WP# 2002-3

Predicting and Analyzing Vehicle Dynamics in a Train-Passenger Vehicle Collision Using EDSMAC

James S. Sobek and William E. Dickinson
Wolf Technical Services, Inc.

ABSTRACT

This paper describes the successful application of EDSMAC to "pre-construct" a staged car/train collision. The paper compares the real-world results of that April 1996 collision with the EDSMAC predictions and with a recent re-analysis of the collision using the HVE system and the current EDSMAC4 program.

Wolf Technical Services, Inc. (WOLF), Indiana Rail Road, WRTV Channel 6, Teen Challenge and Operation Lifesaver worked together to stage a grade crossing collision involving a 1984 Cadillac deVille and an EMD GP-16 locomotive. The purpose of the event was to produce a news program geared to educate the public on the dangers of railroad grade crossings. To ensure that the filming was completed in a safe manner, WOLF was asked to design the collision configuration. WOLF personnel used the EDVAP EDSMAC[1] vehicle dynamics program to determine how to place the car on the grade crossing and to predict the dynamics of the collision once the train struck the car. The vehicle C.G. (center of gravity) position was established at the site. The car post-impact path and rest position were "right on track" and were predicted within inches, showing the accuracy of the EDSMAC program in both reconstruction and pre-construction. Crash dummies and video cameras were in the car. Channel 6 and WOLF provided video coverage from a variety of other viewpoints. Excerpts from that coverage will be shown.

[1]EDVAP was the predecessor of HVE.

INTRODUCTION

For several years, WOLF personnel had been working with Indiana Rail Road in an arrangement where we provided engineering services in exchange for access to their personnel and rail systems. In late March of 1996, the Indiana Rail Road Manager of Special Projects called to tell us that they had been asked to participate in a staged grade crossing crash demonstration in mid-April. Knowing that we did automotive accident reconstruction work, they wanted us to determine how to set up the crash so that signal masts at the site were not destroyed and so that personnel participating in the event were not injured. He said that Indiana Rail Road had decided that they would not participate in the demonstration if they could not secure our assistance and wanted to know if we would help. The reader is left to imagine the grin on our faces as we responded, "Absolutely!"

Personnel from each of the agencies to be involved met at a grade crossing on the southwest side of Indianapolis on Thursday, March 28, 1996 to determine the basic concept and to establish "the rules of the game." Indiana Railroad had agreed to supply the train, track, site and operations personnel. Teen Challenge would acquire a car. Channel 6 would provide video coverage and air personnel. Operation Lifesaver would provide funding and public service support. WOLF would supply engineering services to "pre-construct" the collision.

THE SITE

Bluff Road is a north-south feeder-collector road on the southwest side of Indianapolis. It is a two-lane, blacktop paved city street in an older residential neighborhood. The actual site is located several hundred feet from most of the homes in the area, although one house was located directly east of the actual grade crossing about 100 feet.

In this area, Bluff Road is oriented at about 30 degrees /210 degrees with respect to True North. The track is oriented due north-south. Thus, motor vehicle operators must look sharply over their right shoulders to determine if there is a train coming from the north. The view to the left is much easier, only 30 degrees left of straight ahead.

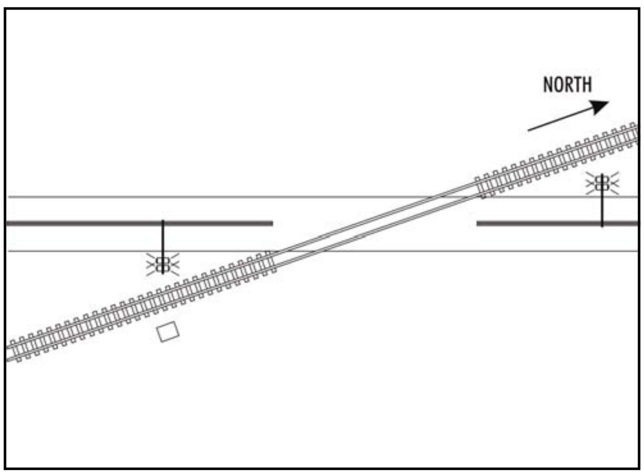

Figure 1. Bluff Road Crossing

The crossing is fitted with cross-bucks, bells, flashing lights and gates. The bells, lights and gates are activated when trains enter the approach circuit. The bells and lights start immediately upon detecting a train. Seven seconds later, the gates come down. Each gate has three lights mounted on it.

