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Downhill Commercial Vehicle Simulations – Part B (Intercity Bus Equipped with an Engine Data Recorder)

Lawrence Jackson, PE, MS
National Transportation Safety Board

Kristin Poland, PhD
National Transportation Safety Board

ABSTRACT

The purpose of this paper is to present a simulation of a large intercity-bus during a mountainous descent. This paper discusses the SIMON simulation of a run-off-the-road intercity bus accident in Canon City, Colorado. The accident highlights some of the unique features in SIMON that allow the simulation of commercial vehicles that descend mountains. The simulation was matched to information from an Engine Data Recorder, and when combined they are a powerful tool.

INTRODUCTION

The purpose of this paper is to present a simulation of a large, commercial intercity-bus during a mountainous descent using the SIMON physics program contained in the Human Vehicle Environment (HVE) system.[1] This paper discusses the simulation of a run-off-the-road intercity bus accident in Canon City, Colorado. The accident involved a commercial vehicle braking on a long, mountainous descent. The simulation required SIMON to estimate the aerodynamic forces on the vehicle, to simulate the forces due to braking on a slippery surface during cornering and to simulate the loss of lateral control. The Canon City intercity bus was built in 1999, reflecting current commercial vehicle technologies including a DDEC IV engine recorder, ABS, and a transmission retarder.

SIMON has several unique features that were needed to refine simulations. The aerodynamic drag was used to slow these vehicles as they descended the mountain and to calibrate the drag in and out of gear. In the Canon City simulation the robust tire and suspension models were needed during the two loss-of-control events and also when brakes and the retarder were applied, – especially during cornering.

The Canon City bus had some of the more sophisticated equipment available. It had a DDEC IV engine recorder that provided one second snapshots of the speed of the bus, the throttle setting, engine rpm, engine load and the status of the brake/retarder. The bus had a transmission retarder that had six settings. At the highest setting the retarder was able to slow the bus at 0.1 G's. Unfortuantely the engine recorder did not differentiate between the brakes or the retarder being on. The bus also had ABS brakes[i]. The ABS turned the retarder off automatically after a 15% slip was detected. The bus also recorded electronic faults, but unfortunately they were not time stamped.

THE ACCIDENT

On December 21, 1999, at about 9:05 p.m. (MST), a 1999 Setra motorcoach carrying 60 occupants (a 72 year-old driver, 52 high school-aged students and 7 adult chaperones) was traveling eastbound on U.S. 50 about 8 miles west of Canon City, Colorado. Witnesses reported that the wind was blowing, it was snowing intermittently, the temperature was below freezing and the roadway was slippery.[ii] After traveling about to mile down the 7-mile grade, passengers

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[i] Unfortunately this was simulated before HVE and SIMON had ABS capabilities.

[ii] See the NTSB weather study for more details. The study indicated that most likely the surface temperature was minus 6 to 8 degrees Celsius (17.6 to 21.2 degrees F), with broken to overcast clouds, with occasional very light to light snow, with northwest winds at 5 to 8 knots (6 to 9 mph). The Colorado DOT was reporting icy spots, slush, and snow on US 50 in the vicinity of Canon City at the time of the accident.

related that the bus "fishtailed"; however, the driver was able to straighten it out. The motorcoach continued down the hill, which had several curves and grades ranging from 3% to about 6%. About 0.75 miles[iii] after the bus began to "fishtail", the driver lost complete control of the vehicle. The vehicle skidded clockwise 180 degrees and went backwards off the north side of the roadway. The vehicle then rolled at least one and a half turns as it went down a 40-foot-high embankment[iv], and came to rest on its roof. (See Figure 1). The driver and 2 students were ejected and fatally injured. The remaining 57 occupants sustained injuries ranging from minor to critical.

Figure 1: Final rest position of the bus.

This segment of the paper will discuss the initial loss of control of the bus just after Milepost (MP) 272, the final loss of control and rotation near MP 273 and the beginning of the overturn sequence which were simulated with SIMON. The simulation starts at about milepost 272. The simulation was matched as close as possible to the information obtained from the DDEC IV engine recorder.

The data from the simulation was compared to speed, throttle, and braking data from the bus's engine recorder in order to validate the simulation. The primary goals of this portion of the study were: 1) To approximate the motion and relative position of the bus as it traveled down the hill from the recorder information and 2) To determine if the retarder on the bus's transmission could have contributed to the loss of control. Since the data recorder on the accident bus did not differentiate between application of the brakes or the retarder, the determination as to whether or not the retarder was on, was based on the longitudinal deceleration rate of the bus and the stability of the bus as it negotiated the roadway.

