Downhill Commercial Vehicle Simulations – Part A (Tractor/Semi-trailer Brake Fade)

Lawrence Jackson, PE, MS
National Transportation Safety Board

Kristin Poland, PhD
National Transportation Safety Board

ABSTRACT

The purpose of this paper is discuss the SIMON[1] simulation of a brake fade for a tractor/semi-trailer in Mountainburg, Arkansas. This accident highlights some of the unique features in SIMON that allow the simulation of commercial vehicles that descend mountains. The relationship between brake lining temperatures and friction was also modeled in order to more accurately simulate the brake fade.

INTRODUCTION

The purpose of this paper is to present a simulation of a large, commercial vehicle during a mountainous descent using the SIMON physics program contained in the Human Vehicle Environment (HVE) system.[2] This paper discusses the simulation of a brake fade for a fully loaded tractor/semi-trailer in Mountainburg, Arkansas as it negotiated a long, mountainous descent. The simulation required SIMON to apply aerodynamic forces on the vehicle and to simulate the forces due to braking. The Mountainburg tractor/semi-trailer was built in 1989 reflecting older commercial vehicle technologies that are still on the road. The brakes were not adjusted properly as discovered through post-accident inspection.

SIMON has several unique features that were needed to refine the simulation. The aerodynamic drag was used to slow the vehicle as it descended the mountain and to calibrate the drag in gear. Brake Designer was needed to account for the hot brake linings and to simulate brake fade.

Literature Review

Heavy trucks and buses utilize air brakes. Most of these are drum type units. Air enters the chamber when the brakes are applied, the push rod moves out turning the slack adjuster which rotates the "S" cam and forces the shoes into the drum. (See Figure 1.)

Brakes operate by converting kinetic energy (motion) into thermal energy or heat. A full stop from 60 mph can raise brake drum temperatures to 600 degrees F. This is about the limit for safe operation. If the brakes aren't functioning properly, or the load is not distributed properly, then some drums might reach 800 - 1300 degrees F[i][3]. The drum will increase in diameter about 0.01-inch per 100-degree temperature rise, so that even at 600-degrees the drums will be 0.055 inches larger than at 50 degrees. The increased drum diameter will increase the pushrod stroke required to apply brakes by about 0.40 inches.

As the drum heats up it expands and moves away from the shoes. With an air brake system, the stroke of the pushrod and thus the distance that the shoes can be moved out into the drum is limited. If the brakes are improperly adjusted, when they get hot it is possible to run out of stroke before the shoes make good contact with the drums.[4]

[i] The Safety Board's Metallurgy investigation of a bus accident near Palm Springs, CA on July 31, 1991 found abnormal microstructure, indicating exposure to temperatures over 1300^0 F followed by rapid cooling.

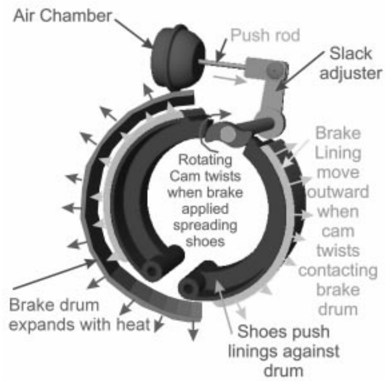
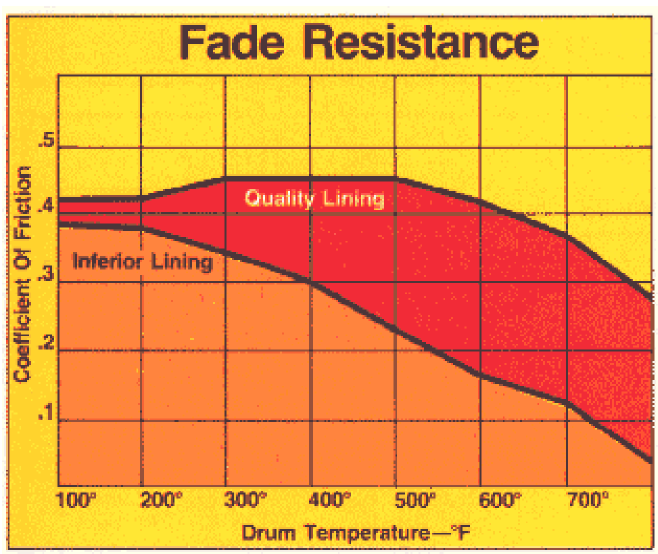


Figure 1: Truck air brake.

