NATIONAL TRANSPORTATION SAFETY BOARD
Office of Research and Engineering
Washington DC 20594

Vehicle Dynamics Simulation Study

By: Shane K Lack

A. ACCIDENT

NTSB File Number:	HWY-00-FH-001
Location:	Intersection of State Route 30A and State Route 7 Schoharie County, near Central Bridge NY
Date:	Oct 21, 1999
Vehicle(s):	1997 International Am Tran 66 passenger school bus 1987 Mack Tandem Axle Dump Truck 1988 Interstate Trailer
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B Group ---PARTICIPANTS

Shane K. Lack	Group Chairman	NTSB Washington DC
Larry Jackson, MS, PE,	Group Member	NTSB Washington DC
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A: ACCIDENT SUMMARY

On Thursday, October 21, 1999, a Kinnicutt Bus Company school bus was transporting 44 students, ages 5 to 9, and eight adults on an Albany City School field activity. The bus was traveling north on SR-30A when it approached the intersection with SR-7. North and southbound traffic on SR-30A was controlled by a combination of stop signs and flashing red intersection control beacons for north and southbound traffic.

Concurrently, an MVF Construction Company dump truck, towing a utility trailer, was traveling west on SR-7. East and westbound traffic on SR-7 were controlled by flashing yellow intersection control beacons. The dump truck was occupied by the driver and a passenger.

As the school bus approached the intersection, it failed to stop and entered the intersection where it was struck on the passenger side behind the rear axle by the dump truck. After impact, both vehicles rotated clockwise. The school bus, after rotating approximately 145 degrees, rolled to rest upright facing south. The dump truck, after rotating approximately 150 degrees, struck a utility pole where it came to rest facing northeast. (See Figure 1, Attachment E)

B: Introduction to Study:

The primary goals of this study were:

1. To provide an estimate of the collision speeds.
2. To determine if the truck/trailer combination could have been traveling the speed limit prior to locked braking.
3. To provide a crash pulse estimate based on the EDSMAC4 crush algorithm for subsequent occupant motions studies.
4. To provide three-dimensional simulated views of the bus drivers approach to the intersection based on survey data and simulations.

This report contains three computer simulations that were conducted using the program EDSMAC4. The first simulation models the collision between the bus and the truck, and approaches shortly before the collision The other two simulations model the bus and truck approaches prior to the points where the collision simulation begins. The primary purposes of these two simulations were to provide timing for the potential views and to examine driver actions prior to impact.

C: Software Description

EDSMAC4

The EDSMAC4 program is a commercially available program based on the Simulation Model for Automobile Collisions (SMAC). SMAC was developed by NHTSA in 1970 in an attempt to develop a program that would achieve improved uniformity, as well as improvements in accuracy and detail in the interpretation of physical evidence in highway accidents. SMAC is a 2-dimensional mathematical program that predicts vehicle dynamics based on mathematical representations of Newton's laws. In order to accomplish this the program requires empirical relationships for some components (e.g., crush properties, tires) that are entered into the program. The user specifies initial speeds angles and driver inputs. The program, through stepwise integration of the equations of motion, produces detailed time histories and collision trajectories. The user then compares the SMAC predicted trajectories and collision deformations with the physical evidence to determine the degree of correlation.

EDSMAC4 is based on SMAC and shares a similar damage algorithm and tire model. It also relies on the same reiterative process in evaluating a collision. Some features not available in the original SMAC that are offered in EDSMAC4 are utilized in this study including the ability to model articulated vehicles.

EDSMAC4 is a physics model in the Human Vehicle Environment (HVE) system. The HVE system incorporates a 3-d environment and vehicles with the two-dimensional SMAC4 simulations and is capable of providing simulated drivers' views as part of the simulation process.

m-smac

M-smac is a simulation model based on SMAC and shares a similar damage algorithm and tire model. It also relies on the same reiterative process in evaluating a collision. M-smac was used in this study to conduct preliminary runs for the EDSMAC4, test the effects of rotational hitch forces, and to determine what the possible effects would be if the trailer's articulation was stopped by impact with the truck following the collision. Some features not available in the original SMAC that are offered in m-smac are utilized in this study including the ability to model articulated vehicles, the ability to model rotational hitch forces, and the ability to model articulation stops in hitches.

