HVE Data Inputs Based on Testing for a Wet Pavement Accident Involving an Intercity Bus and an SUV

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ABSTRACT

This paper will discuss the technique used to simulate a wet pavement accident. It will discuss the weather data, the environment data and the surface friction inputs and the bus tire friction inputs used for an HVE SIMON(1)[1] loss-of-control simulation on wet pavement. By knowing the rain intensity, texture, drainage path length and cross slope of the pavement, it could be determined that the surface was flooded. The surface was documented with an ASTM skid trailer using a treaded and a smooth tire. This data showed that for smooth tires the friction changed both longitudinally every 0.1-mile and laterally between wheel paths, which created a split coefficient of friction. Five of the accident bus's 8 tires were tested at the General Dynamics Tire Research Facility (TIRF), on a smooth surface selected to match the accident site, for cornering and longitudinal friction at different speeds, and with different water depths. The surface used on the TIRF was validated with the ASTM ribbed and smooth tires. The results of these tire tests are presented. Finally, the data inputs for the surface friction factors and the tire in-use factors will be discussed.

INTRODUCTION

In 2002, the National Highway Traffic Safety Administration (NHTSA) reported that there were 2,981 fatal crashes, 207,000 injury crashes, and 479,000 property damage only (pdo) crashes when rain was reported(2). This represents 7.8% of the fatal crashes, 10.7% of the injury crashes and 11.0% of the pdo crashes. Table 1 is a cross tabulation of data from NHTSA's 2003 Fatal Analysis Reporting System (FARS). It indicates that about 12.2% of the fatal accidents during rain involve trucks or other large vehicles such as buses. There were 83 fatal accidents involving buses with more than 15 seats for passengers.

The percentage of fatal crashes that occur on wet pavement are lower now than they were in 1976 to 1977 when the National Transportation Safety Board

[1] References as noted within the parenthesis (1) are included at the end of the paper under references, while footnotes to further explain the paper or provide more in-depth insight do not use the parenthesis.

Table 1 Fatal Accidents by Atmospheric Condition and Cargo Body Type for 2003[4]

Cargo Body Type	Atmospheric Condition										
	Blank	No Adverse Atmospheric Conditions	Rain	Sleet(Hail)	Snow	Fog	Rain and Fog	Sleet and Fog	Other(Smog, Smoke, Blowing Sand or Dust)	Unknown	**Total**
Not coded	231	20	3	0	0	0	0	0	0	0	254
Not Applicable,Not Med./Heavy Truck/Bus	4	32205	2850	129	711	441	42	7	246	202	36837
Van/Enclosed Box	0	1653	206	8	72	50	3	2	18	2	2014
Cargo Tank	0	286	25	2	8	15	0	1	5	0	342
Flatbed	0	516	50	1	15	12	0	0	9	0	603
Dump	0	416	29	2	14	7	0	0	2	3	473
Concrete Mixer	0	56	1	0	0	0	0	0	0	1	58
Auto Transporter	0	29	5	0	0	1	0	0	1	0	36
Garbage/Refuse	0	106	9	1	4	1	0	0	2	0	123
Grain, Chips, Gravel	0	99	7	0	3	3	0	0	1	0	113
Pole	0	40	3	0	0	0	0	0	0	0	43
Bus (seats 9-15 people, incl. driver)	0	17	3	0	0	0	0	0	0	0	20
Bus (seats for more than 15 people, incl. driver)	0	239	16	3	11	8	0	0	3	1	281
No Cargo Body Type	0	104	15	1	1	1	0	0	1	0	123
Med./Heavy Truck or Bus, Other Cargo Body Type (not codes 01-09,20-21)	0	157	14	0	2	5	0	0	2	1	181
Med./Heavy Truck or Bus, Unknown Cargo Body Type	0	300	29	3	10	7	0	0	1	2	352
Unknown if Light or Med./Heavy Truck/Bus	0	111	9	0	1	4	0	0	4	52	181
Total	235	36354	3274	150	852	555	45	10	295	264	42,034

(NTSB) conducted a wet pavement study that indicated 13.5% of the fatal accidents were occurring on wet pavement, yet the pavement was wet only about 3% to 3.5 % of the time, indicating that fatal accidents on wet pavement are over represented by about 4 times[3]. This paper illustrates how to simulate a wet pavement accident, using a severe fatal crash.