When brake linings get hot, the friction provided by the linings decreases. The linings no longer offer the same resistance to the rotation of the drums. Figure 2 shows a graph of drum temperature and the decrease in coefficient of friction as temperatures exceed 600^0F.



Fade resistance testing measures the ability of a lining material to maintain coefficient of friction with increasing temperature.

Figure 2: Drum Temperature versus Coefficient of friction.[5]

A report by Fancher, et al.[6] tested two trucks, a straight truck and a fully loaded tractor/semi-trailer on a 4.7-mile downgrade with grades of 4.5 to 7 percent at low speeds (20 mph for the tractor/semi-trailer to 36 mph for the straight truck). The study was conducted to determine what information should be included in the Commercial Driver's License on braking a truck while descending mountain roads. The study determined that it was better to apply more pressure (about 20 pounds) for 3 seconds and then release for about 6 seconds (called a snub) than to apply brakes at a low level of pressure (10 pounds) and hold them on while descending the mountain. The snubbing resulted in slightly lower brake temperatures. The hottest brakes were cooler if the snubbing strategy was used, but the difference was not large. The study found that rear brake drums cooled at a rate of 0.4^0F/second when the brake temperature was about 300^0F above ambient temperature, or at higher temperatures, 20 minutes to cool from 600 to 200^0F when the vehicle is traveling 50 mph (See Figure 3). Some of the test runs were aborted when the temperature of the hottest brake drums reached 1000^0F. The test measured the drum temperatures in two locations and the lining temperatures in one location. The average of the two drum temperatures was about 100^0F hotter than the reading from the lining thermocouple. In Figure 6a of the Fancher report, the lining temperature was 160 degrees F lower than one of the drum thermocouples. The study indicated that at speeds above 30 mph the rolling resistance, engine drag, and aerodynamic drag was 1 to 2% for these two trucks. The tractor/semi-trailer had a 0.014 G deceleration in gear and a 0.01 G deceleration in neutral[ii]. About 25 snubs or a snub every 8.86 seconds was needed for the straight truck to maintain speed at plus or minus 3 mph[iii]. When a limiting valve was used, large differences in brake temperatures were observed, because the front brakes do almost no work when the limiting valve is employed and low brake pressures are used. The study also noted that very high brake temperatures resulted if some brakes were not doing much work.

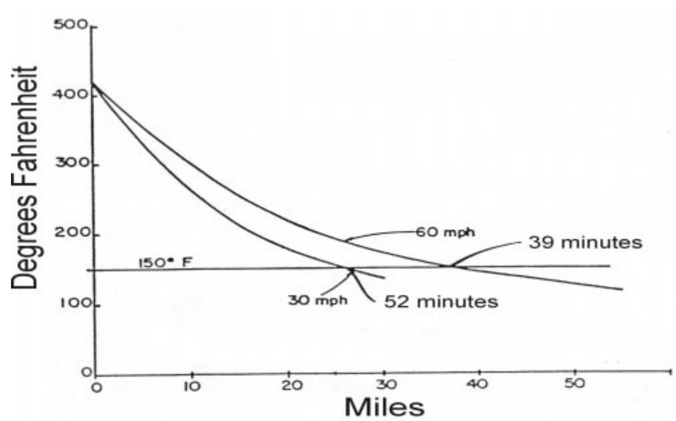


Figure 3: Truck Brake Cooling with distance for S-cam drums at 30 and 60 mph. (At 30 mph it would take the truck about 26 miles or 52 minutes to cool from 410^0F to 150^0F.)[7]

The Grade Severity Rating System[8] (GSRS) computer program was developed to reduce the probability of large truck runaway accidents on severe downgrades. It was designed to determine the maximum safe downgrade speeds for different weight categories of

[ii] Radliniski indicated that parasitic drag on an 80,000 pound rig at 55 mph would be about 205 horsepower, which is about 0.0175 G.[7]

[iii] Similar data on the semi-trailer was not included in the report.

five axle trucks not equipped with retarders. Safe downgrade speeds were determined by a mathematical model based on gross truck weight and physical features of the downgrade to predict brake temperature. The model determined brake drum temperatures generated by maintaining a constant speed on the downgrade plus the temperature generated by performing an emergency stop. The loss of truck brake system efficiency (brake fade) started at temperatures in excess of 500^0F and continued with increasing efficiency loss leading to brake failure at temperatures in excess of 700^0F. Five axle trucks, without retarders, that descended the downgrade at the recommended safe speed were able to safely perform an emergency stop if all brakes were within adjustment.