DDEC IV

The DDEC IV engine recorder provided 60 seconds of data before and 15 seconds after the triggering of the hard brake event, which occurred during the rotation of the bus. The information included 1-second snapshots of the speed of the vehicle, the engine's rpm, the engine load, the throttle setting and if the brake or retarder was applied, although it was not specific as to which one. The DDEC IV only recorded time at 1-second intervals and speed to the nearest 0.5 mph.

Time History

Throughout this section of the paper, several time histories will be referred to including the time as indicated in the DDEC IV, the total simulation time, and the time for the simulation segment. "T_D" will indicate the DDEC IV time. The DDEC IV started 60 seconds before a hard brake and ended 15 seconds later. Five seconds were added to the simulation to stabilize the HVE suspension that bounced initially as the suspension was loaded. T_D time will be synchronized with total simulation time (T_S) and will include increments of decimal seconds. Total simulation time (T_S) was from the start of the simulation, five seconds before the DDEC IV started to record, until the bus came to rest. Each of the 9-segments simulated started at time=0. Segment time will be indicated as "T_{seg}".

Vehicle

The HVE default tractor, a 1993 Freightliner FLD 120 tractor, was also used to build and modify the bus. The bus was powered by a Detroit Diesel, Series 60, 430-horsepower diesel engine. The bus had an Allison model WT-B500R, 6-speed automatic transmission that was equipped with a 6-position retarder. The simulation program can currently model only standard transmissions. Information on the transmission was found on the Allison Transmission web page[2]. The automatic transmission ratios were entered as if they were for a standard transmission. The up and down shifts could be determined from the DDEC IV data using the engine speed and the vehicle speed. The bus's initial weight of 36,079 pounds was used. The brakes for the bus were modified for each brake's chamber size, slack arm length, drum diameter and width, lining thickness and measured stroke based on field measurements. The brakes were in good condition. The brake application and release times

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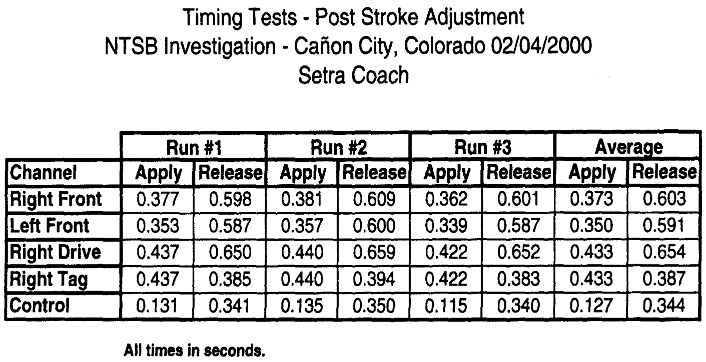
[iii] Based on simulation and matching speed/distance to start location. This distance is from beginning of the bus's lateral slide to the post for MP 273.

[iv] Computed from last upper tiremark to front of final rest position from mapping by NTSB.

were measured and the post-stroke times were added into the brake characteristics. Based on brake timing graphs that were obtained during brake testing on the accident bus[3], a 0.075 second lag time was used in the bus model before the brakes started to apply. The lag time was subtracted from the apply time in Table 1 and used as the rise time in the computer model.

Table 1: Brake timing tests



Timing Tests - Post Stroke Adjustment
NTSB Investigation - Cañon City, Colorado 02/04/2000
Setra Coach

	Run #1		Run #2		Run #3		Average	
Channel	Apply	Release	Apply	Release	Apply	Release	Apply	Release
Right Front	0.377	0.598	0.381	0.609	0.362	0.601	0.373	0.603
Left Front	0.353	0.587	0.357	0.600	0.339	0.587	0.350	0.591
Right Drive	0.437	0.650	0.440	0.659	0.422	0.652	0.433	0.654
Right Tag	0.437	0.385	0.440	0.394	0.422	0.383	0.433	0.387
Control	0.131	0.341	0.135	0.350	0.115	0.340	0.127	0.344

All times in seconds.

Simulation

The Initial Loss of Control (T_D = -1:05 to –0:43)

The first segment developed was from 5 seconds before the DDEC IV hard brake recorded data started until 17 seconds after the DDEC IV started to record or from T_D = -1:05 to -0:43. The simulation was started 5-seconds before the DDEC IV recording to stabilize the HVE bus suspension as the suspension was initially loaded. This segment was terminated after 22 (T_S) seconds because at that time it appeared the bus transmission was placed into neutral and the bus's rolling resistance was decreased. There was no physical evidence to initially locate the bus along the roadway. The location of the bus at the start of the DDEC IV recorded data was initially calculated assuming that the bus left the road near milepost 273 when T_D=-0:10 due to the 2 mph decrease in speed with no brakes being applied from T_D=-0:11. Then the average distance per second was calculated and summed from T=0:10 to 1:00 and found to be a total distance of 4,791 feet. To account for the additional 5 seconds for the bus suspension to become stable at 61 mph, an additional 447 feet was added for a total distance of about 5,238 feet[v] from milepost 273. Thus the bus was placed adjacent to milepost 272[vi] to begin the simulation.