On February 14, 2003, at about 10 a.m., a 1996 Dina Viaggio Motor Coach (bus), traveling northbound on Interstate 35, near Hewitt, Texas, lost control as the bus approached the crest of the hill and as the driver approached slowing and/or stopped traffic ahead. The weather conditions at the time of the accident were reported to be overcast with reduced visibility due to fog, haze, and heavy rain. The bus driver stated that the queue of vehicles ahead of the bus in the right-hand lane was longer and closer to him than the queue of vehicles in the left-hand lane and he decided to move into the space available in the left-hand lane. As he did so, the last vehicle in the queue in the right-hand lane also began to move into the left-hand lane. The bus driver braked harder, the rear of the bus skidded, the bus driver was unable to maintain control, and the bus went off of the roadway and into the grassy median. The vehicle crossed the median and entered the southbound lanes of the highway, striking a southbound 2002 Chevrolet Suburban Sport Utility Vehicle (SUV) occupied by a driver and two passengers. The bus overturned onto its right side. As a result of the accident, two occupants of the SUV and five occupants of the bus were fatally injured, and 31 other occupants of both vehicles received minor to critical injuries.

Figure 1 - On-scene photograph of bus tiremarks and final position

This paper will discuss the technique used to simulate a wet pavement accident. It will discuss the weather data, environmental data and the vehicle tire data needed to simulate a loss-of-control using SIMON. Weather data was obtained from the National Weather Service and calculations were made that indicated the surface was flooded based on the rain intensity, pavement texture depth, roadway drainage path length and the cross slope of the pavement.

The surface was documented with an ASTM skid trailer using a treaded and a smooth tire. This data showed that for smooth tires the friction changed both longitudinally every 0.1-mile and laterally between wheel paths, which created a split coefficient of friction. Five of the accident bus's 8 tires were tested at the General Dynamics Tire Research Facility (TIRF), on a smooth surface selected to match the accident site, for cornering and longitudinal friction at different speeds, and with different water depths. The surface used on the TIRF was validated with the ASTM ribbed and smooth tires. The results of these tire tests are presented. Finally, the data inputted for the surface friction factor and the tire in-use factor will be discussed.

COLLECTION OF DATA

Weather

The NTSB has a staff of three meteorologists, who prepare studies for many of the Safety Board's accidents. Data is obtained from the official National Weather Service (NWS) sources including the National Climatic Data Center (NCDC)[2]. Data they collect routinely includes the data from near-by weather stations using Meteorological Aerodrome Reports (METARs) and special reports (SPECI's), cooperative data recorders, the surface and upper air maps, radar and sometimes satellite imagery. Typically the latitude and longitude for the accident location is required to get the proper weather data. In this case, the closest full weather reporting facility was 10-miles north-northwest of the accident site and they reported 0.12 inches of rain within 23-minutes, immediately after the accident starting at 10:02[(4)]. Another airport, 7-miles west of the accident site, reported 0.19 inches of rain between 9:56 and 10:15. The closest NWS Weather Surveillance Radar – 1988 Doppler was located at Dallas Fort Worth, 67 miles north of the accident site. The images from the radar depicted a large band of echoes moving across the area with the strongest echoes over the accident site at about 9:59, moving to the northeast at 45 knots. The echoes provided an estimated rainfall rate of 1.10 to 2.49 inches per hour for the short duration of about 12 minutes when the very heavy echoes were over the accident site. The 1-hour accumulation of rainfall was 0.25 to 0.50 inches in the accident area. Forty miles northeast of the accident site the maximum precipitation of 1.00 to 1.25 inches were detected. The differences in intensity show the need to look at all weather data sources.