VEHICLE DYNAMIC SIMULATION - MOUNTAINBURG, ARKANSAS

On May 31, 2001, about 3:28 p.m., a southbound Gayle Stuart Trucking, Inc. truck tractor semi-trailer exited I-540 at SH-282 near Mountainburg, Arkansas. The driver was unable to stop at the stop sign at the bottom of the ramp due to the truck's loss of braking capability. The 79,040-pound combination unit was traveling approximately 48 mph when it ran the stop sign and collided with the right side of a westbound 65-passenger 1990 Blue Bird Corporation school bus operated by Mountainburg, Arkansas, Public Schools. The schoolbus rotated 302 degrees and came to rest on its right side on the eastbound shoulder of SH-282. The combination vehicle continued across SH-282 and came to rest on its left side. (See Figure 4.)

Three schoolbus passengers seated across from the impact area were fatally injured; one was ejected. Three of the remaining passengers received serious injuries and three passengers had minor injuries. The driver of the schoolbus sustained serious injuries and the truck driver had minor injuries.

Figure 4: Final rest position of the vehicles (bus on the far right and the truck behind the stop sign).

The vehicle dynamics simulation was based on the vehicle inspection[9], physical evidence at the scene and the mapping of the scene[10] performed by the Safety Board. The simulations were performed using the Human Vehicle Environment (HVE) system developed by Engineering Dynamics Corporation[11].

Vehicle

The HVE default tractor, a 1993 Freightliner FLD 120 tractor, was used to build and modify the tractor. The tractor was powered by a Caterpillar Model 3406B Diesel engine. The HVE default tractor was modified to include a 9-speed transmission, and a 3.90:1 differential. The tractor 's initial weight of 16,805 pounds was used. The brakes for the tractor and the semi-trailer 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 tractor was also modeled with a proportioning valve of the tracor's front brakes.

The semi-trailer was built using a HVE generic 48-foot-long, 1993-Great Dane Flatbed semi-trailer that was modified, and the proper load was added.

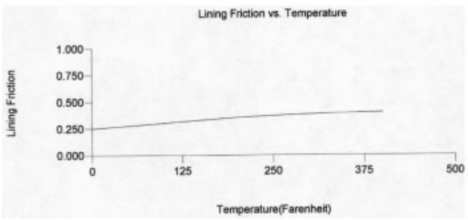
Brake Temperatures

The GSRS program was used by the Safety Board[12] to determine the temperature of the truck's brake drums on the descent from the tunnel. Modifications were made to simulate the truck's out of adjustment brakes. The 11.2-miles of mountain roads were broken into 500-foot segments and for each segment the efficiency of the brakes had to be calculated using the Heusser equations.[13] Thus the GSRS was run about 115 times with a calculation of efficiency for each simulation. From the tunnel to the accident site, the average truck speed was 60 mph.[iv] On the first descent the brake drum temperatures increased from 150^0F to 680^0F according to the GSRS program. The brake drums then cooled to 613^0F on an ascent. On the second downgrade the drum temperatures further increased to 930^0F before cooling to 812^0F on the next ascent. On the third descnt, the brake drum temperatures were predicted to increase to 837^0F before cooling to 809^0F on the 0.4 mile ascent at the top of a small hill, about 3,500 feet before the top of the exit ramp before the accident location. According to the GSRS program, from the top of the hill to the top of the ramp, the brake drums heated to 914^0F, based on a 60 mph speed.

Brake Lining System

The default HVE brake lining values, as shown in Figure 5, were modified to reflect the high temperatures predicted in the GSRS program and the associated lining friction values.