Even with such clear warning, motor vehicle operators will sometimes choose to take the risk and drive around the gates. The purpose of this demonstration was to visually convey the penalty for doing so.

The plan was to place an automobile on the crossing in such a position that it was clear that it had driven around the first gate and was directly on the tracks when the train got there. Recognizing the difficulty of having the train and car both moving, we chose to have the car stationary on the tracks at the moment of impact.

The signal masts on which the lights, gates and bells are mounted are located in the south and north sectors of the crossing. For filming purposes, we chose to have the train heading north while the car was oriented on a generally southbound path, having skirted the north gate. Thus, there was a potential that the car would follow a post-impact path into the north signal mast. One aspect of the "pre-construction" task was to ensure that didn't happen.

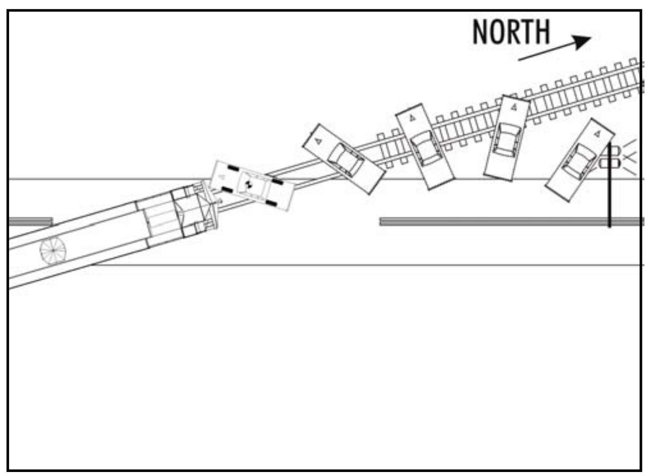

Figure 2. "Undesirable" Result

Secondly, there were to be a number of Channel 6 personnel involved in covering the event from various perspective points. Their safety was paramount. Neither the car, the locomotive, nor any debris was to put them at risk. Finally, Indiana Rail Road wanted to avoid tearing up their grade crossing surface if at all possible. Arranging the collision dynamics such that the wheels did not dig into the rubber crossing surface was desirable.

In order to ensure that personnel aboard the locomotive were not put in harm's way, we agreed that we would remove the car's battery and fill the fuel tank with "No-Flash", a water-soluble liquid soap-type material which fills the air space above the fuel and prevents sparks from setting off an explosion in the event that the fuel tank bursts in a collision.

We chose EDSMAC to perform the "pre-construction" engineering work. The version which we had in-house at that time was EDVAP EDSMAC version 2.51.

THE CAR

Several different cars were available for our use: a Ford Escort with no engine, a Nissan pickup, a Ford Torino and a 1984 Cadillac deVille. Realizing that we wanted to control yaw as much as possible, we selected the longest and heaviest of the four, the Cadillac, in order to get the maximum value for yaw moment of inertia.

The car's engine was still more or less intact, and all the car's components were still installed. This meant that we had a pretty good handle on where the center of gravity would be located.

Applying EDSMAC

The EDSMAC software was well designed to compute the results of vehicular collisions, particularly collisions in which the vehicles were more or less rectangular. It is also designed to deal with those weight values and mass distributions seen in automobiles and reasonably large trucks. And, finally, it is designed to handle friction values normally seen in road vehicle circumstances. It will be seen below that we had to "press" the system somewhat to be able to compute the most likely vehicle behavior in a train/car collision. But, we were successful as demonstrated by the fact that the real-world vehicle motions were nearly identical to those predicted by the EDSMAC simulation.