D: Discussion of Inputs and Various Items Relevant to Simulations

Inputs for the simulations are contained in Attachments G, I and J. Sources for these inputs are summarized in Attachments A, B, C and D. Brief descriptions of simulation inputs are provided below.

Scene/Environment

Scene measurements used for the simulations are based on survey data and measurements taken by Safety Board investigators. A three dimensional scene was built using AutoCAD release 2000 and survey data taken during the course of the NTSB investigation. The scene included signs and beacons. Beacons were 8 inches in diameter and flashed at a rate of 1 cycle per second. Signs were measured and their locations surveyed. Pictures were cropped and scanned onto sign surfaces.

Vehicle weights

The vehicle weights were obtained from measurements made by NTSB investigators during the investigation. The weight of the bus includes the estimated weight of the passengers and the driver. The method of estimating passenger weights is contained in Attachment A.

Vehicle Models

Vehicle dimensions are based on field measurements or manufacturer data. Information sources are identified in attachments A, C and D. The location of the vehicle center of gravity (cg) was estimated using the weights and dimensions from the NTSB investigation.

HVE provides default vehicle models that can be used for simulations. The user can change the properties of these models. The default vehicle used for the truck was the 93-94 Freightliner FLD 120 tractor; for the school bus it was it was a 1990 International Loadstar school bus. The trailer was built on a generic class 4 trailer.

The vehicle body models were from Viewpoint for the dump truck and school bus. The bus was modified to include a side emergency exit door. The trailer model was built by the NTSB based on site survey data gathered by the NTSB.

Moments of Inertia

The moment of inertia of the bus and trailer were calculated using the thin rod approximation (see Attachments A and D). Other possible methods for estimating the moment of inertia are contained in the same Attachments.

The total moment of inertia for the bus used in the simulation includes an estimate of the moment of inertia of the passengers about the cg of the bus. The estimation of the passenger moment of inertia about the cg of the bus is contained in Attachment B.

The moment of inertia of the dump truck was calculated using a formula provided by the University of Michigan Truck Research Institute (UMTRI). Other methods of calculating the moment of inertia are provided in Attachment C.

Tire/Road Friction and Tire Properties

The coefficient of tire/surface friction for the truck tires was 0.55. For the school bus it was 0.55. For the trailer it was 0.6. All values were from default values from the program. The HVE system uses a surface friction factor. The surface friction is multiplied times the tire/surface friction values listed above to get the friction on that surface. For the simulations contained in this report the surface friction factor was 1 for the paved surface. For the grass shoulder the multiplier was 0.85 except for the last 36 feet of grass that the bus traveled on. For this section of grass the combined effects of braking and friction due to the ground was modeled by using a 0.5 multiplier for the friction factor and brake inputs for bus.

Steering Brake and Crush Coefficients.

Driver inputs and crush coefficients were derived as part of the simulation process and are discussed in the sections describing the individual simulations.

<u>D: Computer Simulations</u>

Simulation 1 – The Collision

Several iterations of the collision were run varying the driver inputs and crush properties in EDSAMC4. The simulation that matched the physical evidence the closest (given the vehicle parameters in Attachment G which are outlined earlier in this report) indicated that at impact the bus was traveling approximately 23.6 mph. The truck was traveling approximately 39.5 mph. As a result of the collision the bus underwent a change in velocity of approximately 13.7 mph at the cg while undergoing a rotational change in velocity of approximately 115.0 degrees per second. When the truck impacted the pole it was traveling about 6.5 mph.