[iv] Based on a picture of the truck in the tunnel with a time indicating that the truck traveled 12 miles in the 12 minutes prior to the crash.

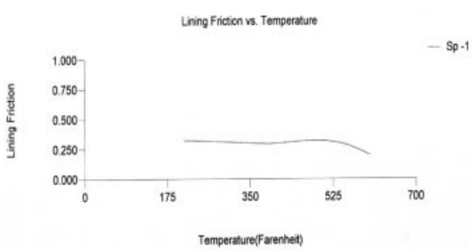


HVE Default Lining Temperature (Farenheit)	Lining Friction
0	0.25
100	0.3
200	0.35
400	0.4

Figure 5: Default HVE brake lining values.

A literature search found drum brake temperature data for several 1984 truck brake linings used in different types of trucking as indicated in **Error! Reference source not found.**. This indicated that friction between the drum and lining started to decrease when the drum temperature was above 500^{0}F.[14]

Several inquiries were made to brake lining manufacturers requesting tables for truck lining temperatures and friction. One company responded with information on heavy-duty truck/semi-trailer brake lining friction versus temperature data. The company official indicated that the data should be considered as typical of popular non-asbestos brake linings used on today's vehicles, both as original equipment and for re-lines. This data ended at 603^{0}F, but the trend for lining friction fall-off with increased temperature was observable. (See Figure 6.)



ave mu	C	F
0.319	100	211
0.303	164	326
0.292	196	385
0.318	250	482
0.266	296	564
0.193	317	603

Figure 6: A typical, popular non-asbestos brake linings used on today's heavy duty vehicles.

The brake company representative was asked if it would be fair to model the 0 point for friction lining at 1,100^{0}F or 200^{0}F lower than what drum temperatures are known to reach, and he responded that it seemed reasonable. Thus a point was added to the company's data for 0.01 friction at 1,100^{0}F. HVE automatically extends a curve through the points, which resulted in negative values. The data point was reduced to 1,000^{0}F and then 950^{0}F and it continued to have negative values (See Figure 7). Another value around 1000^{0}F was not used because there were insufficient points that could be used to decribe the points provided by the brake manufacturer and the end point, and an additional point tended to not drop the curve quickly in the 700^{0}F range.

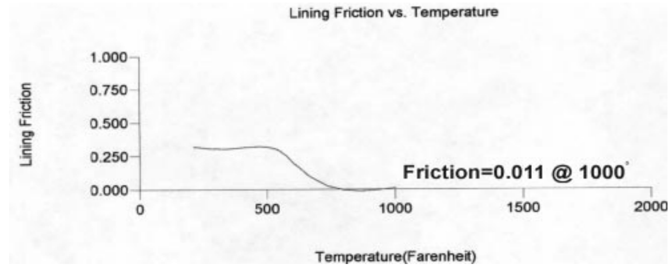
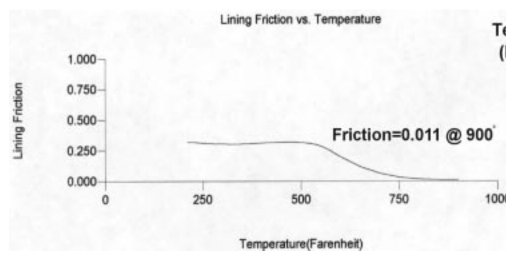


Figure 7: HVE data with friction = 0.011 @ 1,000^{0}F.

Finally, at 900^{0}F the values were all positive. The friction lining temperature curve used for the truck brake modeling in the simulations is shown in Figure 8. This curve is substantiated by the manufacturer data, initially, and by the GSRS report for the final portion that indicated "The loss of truck brake system efficiency (brake fade) starts at temperatures in excess of 500^{0}F and continues with increasing efficiency loss to brake failure at temperatures in excess of 700^{0}F.[8]"



Temperature (Farenheit)	Friction
211	0.319
326	0.303
482	0.318
564	0.266
603	0.193
900	0.01

Figure 8: HVE data with friction = 0.011 @ 900^{0}F.