Roadway

The roadway friction at the accident site was initially tested using a Stalker Acceleration Testing System, after the pavement was wetted, using a 4-door sedan passenger car traveling at 50 to 55 mph. The peak friction ranged between 0.81 to 0.84 and the average sliding friction was 0.56 to 0.58. To simulate or reconstruct the subject accident on wet pavement at high speeds, with commercial tires worn to different tread depths, and varying water depths, this data was insufficient, so additional testing was scheduled using a locked wheel skid trailer with a treaded and smooth tire.

The pavement at the accident site had acceptable wet friction, when tested with an American Society of Testing Materials (ASTM) E274 treaded tire at 40 mph, but low friction with a smooth tire (ASTM 501) at 50 mph, and it varied across the lane (see table 2)[3].

To create the split coefficient of friction in the HVE environment, each lane was sub-divided into two longitudinal sections, and each section was given a different friction value. Initially the

[2] Similar data may be available from Compu-Weather at http://www.compuweather.com/wirf-ve.html

[3] ASTM numbers were similarly obtained on the approach to the accident site on both roadways at about 500-foot increments but are not presented in the interest of brevity. See the docket for more information.

ASTM smooth tire skid numbers were entered as the surface friction factor[4]. Since the ASTM skid trailer provided a skid number for every 0.10-mile, the approach segments were also divided in about 500-foot segments in addition to the two-segments for each wheel path within a lane. The surface was built using AutoCAD Land Development(5). The roadway was then re-built and each 500-foot segment that was half a lane wide was given a different color. Then the AutoCAD file format was exported from a "dwg" to a "3ds" format by colors and then it was transferred in the Unix HVE system and the surface friction values were assigned. The pavement was also rutted and had a low texture depth as indicated in Table 3 and 4(6). However the rutting was not modeled in the environment, as it was complex enough with the split coefficient of friction, but the rutting was considered in determining the potential water depth and what levels of water should be used to test the tires.

The water depth on the roadway was calculated using equation 1, which was developed by TTI(7).

$$WD = 0.00338((1/TXD)^{0.11} * L^{0.43} I^{0.59} * (1/S)^{0.42}) - TXD \quad \text{(equation 1)}$$

Where WD is the water depth above the aggregate in inches, TXD is the average texture depth in inches, L is the drainage path length in feet, I is the intensity of rain in inches/hour, and S is the cross slope of the roadway in feet/feet. Using the various measurements taken on scene (see table 5) it can be calculated that the pavement was flooded from 0.01 to 0.11 inches. The research that developed equation 1 was based on flat surface tests. It is possible with rutting that the depths of water increased.

[4] During later evaluations, the low ASTM numbers created a problem when multiplying the surface friction number times the sliding tire value for the tire times the in-use factor for the tire. The ASTM values were then doubled, which allowed the tire in-use factor to be reduced in half and gave better results.

Vehicle

Was Hydroplaning Possible?

Since the surface of the roadway was flooded, it is possible that if the bus was going fast enough, it would have hydroplaned. The speed at which hydroplaning can occur in a commercial vehicle can be calculated using equation 2(8).

$$S = 23.3P^{0.21}(1.4 / W / L)^{0.5} \quad \text{(equation 2)}$$

Where S is the speed in mph, P is the pressure in pounds per square inch, W is the width of the tire contact patch in inches and L is the Length of the tire contact patch in inches. The Aspect ratio (A_R) of the tire can be calculated using equation 3.

$$A_R = W / L \quad \text{(equation 3)}$$

Table 6 shows the input data for equation 2 and 3 for each of the 8 tires on the bus(9). The front left tire has the lowest air pressure (73 psi) and will therefore hydroplane at the lowest speed (the bus must be going faster than 70.6 mph to hydroplane). The bus was governed at 73 mph, so it was possible for the front left tire to hydroplane and for other tires to approach hydroplaning speeds.