A number of scenarios were examined for this segment using the initial surface friction multiplier from the ASTM skid test[vii] (0.418 to 0.386) for the road surface going around the first curve after milepost 272. At these friction levels the bus could manipulate the curve with out loss of control by braking or with the retarder coming on at 63 mph. Simulations were run to determine the lowest friction multiplier that could be used and still allow the bus to decelerate as indicated on the DDEC IV and negotiate the curve where the bus initially lost control, again based on the DDEC IV data.

The surface friction multiplier value was varied between 0.15, 0.20, and 0.25. With a surface frictin multiplier value of 0.15 and 0.20, the bus could not negotiate the curve. At 0.25 the bus did side-slip and yaw in the area where the DDEC IV indicated sideslip, however the curve could be negotiated. Thus the value of 0.25 was chosen for the minimum surface friction multiplier in the area just before and through the first left curve after milepost 272. Using the Michelin XZA tire values[viii] multiplied by the ASTM skid numbers, the resulting friction levels used in the simulation for the bus's first loss of control at the beginning of the data (T_D= -0:55 to –0:47) (combined longitudinal and lateral) ranged between 0.02 G's when the retarder was initially applied to a maximum of 0.20 G's when most of the forces were lateral. These values are well within friction ranges on snow or ice for tests with commercial vehicle tires.[4]

In preliminary simulations the brakes were modeled as an anti-lock braking system by cycling them twice per second from 85 to 95 percent of the value when the tire began to slide.[ix,x] In these runs the bus was able to negotiate the initial left curve (see Figure 2) without losing control so braking was not used and a retarder was applied. In later applications of the brakes on the downhill after the first 8-second-long application, the brakes were typically applied for less than a second and pressures were very low to match subsequent DDEC IV data.

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[v] Some sideslip appears to have occurred and the bus would have traveled at a higher speed and therefore a further distance.

[vi] This initial assumption appears to be correct within about a half a second based on the rotation of the bus at T_D=-0:04 where the speed recorded was 3.0 mph, most likely as the bus became perpendicular to the direction of travel.

[vii] Colorado Department of Transportation conducted ASTM skid tests at 40, 50 and 60 mph.

[viii] From the HVE default tire values which are based on testing conducted at Calspan Laboratories using the TIRF machine.

[ix] Gerhard Wieder, Bosch responded in an email to Larry Jackson, October 17, 2001 that the system worked at 2-3 Hz and utilized 85 to 95% of the peak friction

[x] HVE was modified to allow ABS after this simulation was completed.

In the initial simulations,[xi] the bus tended to gain too much speed as it descended the mountain road. To reduce the acceleration on the descent, the aerodynamic drag module in SIMON was used to slow the descent of the bus and provide aerodynamic and mechanical drag. The effectiveness of the retarder was evaluated in various positions by the NTSB in actual testing, resulting in measurements of the aerodynamic and mechanical drag on the bus when in gear with no retarder at 0.02 to 0.03 G's.[5] The surface area of the front and side of the bus were calculated and then reduced by 10% based on an EDC recommendation in a training session. The default value for the front aerodynamic drag coefficient of the truck was used (0.72). Initially a side value of 0.08 was used, but this was adjusted slightly in different portions of the simulation to help match the speeds from the DDEC IV. For the initial loss of control, an aerodynamic drag coefficient of 0.08 was assumed over the projected surface area of 61,787.6 square inches (the area of the left side of the bus times 0.9 (10% reduction)), to account for the light cross wind and to slow the bus.