Simulation

The accident was simulated in several parts. Initially the accident was simulated to determine the speed of the truck at impact using EDSMAC4. Then the truck's ascent and descent approaching the accident site were simulated looking at the brake temperature and vehicle stopping performance. Adjustments to the impact location were made based upon the simulated brake temperatures and stopping performance. The best match of the physical evidence occurred when the speed of the bus was 50 mph and the truck was 48 mph at impact.

Although not discussed in this paper, SIMON was used to simulate the truck and bus after the impact separation as the vehicles initially rolled.[15] SIMON was also implemented to simulate the truck climbing the hill before the ramp, descending the hill, and descending the ramp to the impact location. SIMON was necessary for this portion of the simulation to use brake designer.

Initially the truck was modeled at the top of the ramp at 60 to 65 mph, as indicated by his average speed from the tunnel. To be able to slow the truck on the ramp to 48 mph at impact, the temperature of the truck's brake drums had to be around 600^0F to 700^0F at the top of the ramp and the driver had to have applied 80 to 90 pounds of air pressure to the brakes during the descent. The GSRS calculations indicated that the truck brakes were probably about 900^0F at the top of the ramp. In the truck driver's statement, he said that he was traveling about 20 to 25 mph when he exited the highway onto the ramp. Thus, it is not likely that the truck was going 60 to 65 mph when it exited the highway onto the ramp. However to assess the truck speed further, validation of the GSRS temperatures was made by checking two aspects of the GSRS through the use of HVE – the temperatures on the two grades before the ramp, and a surrogate of brake heat up on a grade to the previous grades,

To validate the GSRS results a comparison was made of the cooling of the brakes in HVE on the upgrade and downgrade before the ramp with the GSRS data for the same upgrade and downgrade. The second comparison was to look at the increase of the temperature of the brakes after several applications on the grade adjacent to the ramp in HVE and extrapolate the results back to the previous downgrades to see if it was likely that the brakes would have been heated to 800^0F or more as predicted by the GSRS calculations. These two approaches seemed to validate the GSRS results. Then final truck simulation runs were conducted up the grade using the GSRS starting temperature of 837^0F. The end temperatures from the uphill simulation were input as the starting temperatures for the downgrade. The end temperatures from the downgrade were input as the starting point for temperatures on the ramp. The end point for the ramp simulation was to match the speed of the truck with the impact speed of 48 mph based on EDSMAC4. The details follow.

To assess the trucks speed, a simple 200-foot-wide and 2,500-foot-long 2.2% upgrade was built. Similarly a 3,500-foot-long 3.4% downgrade was built to simulate the downgrade adjacent to the ramp. The 200-foot width was needed because the truck tended to move laterally when the brakes were applied due to the brakes being unbalanced and reduced the required steering inputs which were not input for the brake temperatures.

The first truck simulations were performed to calibrate the truck's aerodynamic, mechanical and tire drag forces. Radlinski[v] provided information to the Safety Board that could be used to calculate drag forces of about 0.017 G's[vi] for a tractor semi-trailer traveling at 55 mph. Based on this information and the simulations, the drag coefficient was reduced from the default value of 0.72 to 0.30 and the truck's surface area was reduced from 12,834 square inches to 7,405 square inches.[vii]

At the start of the simulation, the truck's initial lining temperature, brake drum temperature and the brake adjustment were entered. The brake adjustments were based on what was measured on-scene.[viii] The temperatures were based on the GSRS calculations that indicated that the brake temperature would have been about 837^0F at the bottom of the upgrade, 809^0F at the top of the upgrade, and 914^0F at the top of the ramp. Initially these temperatures were entered as the brake drum temperature at the beginning of the simulations. After running numerous simulations it appeared that the drums were 100^0F to 200^0F hotter than the linings, and the lining temperatures were reduced[ix].

It was noted that the temperatures of the brakes decreased as the truck went up the 2,500-foot-long upgrade. The amount of the temperature decrease varied, depending on the time the truck was climbing the upgrade and the speed of the vehicle. The GSRS calculations indicated an average decrease of about 28^0F if the truck was traveling at 60 mph. The HVE system indicated a decrease in temperature for each working brake of between 24^0F to 32^0F as the truck's speed decreased from 59 to 26 mph as it climbed the hill in 40 seconds. Fancher's research[6] indicated that rear brakes on a truck cooled about 0.4^0F degrees per second when the brake temperature is 300^0F above ambient temperature. This would lead to an estimate that the truck's brakes cooled about 16^0F on the upgrade as the truck decelerated. All the data indicates that the trucks brakes would not have cooled substantially on the upgrades of 1.04, 1.51 and 0.47 miles between the 9 miles of downgrades. At most the brakes may have cooled on the other two upgrades a total of about 61 to 140 degrees at 60 mph, without brakes being applied on the upgrade.