The first and most obvious area where we had to make modifications was weight. It's obvious that no "normal" car weighs 365,000 pounds, the weight of the locomotive which we were using. In order to protect the user from erroneously entering a large mass, the LIMITS.DAT file in the program contains maximum values for weights and other parameters. If a user enters a value which exceeds the corresponding value in the LIMITS file, the program displays a warning and allows the value to be corrected. We edited the LIMITS file so that the program would accept such large masses.[2]

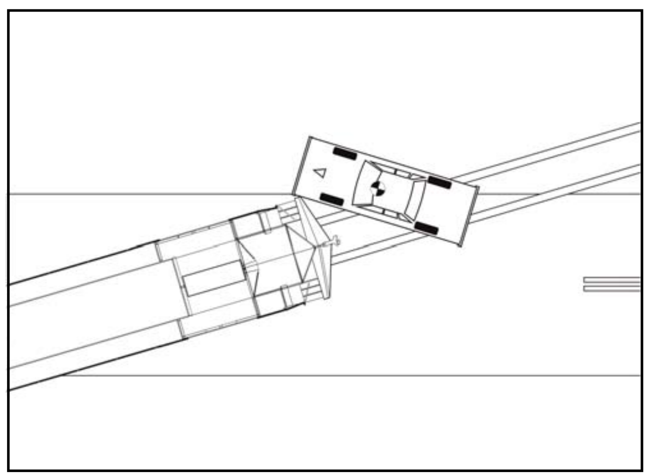

Figure 3. Collision configuration

The collision configuration, as shown above, was selected so that the snowplow on the northbound locomotive would strike the driver's side of the Cadillac in front of the center of mass and the car would rotate

[2]The car's weight was 4000 pounds.

clockwise after the initial impact. The northward velocity imparted by the collision combined with the coefficient of restitution would cause the car to momentarily separate from the locomotive. But, because the coefficient of friction between the car tires and the rubber grade crossing surface would be higher than friction available from train braking, the locomotive would catch up with the car and there would be secondary impact.

One of the Channel 6 videographers was to be located up the tracks about 300 feet. Since we had set up a clockwise rotation with the initial collision of the snowplow, the center of mass of the car would now be going mostly northward, toward that person.

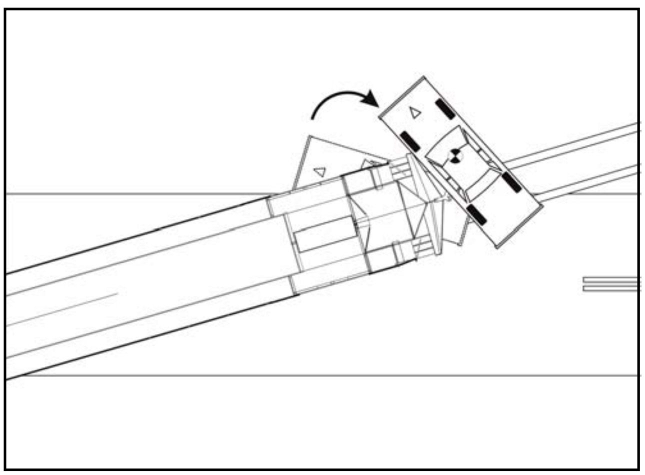

Figure 4. Rotation Control

We needed to now stop the rotation and induce a westward velocity vector so that the car would go off the tracks and onto the reasonably flat and level west edge of the railroad right-of-way. We set the collision so that the locomotive coupler struck the left side of the car well behind the C.G. By placing the snowplow collision slightly forward of the center of gravity, we ensured that the clockwise yaw rate was reasonably low and able to be zeroed out by the contact with the coupler.

EDSMAC assumed a rectangular vehicle, not a vehicle with an extended coupler and an angled snowplow. We wanted the first collision to be at the left edge of the snowplow. This would start a clockwise rotation. Then, we wanted the coupler to stop the rotation and force the car to slide off the roadbed to the left. We modeled the collision in two segments. In the first segment, where we wanted to have snowplow contact, we modeled the locomotive as a 365,000-lb. rectangle 68 feet long and 10 feet wide. In the second segment, we decreased the locomotive width to one foot to simulate the coupler collision. We brought the locomotive into the collision at the planned speed of 25 miles per hour and allowed the simulation to proceed for about 0.25 seconds, until the clockwise rotational rate of the car had built up and the yaw angle was such that the left side of the car was just short of colliding with the coupler.

We then stopped the simulation and recorded position, speed, angle and angular rate values for the car at this point.

We now started up a second simulation, with these values as the automobile initial conditions. But, in this collision, the locomotive width was reduced from its actual value of 10 feet to 1 foot. We also set the locomotive back about 24 inches from where it was at the end of the first leg to account for the extension of the coupler assembly ahead of the left edge of the snowplow.