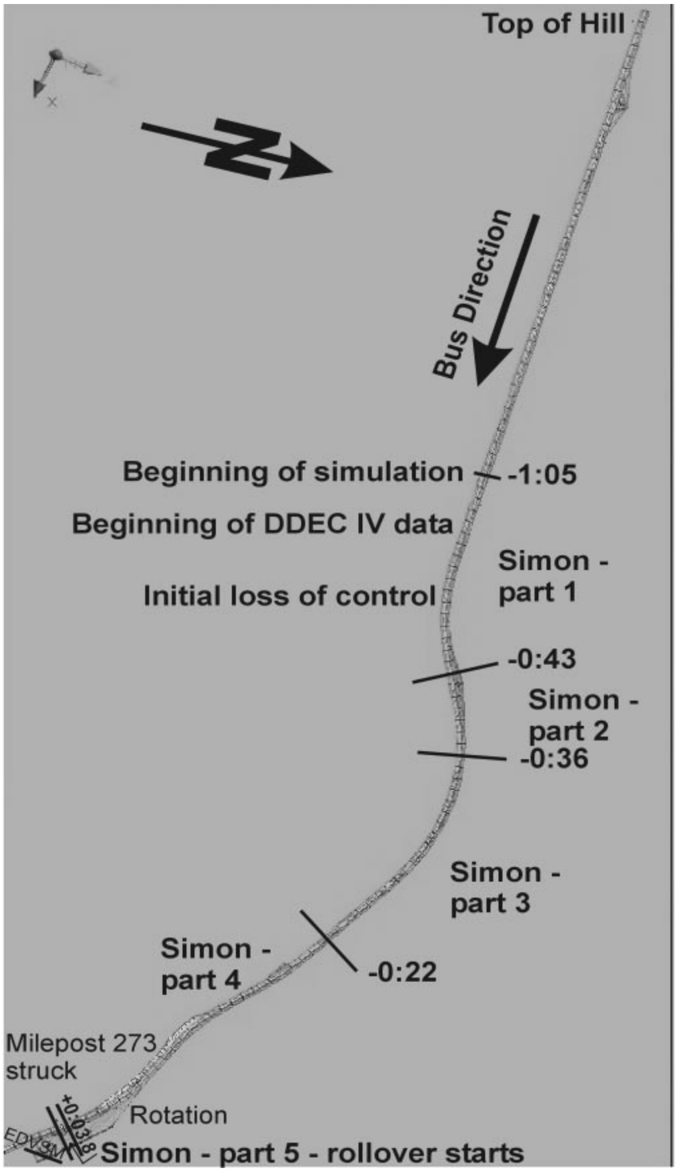

Figure 2 – Simulations assembled to portray the mountain descent

At T_D= –1:00, the brake or retarder was applied according to the DDEC IV. At this time it appeared that the throttle was just starting to increase from 0 to 33.2%. Normally if the throttle is applied the retarder would disengage. In the simulation initially, the retarder was used to control speed and have the bus traveling at 61.0 mph at T_D= –1:00. The throttle was added as indicated in the DDEC IV hard brake report for T_D=-1:00 to T_D= -0:57. Based on the engine speed and rpm data, calculations indicated that the bus was in 5th gear from T_D= -1:00 to -0:59, in 6th gear from T_D=-0:58 to –0:54 and in 5th gear from T_D= –0:53 to –0:44. Gearshifts were simulated accordingly.

From T_D= -0:55 to -0:48 the DDEC IV report indicated that the brake or the retarder was applied. Based on the simulations the best fit occurred when the retarder was applied through the drive wheels at about 700 pounds of force at the wheel. This resulted in total longitudinal decelerations of -0.01 to -0.02 G's when there was not a high lateral force (lateral forces peaked at 0.20 G's in the curve and a peak longitudinal force of -0.03 G's was obtained. In this area, the slope of the roadway was downhill at 6.0%, which would have resulted in an acceleration to the bus of about +0.06 G's. Thus the difference in acceleration due to the contribution from the downhill (+0.06 G's), and the contribution from the retarder (-0.01 to –0.02 G's) was 0.07 to 0.08 G's. This indicated that the retarder was in a high setting – either 4th, 5th, or 6th position based on the testing conducted to measure the retarder as indicated in Table 2. After the accident the retarder lever, that may have been disrupted in the accident, was found in 5th position.

Table 2: - Retarder deceleration in position 4, 5, and 6.

Retarder Position	Acceleration (G)
4	0.06-0.08
5	0.08-0.09
6	0.08-0.10

Table 3 shows a comparison of the DDEC IV speeds relative to the simulation speeds. For reference the vehicle actions as indicated in the DDEC IV. During the time from T_D= -0:51 to -0:46, the simulation and

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[xi] EDVDS was used initially – this program simulates a vehicle towing up to three trailers and is based on the University of Michigan's Transportation Research Institute's Phase 4 program, but because the bus gained too much speed on the mountain descent, it was not used.

DDEC IV do not match. This is the time during which a sideslip occurred because the recorded speeds are not realistic. Therefore, it was concluded that the DDEC IV was not recording the true vehicle speed[xii]. Based on the predicted speeds from the simulation, it appears that between T_D=-0:51 to -0:46, a sideslip was consistent with a retarder application. At T_D=-0:48 the difference between the simulated speed and the DDEC IV speed is 9.8 mph. Based on information from a Bosch official who indicated that at 7 to 8 mph, slip would initiate an ABS event, it can be seen that an ABS event likely turned off the retarder between T_D=-0:48 to -0:47 as shown with the termination of brakes.

Table 3: A comparison of the DDEC IV data versus the simulated data.