In the simulation the truck begins to steer left when the front of the bus is about even with the stop sign on the northbound approach (prior to the front of the bus reaching the stop bar). In order to match the vehicles' final rest positions and trajectories approximately -45.2 degrees (at the steering wheel) of pre-impact left steer was required by the truck. The bus required no pre-impact steering.

Range of Simulation Results

In order to test the sensitivity of the simulation results for given input ranges, simulations were conducted with the truck's impact speed 5 and 10 mph above and below that of the baseline simulations truck's impact speed (39.5mph). Simulations with truck impact speeds of 44.5 mph and 34.5 mph correlated well with physical data bus but exhibited less correlation with physical data than did the simulation contained in this report. This was despite attempts to improve the correlation by:

1. Increasing and decreasing the moments of inertia of the vehicles based on alternative methods of calculating rotational inertia as outlined in Attachments B and C.

2. Removing the occupant inertia from the total inertia of the bus in the simulation.

3. Changing the steering inputs.

4. Combining all three of these changes in various combinations.

Not all possible combinations of the above inputs were attempted.

Simulations with trucks impact speeds of 49.5 mph and 29.5 mph exhibited poor correlation with physical data. Attempts to increase correlation using the methods outlined in the previous paragraph failed to achieve correlation equivalent to those achieved at 44.5 and 34.5 mph. Again not all possible combinations of the possible inputs could be tried.

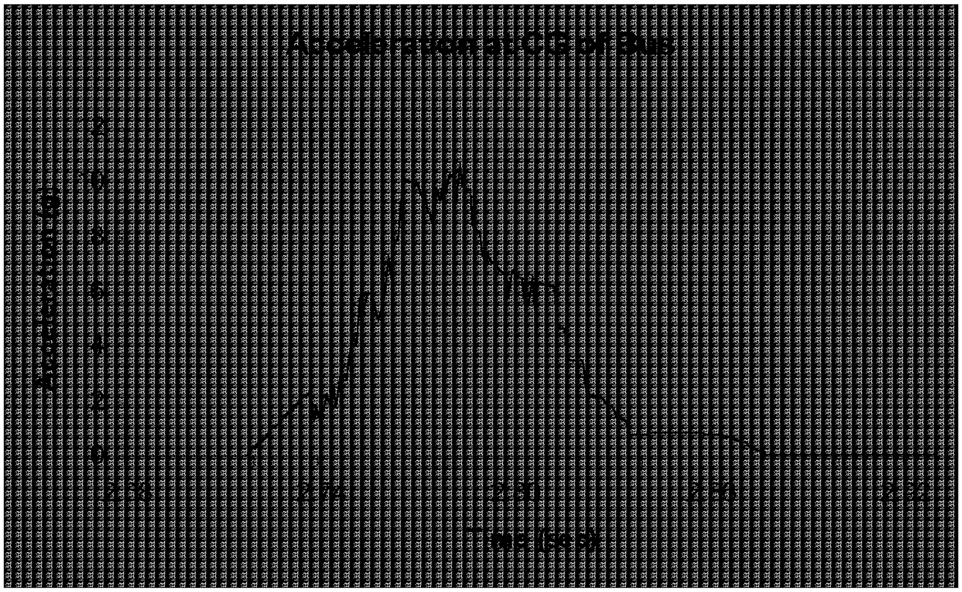
Truck's Pre-braking Velocity

The speed limit on the truck's approach was 55 mph. In the baseline simulation the speed of the truck prior to braking was about 55 mph. Because of the range of braking capabilities of the truck/trailer combination the actual speed could have been above or below this speed. Comparison of the trajectory of the truck and trailer tires in the simulations with the tiremarks indicated that only the trailer wheels were locked prior to impact. (In the simulations, the truck tires tended to travel to the left of the skidmarks due to the effect of the left steer, which was required prior to impact, see Attachment E.) Inspection of photographic evidence confirmed that the trailer tires could account for all of the skidmarks.

