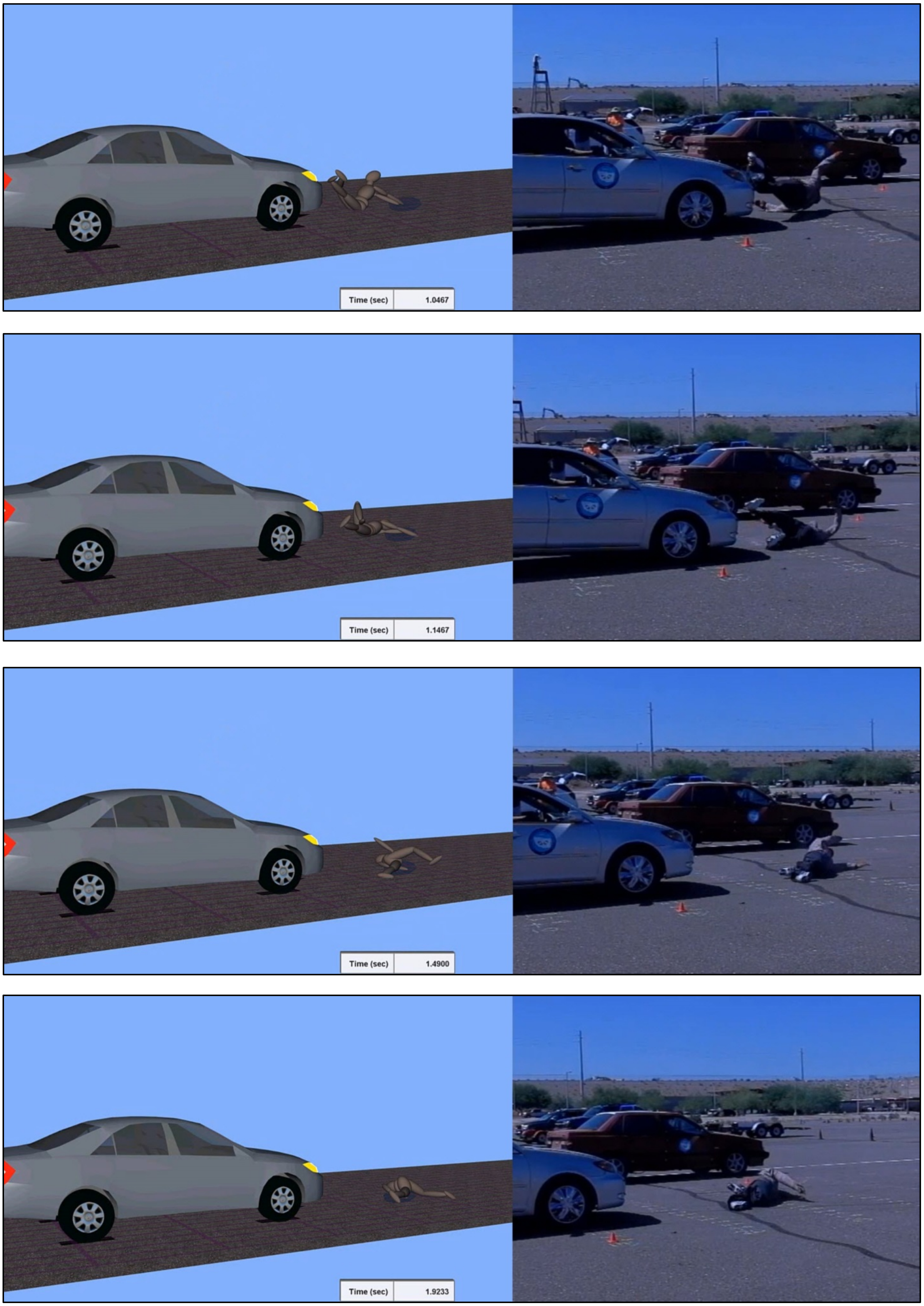

Figure 11 (continued) – Comparison of frames from tracking video

DISCUSSION

The technical literature was reviewed to compare the final force-deflection relationship selected for the simulated dummy's ellipsoid segments against laboratory test data. Force-deflection curves for component testing documented in the van Rooij, Mizuno and Akiyama papers were compared against the combined ellipsoid-contact plane stiffness used in the current GATB simulation.

Both Mizuno and van Rooij presented force-deflection plots based on dynamic impact testing of an approximately 10-pound headform projected into various exterior components of an exemplar automobile at a speed of approximately 25 miles per hour. The headform was instrumented with an accelerometer, from which both its penetration distance and impact force histories were developed.

Akiyama presented the results of static force-deflection testing of the lower leg of a crash test dummy equipped with a foam substrate covered by a "skin".

As can be observed in Figure 12, a plot of selected force-deflection traces from the above refence papers along with the relations from the GATB model, the relations can be grouped roughly into three categories: "soft" structures (blue plot) such as the center of the windshield; "moderately stiff" structures (green plots) such as the vehicle hood and areas of the windshield approaching the frame; and "stiff" structures (orange and red plots) such as the top of the firewall, the hood near the fender, and the dummy tibia.