ASTM Testing – Table 2

Mile Marker	Average FN	Low FN	High FN	Tire	Direction	Lane	Speed (mph)	Wheel Path
326.3	16	14	18	Smooth	Northbound	Right	50	RWP[5]
326.3	20	17	26	Smooth	Northbound	Right	50	LWP
326.3	36	30	43	Smooth	Northbound	Left	50	RWP
326.3	47	46	49	Smooth	Northbound	Left	49	LWP
326.3	48	46	50	Treaded	Northbound	Right	40	RWP
326.3	48	46	51	Treaded	Northbound	Right	41	LWP
326.3	64	63	67	Treaded	Northbound	Left	41	RWP
326.3	63	62	65	Treaded	Northbound	Left	41	LWP

Rutting – Table 3

Station	Right Lane Cross Slope	Right Lane Rut Depth in Left Wheel Path	Right Lane Rut Depth in Right Wheel Path
670+40	1.85%	0.40 inches	0.35 inches
671+20	1.70%	0.42 inches	0.25 inches

Texture depth – Table 4

Left	
Average depth	0.024 to 0.027 inches
Maximum depth	0.038 to 0.057 inches
Minimum texture depth	0.019 to 0.020 inches
Right	
Average depth	0.017 to 0.018 inches
Maximum depth	0.020 to 0.026 inches
Minimum texture depth	0.013 to 0.014 inches

Table 5 – Calculated water depths

L	TXD	I	S					
Drainage Length Feet	Average Texture Depth Inches	Rainfall Intensity Inches/hr.	Slope Surface ft/ft	(1/TXD)^-.11	L^.43	I^.59	(1/S)^0.42	Water Depth above aggregate Inches
34.6	0.017	2.49	0.009	0.6387	4.59	1.713	7.2313	0.106
11.6	0.029	1.1	0.012	0.6774	2.869	1.057	6.4083	0.016
36.7	0.017	2.49	0.009	0.6387	4.708	1.713	7.2313	0.109

[5] RWP – right wheel path, LWP – left wheel path

Table 6 – Calculated Hydroplaning speeds

Left side wheels			
Aspect Ratio	Width	Length	Aspect Ratio (W/L)
Front	9	9.75	0.923
Dual			
Outside	9.375	10.25	0.914
Inside	9.5	10.25	0.926
Tag	7.75	9.625	0.805
	Aspect Ratio		
	Left Outside	Pressure	**Hydroplaning Speed**
Front	0.923	73	70.6
Dual			
Outside	0.914	92	74.5
Inside	0.926	87	73.2
Tag	0.805	92	79.4
Right side wheels			
Aspect Ratio	Width	Length	Aspect Ratio
Front	9.25	10.375	0.891
Dual			
Outside	9.5	11.375	0.835
Inside	9.625	11.5	0.836
Tag	9	9.5	0.947
	Aspect Ratio		**Hydroplaning Speed**
	Left Outside	Pressure	
Front	0.891	94	75.8
Dual			
Outside	0.835	94	78.3
Inside	0.836	90	77.5
Tag	0.947	92	73.2

The bus driver stated that he drove at 65 mph until the intensity of the rain increased to "hard" rain, requiring the windshield wipers to be set at the second highest setting. The driver stated that he reduced his speed to 60 mph to accommodate for the increased intensity of rain. A witness[6] in a 1-ton truck passed the bus 1 to 2 miles south of the

[6] See the Human Performance Investigation Factual Report, Burton H. Simon, Group Chairman

accident scene and observed the bus traveling at about 60 to 65 mph. The speeds cited by the driver and the witness and later confirmed by the simulation, would not result in hydroplaning, but could result in partial hydroplaning[7].