T_D (sec)	DDEC IV Speed (mph)	Simulation Speed (mph)	Vehicle Actions
-1:00	61.0	60.84	Brake/Retarder/Throttle
-0:59	61.5	61.62	Throttle
-0:58	63.0	62.87	Throttle/Upshift
-0:57	64.0	63.82	Throttle
-0:56	64.0	64.25	
-0:55	64.0	64.05	Brake and/or Retarder
-0:54	63.5	63.75	Brake and/or Retarder
-0:53	63.5	63.44	Brake and/or Retarder/Downshift
-0:52	63.0	63.10	Brake and/or Retarder
-0:51	63.0	62.72	Brake and/or Retarder
-0:50	61.0	62.27	Brake and/or Retarder
-0:49	57.5	61.79	Brake and/or Retarder
-0:48	51.5	61.28	Brake and/or Retarder
-0:47	58.0	60.95	
-0:46	60.5	61.02	
-0:45	61.0	61.19	
-0:44	61.5	61.49	
-0:43	62.0	61.88	Downshift to Neutral

The retarder applied braking through the drive wheels or the second axle of the bus. For any given tire/surface interface there was only a certain value of friction available. If all the friction was demanded laterally to go around a curve, there was not any available for slowing in the curve. Similarly if all the friction was required to decelerate, there would be no additinal friction available for lateral forces to negotiate a curve. Negating the effects of tire design (for some tires there is less lateral friction than longitudinal friction due to the design of the sidewalls), the relationship for tire friction is as follows:[6]

$$\text{Friction}_{\text{total}} = (\text{Friction}_{\text{longitudinal}}^{2}+\text{Friction}_{\text{lateral}}^{2})^{1/2}$$

On slippery surfaces, when the retarder is applied, the wheels try to slow while spinning in the longitudinal direction. This reducess some of the available friction from these tires. If the vehicle is negotiating a curve, the tires slide laterally if the combined longitudinal and lateral forces exceed the total available friction. Since the effective vehicle deceleration was -0.05 to -0.08 G's, and only the second axle was slowing the bus, the tires at the second axle were pulling a higher G-level at the tire road interface inversely proportional to the weight on the axle to the entire bus. Thus the tires on the second axle were pulling 0.11 to 0.17 G's longitudinally. As can be observed in this portion of the simulation, the vehicle was negotiating a left curve and the tires slipped to the right or outside of the curve. This rotated the bus counterclockwise, as viewed from above.

Figure 3 shows the location of the bus when the tires started to slip. The initial slips occurred at T_D=-50.37 seconds for the right #2 axle, -50.10 seconds for the left # 2 axle and -50.07 for the left #1 axle. This is 0.63 seconds after the maximum steering input of -50-degrees as the bus goes around the corner to the left. The design speed of the left curve was 50 mph and the advisory speed plate posted on the reverse curve sign before the curve was 55 mph. The speed limit for the road was 65 mph. The DDEC IV indicated the bus was traveling at 64 to 63 mph just prior to the curve. The bus's speed was below the speed limit, but above the design speed and the advisory warning speed for the curve. The lateral acceleration developed by the bus was about 0.20 G and the longitudinal acceleration on the retarder axle was 0.11 to 0.17 G for a total acceleration of 0.23 to 0.26 G, which approaches the maximum available friction that could be expected on a snowy, slippery surface.

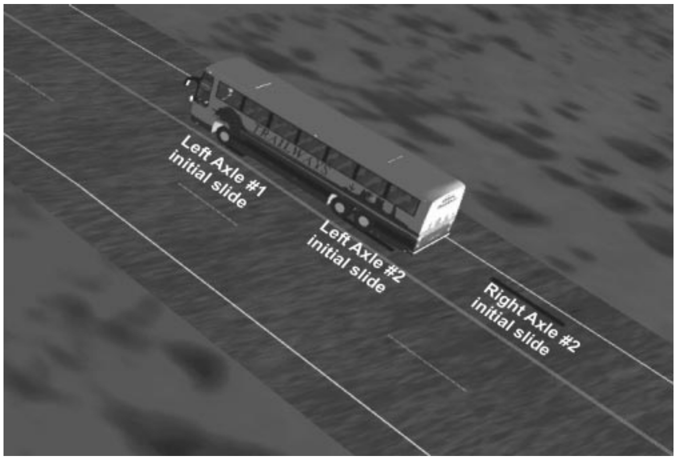

Figure 3: A view of the simulation showing when the bus tires began to slip.

[xii] In this part of the simulation the speed shown is the resultant speed of the vehicle and not the longitudinal speed. The speed shown by the DDEC IV appears to be the longitudinal speed.

In this first loss-of-control, several factors combined to result in the initial loss of control that resulted in the bus turning and yawing perhaps as much as 25-degrees. The first of these factors was the reduced surface friction due to the speed of the bus on a road with snow and slippery conditions. The second factor was the application of the retarder to slow the bus on the downgrade in a high range (4th, 5th or 6th position) that demanded longitudinal friction and reduced the available lateral friction. The third factor was the 1,273-foot radius curve had a design speed of 50 mph, an advisory speed of 55 mph and was being traversed by the bus at 61 to 63 mph.