Comparing the test data plots against the GATB force-deflection relations (black traces), it appears that the GATB relation seems to fall nearest the range of the "moderately stiff" structures (green).

Examining two of the green plots in more detail against the GATB relations in Figure 13, one can observe that the GATB relation for the loading portion of the force-deflection curve aligns very closely with the van Rooij test data for headform impact tests conducted approximately 4 inches away from the frame of the windshield.

Figure 13 also depicts that, at this level of maximum deflection, the default GATB relation for the unloading portion of the curve would tend to have the contacting objects unload on a path very similar to the loading path. By increasing the slope of the unloading curve by a factor of 2.03, the GATB relation in the current study better mimics the dynamic headform impact test data. However, as depicted in the colored plots in Figure 13, in the physical tests, unloading occurred even more rapidly, suggesting that further increasing the slope of the unloading path in GATB might better mimic real-world testing. The authors found, however, that further increases in the slope of the unloading path did not improve the trajectory of the simulated dummy. It is unclear if this is a result of the representation of the unloading path as a linear relationship in GATB (versus the clearly non-liner unloading path of the physical tests), or other factors, such as dummy damping and/or joint stiffnesses, neither of which were examined in this study.

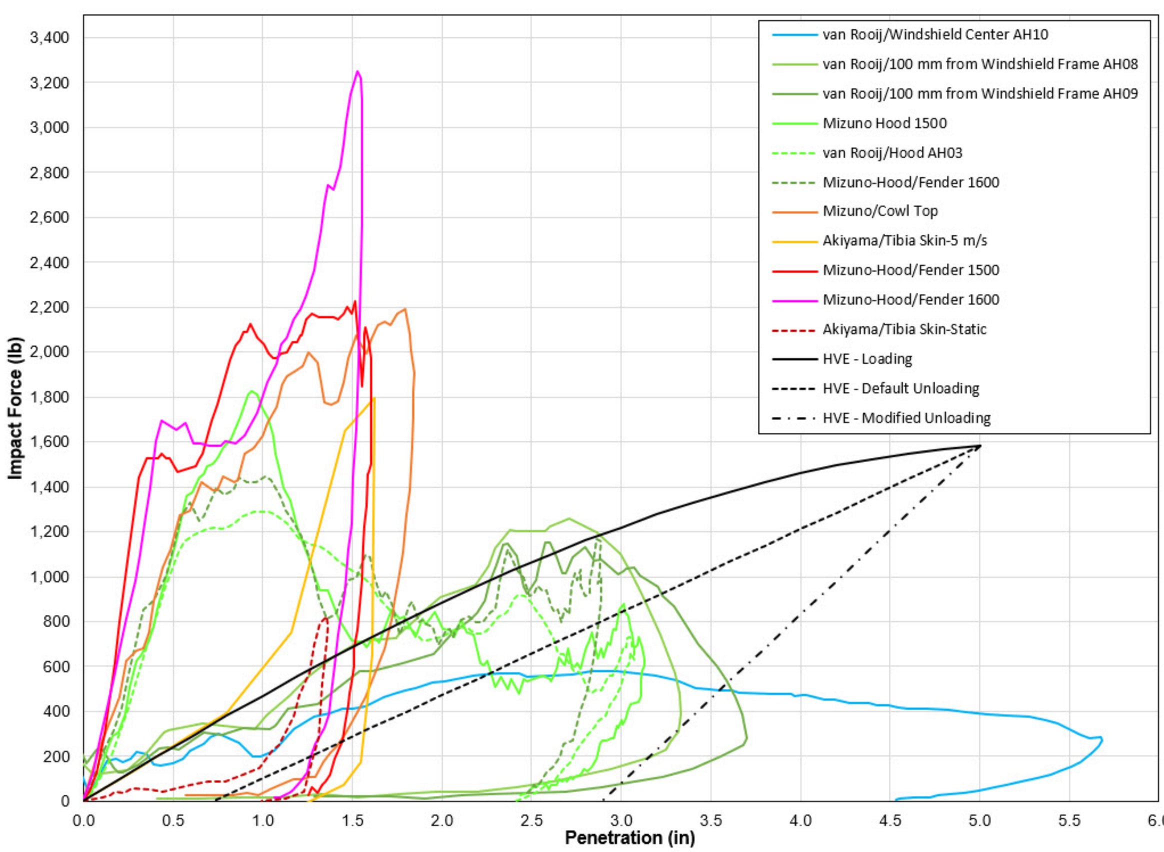

Figure 12 – Force-deflection plots from the literature and HVE

SUMMARY, CONCLUSIONS, AND OBSERVATIONS

- The HVE physics module GATB was used to model a staged vehicle-pedestrian collision in which the vehicle motion history and pedestrian orientation at impact was known.

- The default force-deflection relationship for the simulated dummy's body ellipsoids as provided in GATB was adjusted to optimize the resulting motion of the dummy against the motion of the test dummy as provided in test video.

- By increasing the slope of the unloading portion of the force-deflection curve from 370 lb/in to 750 lb/in, the motion of the simulated dummy very closely matched that of the test dummy when compared via a qualitative video analysis.