[v] The drag was 205 HP for an 80,000 rig going 55 mph.[7]

[vi] For comparison, an 80,000-pound tractor semi-trailer had a 0.014 g coast down in gear and 0.010 g in neutral at low speed.[6]

[vii] The default vehicle was a conventional Freightliner with a sleeper and an aerodynamic deflector on top of the tractor with a height of 150.9-inches. The accident tractor was a Kenworth conventional cab with a sleeper birth that was shorter and had no aerodynamic deflector (based on mapping, the height of the damaged tractor was about 106-inches).

[viii] Most of the brakes were out of adjustment or not functioning properly due to broken components.

[ix] This agrees with the data from which showed 100^0F to 160^0F differences between the linings and the drums.[6]

The speeds used on the upgrade (59 mph to 26 mph) were used for the final run. It became apparent that with the high starting brake temperatures at the bottom of the upgrade, the driver needed to slow the vehicle on the upgrade using gravity, without applying the brakes and heating them higher in order to be going a speed of about 48 mph at impact.

On the 3,500-foot-downgrade that was built for simulating the truck's brakes, and determining temperatures, brakes were applied, held, and snubbed. The snub cycle used was one second for the brakes to apply from 0 to 30 pounds, three seconds at 30 pounds, and then one second for the brakes to release back down to 0 pounds. The brakes were held off at 0 pounds for 5 seconds and the cycle was repeated every 10 seconds. The brake application pressure of 30 pounds was used because the truck's brakes were in poor adjustment and 20 pounds had little or no effect on truck speed. This is similar to what was recommended by Fauncher's research (except he used 20 pounds on about a 9 second cycle). We assumed snubbing was used because it is the recommended practice for CDL[x] drivers and it provided the best-case scenario because it did not increase temperatures as much as steady brake application for an extended time.

To look at how the temperature of the brakes would increase with a series of brake snubs, the brakes were snubbed on a 3,653-foot-long 3.36% downgrade with the truck starting from 60 mph and slowing to 51 mph. After just 5 snubs the working brake drums and linings on the semi-trailer increased from 200^{0}F and 100^{0}F[xi] respectively at the start to 729^{0}F to 802^{0}F for the drums and 327^{0}F to 560^{0}F for the linings.

On this stretch of the roadway, braking was necessary for the truck to maintain a controllable speed. Since the rolling resistance of tractor semi-trailers is about 0.014 G's to 0.017 G's, all slopes greater than 1.4% to 1.7% would accelerate the truck unless the brakes were used. The first downgrade was 2.7% for 3.84 miles. If the truck was initially traveling at 60 mph, which was the average speed from the tunnel to the accident site, the truck's speed would have increased to 97 mph at the end of this grade if brakes were not used. In this segment of road there were numerous curves, most with design speeds of about 65 mph. Therefore, braking would have been necessary to maintain controllability. Similarly for the second downgrade the truck speed theoretically would have increased to 81 mph without braking, which is again not considered feasible for this roadway design. On the third downgrade the truck's speed would have accelerated very slightly as the rolling resistance and grade were almost equal to each other and therefore speed was more stable. Then on the downgrade before the ramp, braking would again have been necessary to counteract the truck's tendency to increase to 72 mph, if braking were not applied.

From this simplistic approach, it can be determined that the truck brakes would easily be in the 800^{0}F to 900^{0}F range. There was only about 3.5 miles where the truck was ascending a hill or on a downgrade that was not steep enough to accelerate the truck. At the 60 mph speed from the tunnel to the accident site, the truck's brakes would have been able to cool for about 3.5 minutes or only about 84^{0}F-210^{0}F. This approach also confirms the GSRS and indicates that the truck brakes that were working were functioning at a temperature of 800^{0}F or more prior to the upgrade.