When the available friction was exceeded, the bus started to yaw (see Figure 3). First, the right #2 wheel slipped as a result of the speed, the curve, and the retarder. Next, the left #2 wheel slipped. Then, the front left #1 wheel slipped and then the rest of the wheels started to slip. Eventually the retarder was presumably turned off by the activation of an ABS event for four seconds, but before it reactivated, the vehicle transmission went into neutral, disabling the retarder completely, based on the DDEC IV report.

Continuing down the hill (T_D=–0:43 to –0:22)

The next 21 seconds of the DDEC IV data were simulated in two SIMON runs as indicated in Figure 2. In these simulations the bus descended the mountain and rounded a right curve prior to entering the left curve near milepost 273 where the bus went off the road. In this section the bus was in neutral and continued to gain speed at the rate of about 0.5 mph per second from 62 mph to 70.5 mph, according to the DDEC IV. In the curves the simulations indicated that the bus was experiencing lateral forces of 0.25 to 0.35 G's. The DDEC IV data did not indicate any significant loss of control, but the bus was on the threshold for the reduced friction conditions due to the weather, as many of the preliminary simulations were unsuccessful. In this segment the brakes were applied four times according to the DDEC IV, each time for about a second and at low brake pedal pressures based on the simulations. The brake applications had little or no significant effect on slowing the bus. In a few locations the bus needed additional braking in the simulations to match the DDEC IV speeds. These applications were short in duration and could have been applied between the DDEC IV's one second sampling. These sections tied the initial loss of control and the final loss of control and helped to confirm the initial position of the bus at the start of part 1.

Final Loss of Control and Spinout (T_D –0:21 to +0:03.8)

This portion of the simulation examined how the bus spun out of control and the beginning rollover of the bus. In this segment, the bus struck the milepost marker and several delineators and the marks on the bus were used to determine the bus's position on the roadway. The right side of the bus went off the road to the right (south side) on a left curve, yawed counter-clockwise, struck milepost marker (MP) 273 and the adjacent delineator near the bus's right rear wheels, returned to the road and the front of the bus crossed the centerline (see Figure 4 at time T_D=-0:09.2 and –0:08.6) The bus then rotated clockwise about 180-degrees and as it spun, the left rear corner of the bus, near the bumper, struck another delineator on the opposite side of the road (north side – Figure 4 T_D=-0:04 – note the viewpoint changed and is looking the opposite direction for the last 3 frames in the figure). As the bus straightened and traveled backwards on the north shoulder it may have bent another delineator slightly to the north with the right side of the bus, forward of the front tire. The bus then struck another delineator with the rear bumper just to the left of the center of the bumper (Figure 4 - T_D=+0:02.1- note the bus is moving backwards in the last two frames of the figure). The bus then rotated about 12 degrees clockwise and rolled clockwise 22.7 degrees before the simulation was stopped, because the bus did not completely rollover, but instead slid sideways. The bus did not rollover due to the low friction value initially used on the slope and the relatively smooth surface did not act as a tripping mechanism, as was indicated by the furrows and struck buried rocks on-scene.

When this segment of the simulation started, the bus was about 0.76 miles past Milepost 272. In this area, the roadway is straight and it has a 4.86% downgrade. The DDEC IV report indicated that brakes were applied for three seconds between T_D=-0:21 to –0:19 (see Table 4). The simulation required a 26.8 pound brake pedal application followed by very light applications of brakes for the next two seconds to maintain the DDEC IV speeds.

At T_D=-0:19 to –0:16 the DDEC IV data appeared to be inaccurate for one or more seconds, in that the bus accelerated too much (1 mph with brakes on, at T_D=-0:17 to –0:16). In the initial simulation segment, the bus lost speed according to the DDEC IV when the bus slipped and yawed, which would indicate that perhaps the data at T_D=-0:18 to –0:17 could be low due to yawing. If T_D=-0:18 to –0:17 were low, braking would have to be reduced prior to this time and T_D=-0:16 to –0:12 could be matched more closely with a slight decrease to the bus's aerodynamic drag.

At T_D=-0:11 to –0:10 seconds, the bus was yawing off the side of the road and the DDEC IV speeds were incorrect because the speed was being measured along the longitudinal axis of the bus which changed direction as the bus yawed (see Table 4). Thus only a part of the bus's speed was measured when it was yawing. When the bus began a rotation, DDEC IV speeds changed quickly during the rotation and it appeared as though the longitudinal velocity was very close to the reported DDEC IV speeds. This resulted because in the DDEC IV data, a speed sensor on the transmission's output shaft monitored the vehicle's speed and the wheels were turning the shaft in the longitudinal direction only. At T_D=-0:04 seconds, the bus was almost perpendicular to the direction of travel and the forward speed of the tires was also 0 mph (reported in the DDEC IV as 3.0 mph). The DDEC IV does not differentiate between forward and backward velocity. After the bus started to travel rearward, it traveled at a speed of 29 to 44 mph. The bus then struck the delineator with the rear bumper and began to rotate clockwise down the hill. The speed of the vehicle is not reported accurately in DDEC IV data as the bus yaws on the hill. (T_D +0:01 to +0:03).