The range of deceleration rates for the tractor/trailer combination with locked braking was calculated to be between 0.28 and 0.47 g's based on the inspection of the truck and trailer brakes systems. (This calculation was performed by the Highway Factors Group.) The deceleration of the truck/trailer combination during the approach phase of the simulation contained in this report is 0.35g.

Crash Pulse Estimate

The simulation crash pulse for the cg of the school bus for is given below.



Because the bus experienced a rotational acceleration the crash pulse and delta v rearward of the cg would have been greater than at the cg.

In EDSMAC4 the vehicle is represented by a two dimensional rectangle. Vertical forces are neglected. During a collision time step the periphery of each vehicle's rectangle deforms to equalize the forces between vehicles. The direction of the force relative to a vehicle at each time step is dependent on the crush profile shapes and the orientation of the vehicles relative to one another. Because a collision is broken down into several time steps the magnitude and direction of crash forces can change several times over the duration of a collision.

The crash forces at each time step during a collision are a function of crush depth and the two-dimensional damage width and are characterized by the equation:

1) $F = (BX + A)*W$

Where:

F= the total force for that damage width
A = is a user entered crush coefficient
B = is the user entered intercept
X = the depth of crush (The perpendicular distance from the undamaged rectangle to the crush profile)
W = the damage width (the program breaks the damage width into small sections)

F is applied perpendicular to the collision interface. Another force, the inter-vehicle friction force is based on a fractional multiple of F and is applied tangentially to the two-dimensional collision interface. This coefficient is entered into the program by the user. A small amount of restitution is added at the end of each time step. The coefficients A and B are sometimes obtainable from crash test data.

Crash test data for the A and B coefficients was not available for the truck or bus in this accident. Crush coefficients in the EDSMAC4 program were varied during the simulation process in order to best approximate the crush profiles. The final simulation (the simulation contained in this report) approximates the vehicle crush profiles while correlating pre- and post trajectories of the vehicles and final rest positions.

Simulation 2 – the Bus Approach to the Intersection

The primary purpose of this simulation was to provide timing for approach of the bus and the potential views. In the simulation the bus is initially traveling at a speed of 30 mph approximately 850 ft south of the point of impact. (The bus' initial speed is based on 0.1 g acceleration over 311 feet of travel from the west bound off ramp stop bar from Interstate I-88. The calculation used here assumes that the driver stopped or slowed to a low speed at the off ramp.) From 30 mph the bus accelerates to 45 mph, at about 0.1 acceleration. After reaching 45 mph the bus decelerates at a rate of 0.1 g until reaching a speed of 24.5 mph, eighty-eight feet south of the point of impact where the collision simulation begins (about the point where the stop sign is).

Steering inputs (see Attachment J) for the simulation were adjusted to keep the bus in the center of the lane of travel.

Simulation 3- The Truck Approach to the Intersection

The primary purpose of this simulation is to provide time/distance for the potential views. In the simulation the truck/trailer combination is initially traveling at 54.5 mph and maintains a constant speed until reaching the initial position in the collision simulation.

Steer and braking inputs are contained in attachment I. Inputs were adjusted in order to maintain the truck in its lane of travel at a constant speed of about 54 mph.

I: Potential Views

Two simulated views of the bus driver's approach to the collision were built by combining the approach and collision simulations. Both views are of the same approach/collision scenario.

In the potential views the bus is initially traveling at a speed of 30 mph, (the speed it would have been traveling if the driver had exited the freeway, stopped, and accelerated at about 0.1 g). The bus accelerates at about 0.1g until reaching a speed of 45 mph. The bus then decelerates at 0.1 g until reaching a speed of 24.5 mph about 2.47 seconds prior to impact (approximately 88 feet prior to impact). The bus then maintains an almost constant speed up until impact.

The truck approaches the intersection at 54 mph. Approximately 2 seconds prior to impact the truck is steered to the left and braking is applied.