<u>Results</u>

The results of the simulation indicate that the maximum temperatures of the truck brakes were reached at the bottom of the second downgrade. At the bottom of the third downgrade, about 1-mile prior to the ramp, signs were present that indicated the exit and the truck service facility. The simulation showed that the truck was likely going about 59 mph (plus or minus 2 mph) at the bottom of this grade and the throttle was not applied, allowing the truck to coast up the hill, reducing its speed to about 26 mph at the top of the hill. (The truck could have been as slow as 20 mph at the top of the hill, but only 1 or 2 mph faster than 26 mph.)[xii]

As the simulated truck was descending the grade prior to the ramp, the brakes were likely snubbed about 9 times, the temperature of the semi-trailer's working brake drums increased to about 900^{0}F and the lining temperatures increased to about 850^{0}F. The first seven brake applications slowed the truck, but less effectively with each application of the brakes. After the seventh brake application the truck accelerated more with each additional brake application, indicating that the brakes were fading. In the simulation, when the linings were above 750^{0}F, the friction between the drums and the linings was programmed to be lower

[x] Commercial Driver License

[xi] Typically truck brake temperatures are around 150^{0}F for properly adjusted brakes in normal operation. Because this was a mountainous area with numerous curves a slightly elevated starting temperature of 200^{0}F was used for the drums. Research shows that linings are usually 100^{0}F less.

[xii] The driver stated he had slowed to 20 to 25 mph at the top of the ramp, but the simulation indicates it had to be at the top of the hill because the truck was not able to slow from 60 mph to 25 mph on the downgrade with the brakes in the condition in which they were found.

than 0.01, so the increase in brake drum temperatures was very gradual, but it did increase. Even when the brakes were not applied, the lining temperatures were increasing, indicating at these high operating temperatures that there was a thermodynamic exchange of heat occurring between the hotter brake drums and the cooler linings. At the top of the ramp, the semi-trailer's working brake drums would have been at about 889^0F to 908^0F, which agrees closely to that calculated by the GSRS (914^0F). During the simulation no tiremarks were observed prior to impact, indicating that at these high temperatures the brakes did not lock.

The downgrade descent was modeled with starting speeds of 20 to 28.7 mph. With a starting speed of 28.7 mph at the top of the grade, the truck needed to be placed in 6th gear to start the simulation and the truck gained more speed than if it was in a lower gear. As a comparison the truck gained 10.6 mph on the downgrade starting in 6th gear as compared to 5.5 to 6.7 mph if the truck started in 5th gear. This highlights that the use of proper gears can make a significant difference in the trucks performance on the grades. Since the truck was not equipped with an engine recorder, it cannot be determined precisely how the truck was driven and the speed ranges used.

On the ramp the brakes were snubbed in the simulation for 3 seconds at 30 psi, and then 7 seconds later the brakes were applied at 90 psi and held on at 90 psi until the truck entered the intersection.[xiii] Due to the steepness of the downgrade on portions of the ramp (typically 4 to 5% with one slope of 9.42% for 293 feet), and the temperature of the brakes obtained prior to reaching the ramp, the brakes could not provide noticeable retarding forces, even when applied fully, and the truck accelerated in the simulation from 31.2 to 47.6 mph on the ramp. The truck actually accelerated to 48.2 mph just before the intersection, but it slowed to 47.6 approaching the intersection due to the change in grades; the grade reduced to 1.57% and then to 0.3% closer to the intersection where the aerodynamic and mechanical drag slowed the truck.

Most likely the truck was traveling 55 to 60 mph at the bottom of the down slope, and it decelerated to 22 to 27 mph at the top of the grade, which was low enough to be in 5th gear. Then the truck accelerated to 29 to 34 mph at the top of the ramp, slowed enough to be in 6th gear for a portion of the descent on the ramp. The truck struck the bus at about 48 mph (see Figure 9), which would have required the truck to be in 7th gear or higher. The driver said that he attempted to downshift on the ramp from 6th gear to slow the truck. However, due to the speeds at which he was traveling it was not possible to downshift, and in his panic the driver likely shifted into 8th gear. Post-accident inspection found the vehicle in 8th gear.