We started the second simulation and allowed it to run to completion. For the grade crossing surface, we had chosen a friction coefficient of 0.75, knowing that three of the car's tires were going to be sliding more or less sideways, but free-wheeling. The car was in Park, so the rear wheels were locked after impact. (In the real world, as will be seen below, the fire safety crews wet down the crossing surface and the friction was accountably lower than for a dry surface.) The fourth tire (left front) was going to be jammed by the collision, so we locked it midway through the collision process.

The EDVAP software did not allow us to have a shaped roadbed surface, but we did define two coefficients of friction. The boundary was set parallel to the highway surface at the north edge of the crossing surface. We were not sure exactly what the drag value would be for the loose roadbed ballast stone, but, we chose a value of about 0.5, substantially lower than for dry pavement, but enough to account for the tires digging into the ballast, which we knew that they usually do in real grade crossing incidents.

When we allowed the car to slide to rest, we found that, if the train hit the car at about 25 miles per hour, the car would be knocked and carried up the tracks about 114 feet before coming to rest on the west side of the tracks about 10 feet from the center of the tracks. We expected the car to rotate counterclockwise about 70 degrees during its post-impact motion.

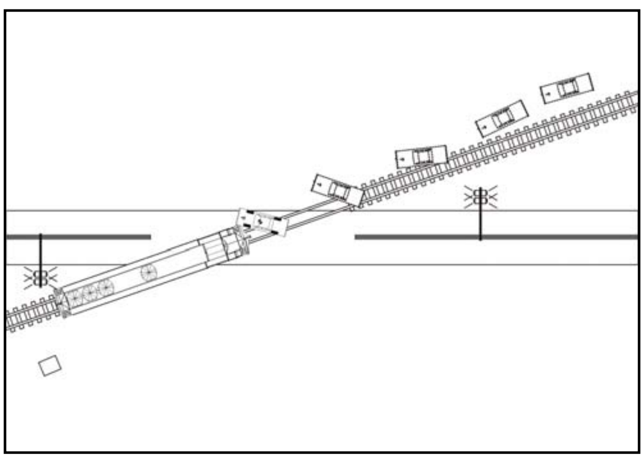

Figure 5. Predicted vehicle path

During our EDVAP simulations, we found that the locomotive responded to the collision forces by rotating a few degrees clockwise as it continued north. We knew that, in the real world, the locomotive wheel flanges would prevent that yaw rotation, but in order to simulate the collision as thoroughly as possible, we raised the yaw moment of inertia from its computed value of 105,000 lb-sec^2-in to about 2,000,000 lb-sec^2-in. While this value is significantly lower than the real value would have been, it limited the simulated rotation of the locotve to an acceptable value. (For comparison, the car's yaw moment of inertia was 29,294 lb-sec^2-in. We used an estimated value of 25,000 lb-sec^2-in in our EDVAP model.)

The predicted damage pattern on the car was based on the default crush stiffness values for the car. The locomotive was initially a generic pickup truck, lengthened and increased in width to become a 365,000-lb. vehicle. We did not attempt to model the very high stiffness of the locomotive. Rather, we used the default value from the program. The locomotive's huge mass and rotational inertia were the controlling factors. Correctly capturing the stiffness would not have significantly changed the outcome.

THE SET-UP

Weather cooperated, and Saturday, April 12, 1996 was a cool, cloudy, breezy morning. Rain threatened, but was never realized.

In our EDSMAC simulation, we had used a center-of-gravity location based on various publications that we keep in our office. But, the day before the actual demonstration, we learned that we were going to have three crash dummies in the front seat of the car. We also realized that the car was going to have water added to the fuel tank and video cameras installed in the back seat. All of these were going to have some influence on the location of the center-of-mass, but a negligible effect on overall car mass. So, we went to the site prepared to determine the actual location of the center-of-mass with everything installed. We located an 8-foot piece of steel pipe and a car jack. Once all the hardware was installed in the car, we put the pipe under the car laterally so that we could support the car in the center with the jack. We jacked up the car several times until we found the point where the pipe held the car completely balanced so that neither the front nor the rear wheels touched the ground. When we found that point, we painted a C.G. symbol on the driver's door at an estimated height of 22 inches.