The 3-axle bus had ABS on its rear tag axle with type 16 rotochambers, but the system did not work[8]. The bus had type 36, S-cam brakes on the drive axle and type 24 rotochamber brakes on the front axles[9]. The brakes were modeled as S-cam brakes. The brake adjustments were measured as well as many other attributes during the vehicle examination such as engine, transmission, rear axle and length measurements, which were used in the HVE vehicle model.

Tire Testing

Based on all the variable factors that are involved in this accident, a contract was initiated with General Dynamics to test the tires from the bus at different speeds and water depths on a surface similar to that at the accident site. This testing was to be conducted using General Dynamics' Tire Research Facility (TIRF) to test five bus tires from the accident vehicle that have various tread depths to determine their braking, cornering capabilities and the water drag under conditions similar to those of the accident. Much of the Human Vehicle Environment (HVE)[(10)] tire data is based upon testing conducted using the TIRF.

Previously the Safety Board used the TIRF machine to measure the friction of two bias-ply regrooveable bus tires from the Luling, Texas accident that occurred on November 16, 1980[(11)]. In these tests, the "Safety Walk" surface was honed to reduce the wet skid number to a value that approximated the ASTM treaded traction test result of 23 on the highway. Tests were conducted with a water depth of 0.02 inches. There is not a lot of data since the early 1980's available on radial bus tires, with different tread depths, speeds, water depths and on smoother surfaces. The Safety Board had conducted limited testing at one or two other accident sites with bus tires and commercial tire testing machines. A 1996 SAE paper[(12)] provided some information on commercial tires that was conducted using the University of Michigan Transportation Research Institute's (UMTRI) Mobile Truck Tire Traction Dynamometer to test nine commercial tires. These tests were conducted at speeds of 25, 40 and 55 mph, and not the speeds suspected in this accident. However they did provide some useful data for developing a tire test matrix. In 2002, a Blythe and Day paper[(13)] conducted tests on automobile tires, and this formed a good outline to further structure wet tire testing on the

[7] A tire needs to push the water on the surface out from the contact area between the surface and the tire. As speeds increase the tire has to push more water. This requires more force from the tire's downward load that cannot be applied to the forces between the tire and the surface. As the speed increases more water is pushed out of the contact surface and the tire approaches hydroplaning. The available friction between the tire and road reduces with higher speed and this phenomenon is called partial hydroplaning.

[8] The system was examined by Bendix, who found that the ABS had shut down (as designed) prior to the accident due to a recurring short of unknown origin in the vehicle's wiring system. In addition, the leads for the left and right side wheel sensors were reversed from their correct orientation at the time of their inspection.

[9] For more information on the engine, transmission, inertial properties, location of center of gravity, etc see the Vehicle Dynamics Simulation Study, Docket 56493, Items 70 to 80.

accident bus's tires. In addition, Blythe and Day provided invaluable guidance periodically during the development of this project.

General Dynamics Tire Testing

Five bus tires were tested using General Dynamics Tire Research Facility (TIRF). The tires were tested for cornering and for longitudinal braking. The cornering tests were conducted as the tire turned from 0- to 15-degrees. The five tires were selected to include the front tire which was the best tire with an average tread depth of 14/32-inch[10] and four drive axle tires that ranged from an average of 4/32 to 8/32-inch[11]. Testing was conducted at 3 speeds – 40, 60 and 70 mph, and with 3 water depths – 0.02-, 0.11- and 0.19 inch. The speeds were chosen to bracket the estimated speed of the bus as it lost control and hit the Suburban. The water depths were selected to match the minimum water depth (0.02-inch), which was also the ASTM testing water depth, the maximum depth calculated for the drainage path lengths using equation 1 (0.11-inch), and the 0.19-inch depth was added to account for the rutting and the maximum capability of the TIRF for the required testing. Not all the tires were tested under all the conditions; instead a matrix was developed to reduce the number of tests. Testing was conducted on a surface that was selected to more closely replicate the surface at the scene[12]. The front tires were quite similar in tread depth, but the air pressure was different, so tests on one front tire was conducted at two different air pressures.