In the views the bus is about 150 feet south of the stop sign when it (the bus) first becomes visible in the truck driver's field of view. When it enters the truck driver's potential field of view the bus is traveling at about 35 mph and decelerating at about 0.1 g. The bus continues to decelerate at this rate until reaching the stop sign at which point it is traveling about 24.5 mph. During the bus' approach to the stop sign the truck maintains an almost constant speed of 54 mph in its original lane of travel. As the front of the bus reaches the stop sign (the stop sign is about 30 feet south of the stop bar), the truck begins to steer left. This left steer begins approximately 3.6 seconds after the bus first enters the truck driver's potential field of view.

Selected frames from the simulated views are contained in Attachments F and K. In the views the camera is placed to approximate the bus drivers view and eye height. Sign location and sizes are based on NTSB survey data and pictures.

The first view (see Attachment F) shows a simulated view of what the bus driver may have seen looking straight ahead as he approached the intersection. In this view the intersection and flashing beacon are visible; however, for at least part of the approach the stop sign at the intersection appears partially in front of the large orange commercial pumpkin patch sign. The stop sign then diverges from the commercial sign but remains in close proximity to the commercial sign in the driver's field of view.

The second potential view (see Attachment K) gives a simulated view of what the bus driver may have seen during the approach to the intersection if looking to the right. In this case the, the bus driver's view of the truck is obstructed by the passenger side mirror and the A pillar during portions of the approach. The location of the A-pillar and mirror in the simulation were taken from a combination of data gathered during the NTSB investigation and portions of a Viewpoint model.

Summary and Discussion of Results

The results obtained from the EDMAC4 simulation indicate that at impact the bus was traveling about 23.6 mph. The truck was traveling about 39.5 mph at impact. As result of the collision the bus underwent a change in velocity of about 13.7 mph at the center of gravity (cg) while undergoing a rotational change in velocity of about 115.0 degrees per second. Because the bus experienced a rotational acceleration the crash pulse and delta v rearward of the cg would have been greater than at the cg.

Simple parametric analysis performed during this study indicated that a conservative range of impact speeds for the truck would be 34.5 mph to 44.5 mph.

The simulation results also indicated that the truck could have been traveling the speed limit (55mph) when the driver locked its brakes.

The simulation indicated the bus was going about 23.6 mph at impact. The bus exited the ramp at the interstate and accelerated to at least 23.6 mph. Calculations indicated that the bus could have accelerated to about 45 mph and then decelerated prior to the impact.

The simulation crash pulse for the cg of the school bus is given in Figure 1 on page 10. The peak acceleration for the estimate was about 10.9 g's. Because the bus experienced a rotational acceleration the crash pulse and delta v rearward of the cg would have been greater than at the cg.

There are no driver inputs required for the simulation, such as steering or braking inputs, which would indicate that the bus driver reacted to the impending collision. There are driver inputs, including steering and braking input prior to the collision, that indicate that the truck driver reacted to prior to the collision.

Simulations in this report were used to create two potential views of the bus driver's approach to the intersection The first view (see Attachment F) shows a simulated view of what the driver may have seen looking straight ahead as he approached the intersection. In this view the intersection is clearly visible; however, for at least part of the approach the stop sign at the intersection appears partially in front of the large orange commercial pumpkin patch sign. The apparent convergence and subsequent divergence and close proximity of these two signs could potentially divert a driver's attention away from the stop sign and towards the commercial sign.

The second potential view (see stills in Attachment K) gives a simulated view of what the driver may have seen during the approach to the intersection if he looked to his right. In this case the, the driver's view of the truck is obstructed by the passenger side mirror and the A pillar during portions of the approach.

The simulations and simulated views also indicate that the bus could have been south of the stop sign and braking when the truck driver was first able to see the bus. If in fact the bus was slowing as it approached the stop sign, the truck driver may have thought it was coming to a stop and not have reacted as quickly as he would have otherwise.

While the actual timing of the bus and truck approaches to the intersection is not known, and driver actions during the approach are uncertain, these views illustrate factors, which could have affected the bus driver's response.

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