- The adjustments made to the simulated dummy's force-deflection properties compare favorably to technical literature documenting the force-deflection relationships of dummy headforms being projected into vehicle windshields at a speed of approximately 25 miles per hour.

- It is expected that accident investigators would be able to use the refinements developed in the current study to guide their own reconstructions of vehicle-pedestrian accidents when using GATB.

- While the current study examined the front of a passenger vehicle striking a stationary and standing pedestrian, it is expected that GATB could also be employed when analyzing vehicle-pedestrian accidents of other configurations. Further GATB modeling of alternate collision configurations, including differing vehicle body styles, alternate vehicle impact locations and dummy sizes, as well as moving dummies, is desired.

- The current study did not examine the effect of adjustments to other input parameters to the GATB model, such as joint stiffness or damping, but given the close modeling of the trajectory of the test dummy, it is expected that these input parameters have effects that are secondary to the force-deflection relationship between the simulated dummy ellipsoids and the contact planes.

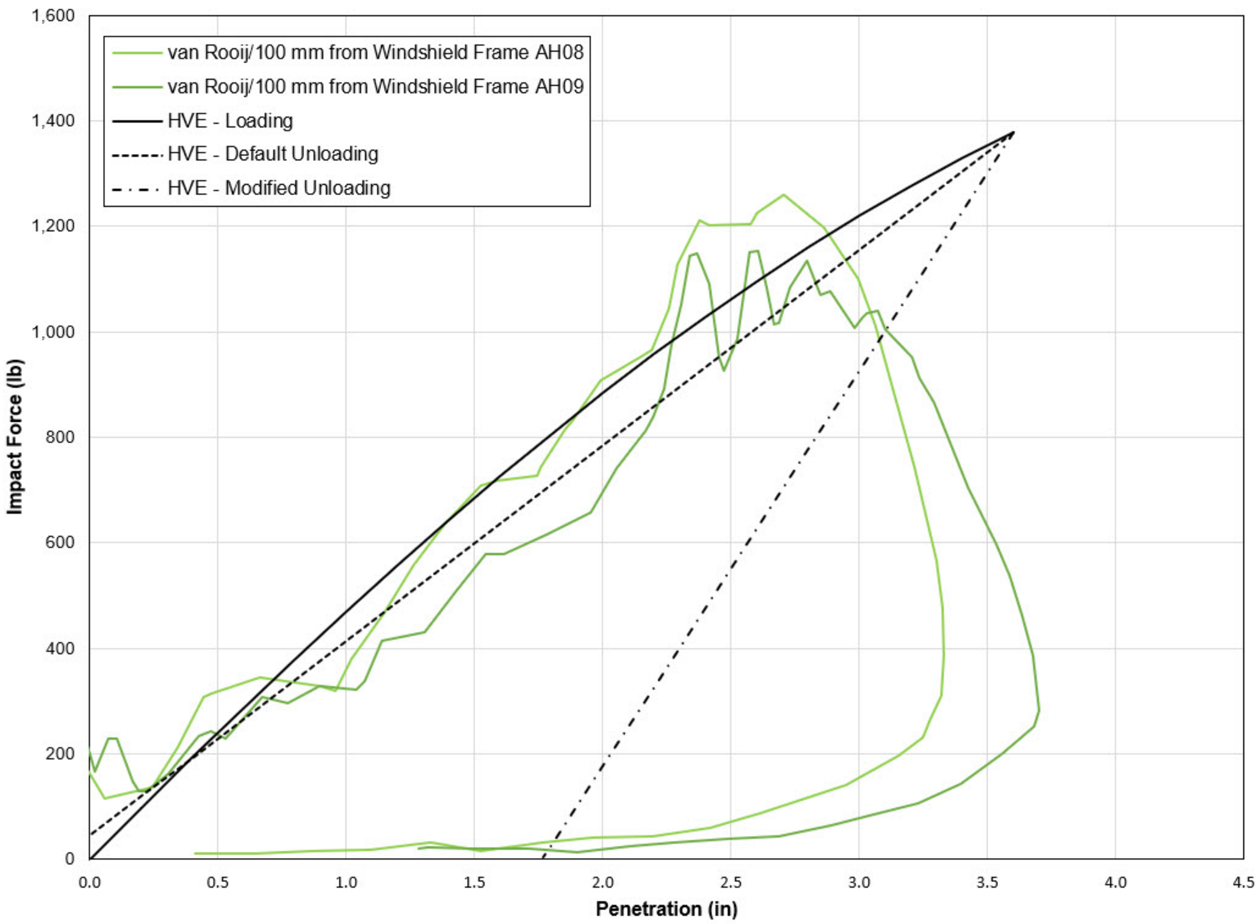

Figure 13 – Force-deflection plots from van Rooij and HVE

ACKNOWLEDGMENTS

The authors would like to acknowledge the SATAI researchers who set up, carried out, and documented the crash test which forms the basis for this analysis.

The authors would also like to thank Ian Seabury, B.S.M.E of Dial Engineering for his technical assistance in preparing this paper.

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