We then lowered the car off the jack and moved it off the road until it was time to conduct the actual car crash.

INTO THE LOOKING GLASS

Channel 6 TV had arranged to produce a special effect for their production by taping the approach of the locomotive at full speed right into their camera. Not being particularly interested in destroying several thousand dollars in camera equipment, they purchased a 6-ft x 6-ft plate glass mirror and mounted it in a wooden frame. They placed the mirror at a 45-degree angle across the tracks in the same position that the car would ultimately be. A video camera was then placed at 90 degrees with respect to the tracks looking at a 45-degree angle into the mirror. The reflection in the mirror was, therefore, a virtual image of the train coming right at the camera.[3]

This run served two purposes: first, to obtain the spectacular image of the train coming right at the viewer, and second, as a "dress rehearsal" for the real thing.

There were lots of people who had gathered at the site. Many were in one way or another associated with the demonstration: Indiana Rail Road personnel, Operation Lifesaver representatives, Perry Township Fire Department firefighters, Marion County Sheriff's Department deputies, WOLF personnel, WRTV videographers, producers and air personalities, and others. In addition, many people in the neighborhood had come to see what "all the doings" were. By the time of the actual crash sessions, a crowd of nearly 100 people was in the area. Safety was paramount. We had to define clear zone areas where no persons could be located. One WRTV camera was located directly up the tracks about 300 feet north of where the car was on the crossing. We had to define a point where, if the train crossed that line, the camera operator was to pull his camera and tripod and get off the tracks.

The mirror collision probably generated more applause than the actual car crash. That is probably as it should be in that the car crash produced its intended results, a sobering warning of just what happens when a train hits a car. One potentially dangerous event occurred during the mirror crash: a piece of the 2" x 6" lumber frame used to mount the mirror stayed ahead of the locomotive, being pushed along the rail by the right front wheel. For a short period of time, we were concerned about a potential derailment of the locomotive. But, fortunately, it came free and the locomotive stopped before reaching the cameraman.

IT ALL COMES TOGETHER

Finally, at the scheduled time of 2:00 p.m. (more by luck than intention), we had the car on the tracks with its C.G. positioned properly with respect to the head end coupler of the locomotive.

---

[3]The image was, of course, reversed right to left, but this was corrected in post-production

WRTV personnel had mounted a small camera on a tripod in the back seat of the car next to the driver's side rear window. They had used nylon tie-wraps to lash the tripod to the window crank handle. Our impression of such a mounting method was that it was destined to fail due to the high g's we expected in the collision. But, that was their choice and we didn't comment. Cables were strung from the right side of the car to a video equipment van, which was set up on the west side of the road south of the collision site. Based on our prediction that the car would go about 114 feet north of the point of impact, they had laid out about 200 feet of signal cable to feed the van. This cable was laid on the crossing and dirt to the west of the point of impact so that it would pay out in a reasonably organized fashion and not get cut by the locomotive wheels.

The three dummies had been placed in the front seat of the car without their seat belts attached. A second camera had been installed in the back seat pointed toward the dummies to get some sense of how they moved during the crash.

No-Flash had been poured into the fuel tank, and the road had been hosed down to wash away the mirror debris from the previous run. The water on the rubber crossing surface probably reduced the drag coefficient somewhat. (Video from the camera directly up the tracks showed the water shooting out from under the tires as the car was shoved north over the crossing surface.) But, the lower friction probably protected the crossing surface by keeping the right side tires from demounting. If a tire had come off the rim, the rim would likely have ripped up the rubber mat surfaces.

The car was set at an angle of about 200 degrees with respect to True North, which implied that it had come around the north gate and was returning to its southbound lane as it crossed the tracks. The positioning was "fine-tuned" by bringing the locomotive right up to the car and then moving the car until the C.G. symbol was about halfway between the coupler and the left end of the snowplow. The coupler would enter just forward of the left C-pillar, which would put it behind the C.G, thereby causing the desired counterclockwise rotation.

The locomotive backed south to the Banta Road crossing (about one-quarter mile south of the crash site). The gates/lights/bell were activated at the crossing and warnings were called to all persons at the site that we were about to proceed. The train crew was notified by radio to start their run. The locomotive came around the curve into the site sounding its horn aggressively up to the point of impact.