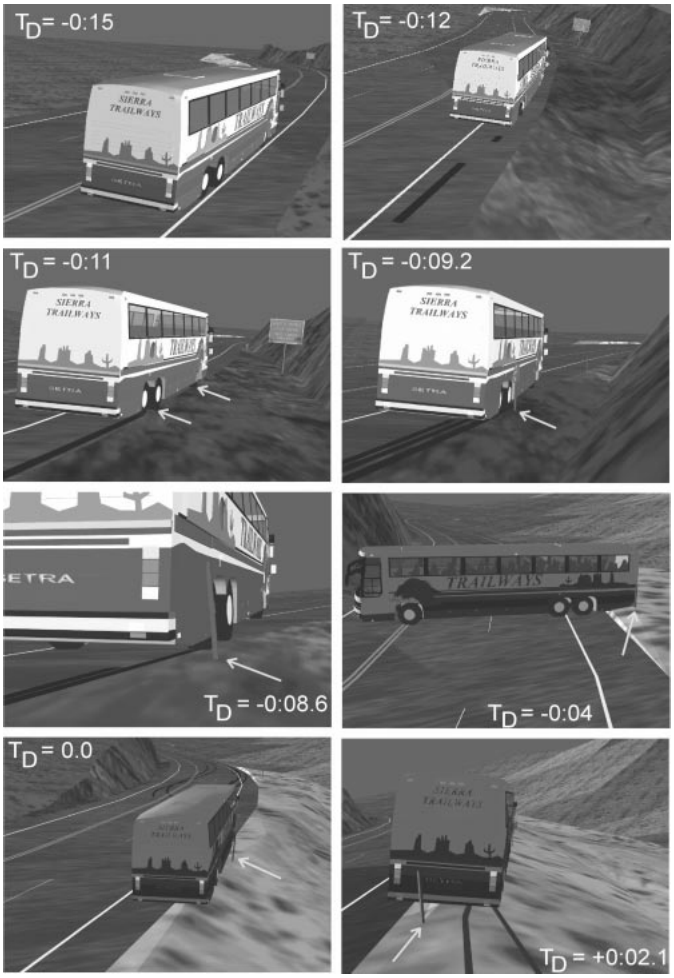

Figure 4 - The bus positions and impacts with delineators and mileposts from the simulation. Note the last three frames are shown from the opposite direction as the bus rotated around and continued backwards.

Table 4: A comparison of the DDEC IV data versus the simulated data, continued. (U-vel is positive(+) toward the front and v-vel is positive(+) toward the right)

T_D (sec)	DDEC IV Speed (mph)	Simulation Speed (mph)	Simulation u-vel (mph)	Simulation v-vel (mph)
-0:22	70.5	70.57		
-0:21	69.5	69.72		
-0:20	69.0	69.25		
-0:19	69.0	68.91	68.90	-0.08
-0:18	68.5	68.46		
-0:17	68.5	68.25		
-0:16	69.5	68.25		
-0:15	69.0	68.26		
-0:14	69.0	68.25	68.24	0.80
-0:13	69.5	68.28		
-0:12	69.5	68.43	68.40	1.89
-0:11	67.0	68.63	68.60	1.70
-0:10	65.0	68.81	68.70	3.86
-0:09	68.0	68.81	68.28	8.48
-0:08	66.0	68.06	67.01	11.92
-0:07	60.0	67.04	66.82	-5.47
-0:06	47.5	64.07	59.02	-24.90
-0:05	25.5	58.10	42.05	-40.05
-0:04	3.0	49.38	17.48	-46.06
-0:03	-	43.85	3.10	-43.72
-0.03	-	41.17	-3.01	-41.00
-0:03	19.0	38.70	-8.85	-37.57
-0:02	44.0	29.93	-26.13	-14.57
-0:01	36.0	28.94	-28.89	1.74
0:00	28.5	29.55	-29.53	1.11
+0:01	11.0	30.36	-30.35	0.80
+0:02	2.5	31.30		
+0:03	3.0	32.55		

The speed limit in this segment, as on the rest of the downgrade, was 65 mph. Before the bus went off the road to the right there was a winding road sign with an advisory speed plate of 55 mph. The design speed on the highway plans was 50 mph. As the bus went into the curve it was traveling about 69 mph based on the DDEC IV report. The simulation indicated that the bus could have negotiated the curve if it had steered more, prior to going on the shoulder and stayed in the lane, if the 0.25 G friction surface was available, and if the brakes were not applied, as indicated in the DDEC IV report. The bus was on the threshold of exceeding the calculated safe speed in the curve of 69.1 mph as it negotiated the curve at 69.5 mph, according to the DDEC IV, on the shoulder if the friction was 0.25 G's. When the bus ran off the edge of the pavement, the change in slope[xiii] and the lowering of the friction would have resulted in the bus sliding out and yawing in the curve as it did in the simulation, and as observed in the physical evidence when the milepost sign struck only the rear portion of the bus near the rear wheels.