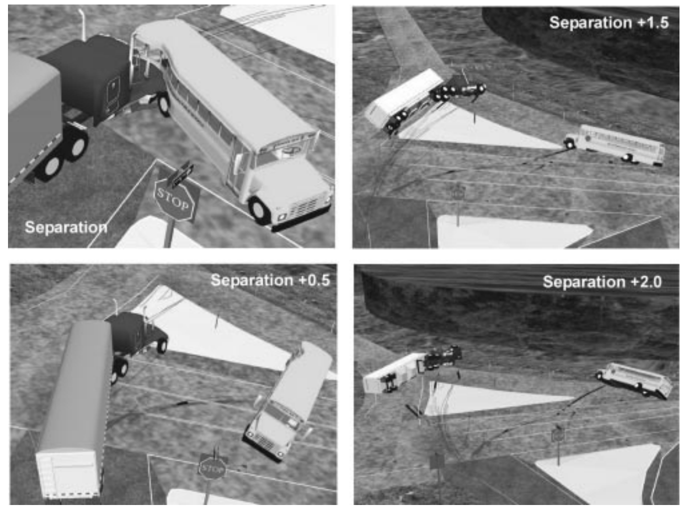


Figure 9 - SIMON simulation after separation

SUMMARY

The simulation of the Mountainburg accident highlighted 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. Brake designer and the ability to modify the brake lining friction/temperature curve assisted in simulating brake fade. Simulation of a steep upgrade or downgrade can be quickly setup by using a wide flat surface that is elevated to the correct slope for the highway grade. Several of these ramp segments can be studied sequentially as different cases, with the temperatures of the drums and linings at the end of one segment used as inputs into the next segment. On longer downgrades the use of the GSRS program with SIMON can help to highlight initial brake temperatures to start the SIMON simulation. Research is needed to fully define the lining temperature versus friction relationship at temperatures in excess of 600^0F.

[xiii] The driver's statement indicated that he "stood on the brakes …, he noticed that the air gauge was indicating 90 pounds… and he pulled the hand brake for the trailer brake."

REFERENCES

[1] Simulation Model Non-linear, SIMON Simulation Model, Version 1 , Engineering Dynamics Corporation, April 2002
[2] Engineering Dynamics Corporation, Beaverton, OR
[3] Mayflower Contract Services, Inc., Tour Bus Plunge from Tramway Road and Overturn Crash, Palm Springs, California July 31, 1991, NTIS No. PB93-916201, NTSB/HAR-93/01, adopted on 4/13/93
[4] http:/www.e-z.net/~ts/BRAKPG.HTM
[5] http://www.e-z.net/~ts/ts/Brakfade.htm
[6] P. Fancher, C. Winkler, M. Campbell, "The Influence of Brake Strategy on Brake Temperatures in Mountain Descents", UMTRI-92-11, March 1992.
[7] Radlinski & Associates, Inc., Braking Performance of Heavy Commercial Vehicles, February 1 & 2 course for NTSB
[8] Johnson, Walter A. DiMarco Richard J., Allen, R. Wade, The Development and Evaluation of a Prototype Grade Severity Rating System, FHWA/RD-91/185, March 1982
[9] Vehicle Group Chairman's Factual Report, Larry L.Yohe, Group Chairman, NTSB Project ID- 48858 , NTSB Accident number HWY00MH036
[10] Highway Group Chairman's Factual Report, Mark Bagnard, Group Chairman, NTSB, NTSB Project ID- 48858 , NTSB Accident number HWY00MH036
[11] HVE Operations Manual, Version 2, Third Edition, Engineering Dynamics Corporation, Beaverton, OR, July 1999.
[12] Bagnard, Mark, Highway Reconstruction Analysis, Mountainburg, AR, 12/4/2001, NTSB Project ID- 48858 , NTSB Accident number HWY00MH036
[13] Heusser, Ronald B., Heavy Truck Deceleration Rates as a Function of Brake Adjustment, SAE 910126
[14] Technical Brake Service Manual, Brake Technology Co., Inc., 1984
[15] Vehicle Dynamics Simulation Study, Lawrence E. Jackson, Group Chairman, December 20, 2002, NTSB Project ID- 48858 , NTSB Accident number HWY00MH036