In addition to the numerous WRTV cameras, WOLF personnel had two of our own cameras operating, one aboard the locomotive and one on the hill to the east of the grade crossing.

The locomotive made contact with the car exactly as planned. The car was shoved from the crossing to the north and slid off the tracks to the west side of the locomotive. As the car rotated counterclockwise, it was clear that the WOLF EDSMAC prediction was "right on track." (Knowing that there was a live microphone on the east camera, the plan was to be quiet while covering the whole process. But, if one listens closely, a soft exclamation, "Yes!" can be heard as the car disappears from that camera's view.) The car had gone into the safe zone as planned, no one was injured and no equipment was damaged.

Talking to the train crew immediately afterward, we found that the collision speed had been about 22 or 23 miles per hour, a little slower than planned.

Knowing where the car had been positioned (the post-impact tire marks were also evident), we were able to measure the distances which the car had traveled up the tracks. Whereas we had predicted that it would go about 114 feet north and about 10 feet west, it actually went about 112 feet north and 8 feet west, about 1.9 percent less than predicted. The left rear corner of the car was just clear of the left side of the locomotive as the car slipped off the tracks and down the ballast stone. While it is tempting to account for the slight reduction in throw distance by noting that the locomotive collision speed was a little lower than planned, we are not sure that the variables were so closely defined in all areas that this would be justified.

WRTV air personnel conducted interviews at the scene to document what had happened to the car, how the dummies had fared, and whether or not there would have been any survivors in a "real-world" event.

While there were, of course, no data recorders in the car to measure the linear and angular accelerations, the video records produced by all of the cameras clearly show that the car did rotate first clockwise and then counterclockwise about the amounts that we had predicted in the time frame we predicted. The post-impact distance was within a few feet of the predicted value when compared with the EDSMAC calculations. We have declared that the "pre-construction" using EDVAP and EDSMAC was a success.

RE-ANALYSIS WITH HVE

As a demonstration of the ability to use HVE for the same purpose, we used the same general techniques in EDSMAC4 to re-analyze the collision. We entered the same vehicle masses, using a modified "truck" to represent the locomotive. Instead of treating the collision in two separate legs, we installed a rigid block on the front of the locomotive to function as the coupler. This produced the proper rotational sequence without breaking the process into two legs, making the analysis easier.

By way of creating a more realistic scene, we conducted a site survey at the crossing. The track orientation, curvature, and slope were all modeled in AUTOCAD and used as the environment in the HVE system. We also surveyed the hill on the east side of the crossing.

By comparing frame grabs from the hillside camera with the current site, we determined exactly where the camera had been located during the crash demonstration. We surveyed that point into our scene drawing. We have been able to show the HVE simulation from that same viewpoint and "fade" from the HVE graphic to the actual video for comparison.

The HVE EDSMAC4 analysis predicted the car would travel about 109 feet north and 8 feet west, with a locomotive impact speed of 25 miles per hour.

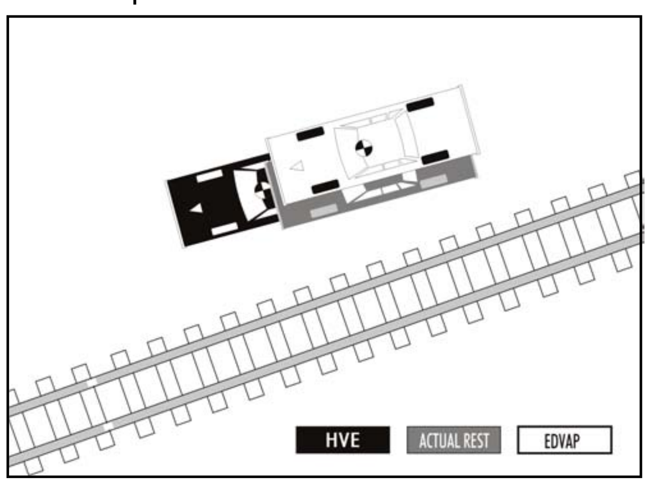

Figure 6. EDVAP, HVE & Actual Rest Positions

Final Comments

Using EDSMAC, WOLF successfully completed the assigned tasks for this demonstration. The vehicle traveled to its rest position in the safe zone without damaging any equipment. Everyone involved in the demonstration, both on the ground and in the locomotive was safe.