In this segment of the simulation four factors combined to result in the final loss of control. The first factor was the reduced surface friction due to the road surface conditions and the high speed of the bus. The second factor was the bus appeared to not have been fully cornering early in the curve as it left the road onto the shoulder. The third factor was the bus went onto the shoulder and then off the shoulder onto the snow and grass. As the bus ran off the road, the super-elevation decreased which would have reduced the critical speed in the curve for the bus. When the tires were off the pavement the bus began to yaw as the critical speed for the curve, the super-elevation and the available friction were exceeded. Then the rear of the yawing bus struck milepost 273 and the next delineator. The fourth factor was the bus had to be steered hard left to get the bus back onto the roadway after hitting the milepost marker, and then quickly steered hard right to avoid going off the other side of the road. The corrective right steer had to be of short duration, once the bus was straightening out or it would have continued to rotate, according to the simulation.

After the bus had rotated more than 180 degrees and was headed backwards along the north edge of the embankment, the bus had a little more steering added to try to return the bus to the roadway while traveling backwards down the edge of the road. With the right wheels in the snow, the bus slipped further down the embankment and rolled over. During these maneuvers the DDEC IV indicated that brakes were not activated.

The Initial Roll (T_D = +0:03.8 - +0:04.8)

Only a one second segment was simulated as the bus rolled from 22.7-degrees[xiv] to 87.9-degrees (just before impact with the ground). In order for the bus to roll and first impact the ground in the area where front windshield glass and pieces from the right side mirror were found, the surface friction multiplier was increased to 1.74. This increase caused a trip as the bus tires slid sideways in the dirt as evidenced by the rear tire furrows on-scene. In addition the tires may have been snagged on some of the large rocks that were observed embedded in the embankment and the dirt and grass that was in the tire rims.

The SIMON simulations also indicated minor problems with the super-elevation, the roll of the vehicle, and the vertical bounce just before the horizontal curve as a result of a change in vertical alignment. In the interest of brevity, these areas were not discussed in this presentation.

CONCLUSIONS

The Canon City accident highlights some of the unique features in SIMON that allow the simulation of commercial vehicles that descend mountains. Aerodynamics may have to be adjusted to account for mechanical and aerodynamic drag. Perhaps the most important aspect highlighted was the strength of combining the engine data recorder data with a simulation to highlight factors and eliminate factors that may have contributed to a side-slip or a loss-of-control. In the simulation, it was possible to show the vehicle's relative position to the environment when critical actions were occurring. The simulation demonstrated that the transmission's downshift was not involved in the initial loss-of-control. The simulation showed that the bus lost control initially as steering was being increased as it entered a curve from a spiral curve at 63 mph with the retarder in a high setting. The simulation showed that the bus's second loss of control occurred when the bus drifted off the shoulder to the right and hit the milepost marker. The bus needed a large steering input to recover from being on the shoulder, and a similar corrective steering to keep the bus from going off the other side (left) of the road. In the corrective steering the bus was oversteered, and began to rotate 180-degrees clockwise. As the bus rotated, SIMON replicated the speeds shown by the DDEC IV and indicated that the bus was within 30 to 50 feet of where it should have been when it was perpendicular to the road.

REFERENCES

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[1] Engineering Dynamics Corporation, Beaverton, OR
[2] http://www.allisontransmission.com/product/series/b500_specificationsheets.jsp
[3] Bendix Commercial Vehicle Systems – Setra Bus Inspection, Item 5, Project ID 48373, Accident No. HWY00FH011
[4] Navin, Francis, Macnabb, Michael, Nicolletti, Connie; "Vehicle Traction Experiments on Snow and Ice", SAE 960652, 1996
[5] Vehicle Dynamics Simulation Study, Lawrence E. Jackson, July 20, 2002, Project ID 48373, NTSB Accident ID HWY00FH011
[6] Clark, Samuel K., Mechanics of Pneumatic Tires, National Bureau of Standards, Monograph 122, November 1971

[xiii] One tire was on the shoulder and one was on the assumed grassy/snowy area near milepost 273, so the effects would have been theoretically between the two calculations for on the shoulder and on the dirt slope, but the tire on the dirt slope would have started to slip and governed the safe speed.

[xiv] Due to the slope of the embankment, the roll started at 22.7 degrees.