The most critical surface in the simulation was in the area where the bus initially began to lose control and yaw. In the right lane near milepost 326.3 the ASTM skid number[13] was an average of 20 with a low of 17 and a high of 26 in the left wheel path and an average of 16 with a low of 14 and a high of 18 in the right wheel path[14]. At the General Dynamics facility the surface was tested with the ASTM treaded and smooth tire and the surface had the friction levels as indicated in Table 7:

Table 7 - ASTM Tire Tests on the General Dynamics Surface

Tire	Speed (mph)	Water depth (inches)	Normalized Longitudinal Force (friction)
Grooved	40	0.02	0.68
Grooved	60	0.11	0.14
Smooth	40	0.02	0.26
Smooth	50	0.02	0.12

This indicates that the surface at General Dynamics had a slightly lower friction with a smooth ASTM tire at 50 mph, but a slightly higher friction with a grooved ASTM tire at 40 mph with 0.02 inches of water. The results of the longitudinal tire testing are indicated in table 8:

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[10] The front tires were Firestone FS400. The front tires were basically similar, except the left front tire had 73 psi and the right front tire had 94 psi. The right front right tire was used, but it was run at both tire pressures.

[11] The drive axle tires were Firestone HP-3000 LP. The minimum tread depths measured from left to right were 3/32, 3/32, 5/32 and 6/32-inch but the average tread depth is indicated in table 7.

[12] The surface used was 180-grit sand paper developed by 3-M. The TIRF machine usually uses 120-grit surfaces for dry pavement testing and 80-grit surface for wet pavement testing.

[13] At 50 mph with a smooth tire and 0.02 inches of water

[14] The ASTM treaded tire in the right lane at 40 mph had an average of 48, a high of 51 and a low of 46 in the left wheel path and an average of 48, a high of 50 and a low of 46 in the left wheel path. A skid number can be divided by 100 to give a close approximation for friction at the test conditions.

Table 8 – Longitudinal Peak and Slide Friction on wet surfaces

Longitudinal Friction

Run	Tire #	Initial Avg. Tread inches	1/32 inch	Tire Position	Velocity (MPH)	Water Depth (Inches)	Tire Air Pressure (psi)	Peak NFX	Slide NFX
Water depth 0.11									
17	1	0.454	14	LFS[15]	60	0.11	73	0.52	0.27
42	1	0.454	14	RF	40	0.11	94	0.54	0.25
18	1	0.454	14	RF	40	0.11	94	0.62	-
18	1	0.454	14	RF	60	0.11	94	0.48	0.29
18	1	0.454	14	RF	70	0.11	94	0.41	0.25
19	1	0.454	14	RF	40	0.11	94	0.56	-
19	1	0.454	14	RF	60	0.11	94	0.50	-
19	1	0.454	14	RF	70	0.11	94	0.40	0.22
39	1	0.454	14	RF	40	0.11	92	0.62	-
42	4	0.154	4	LRO	40	0.11	92	0.54	0.25
20	4	0.154	4	LRO	60	0.11	92	0.21	0.12
36	2	0.146	4	LRI	40	0.11	87	0.60	0.24
21	2	0.146	4	LRI	60	0.11	87	0.27	0.12
21	2	0.146	4	LRI	70	0.11	87	0.17	0.09
33	3	0.231	7	RRI	40	0.11	90	0.58	0.28
23	3	0.231	7	RRI	60	0.11	90	0.27	0.13
23	3	0.231	7	RRI	70	0.11	90	0.18	0.09
22	5	0.261	8	RRO	60	0.11	94	0.23	0.12
Water depth 0.19									
40	1	0.454	14	RF	40	0.19	94	-	-
26	1	0.454	14	RF	60	0.19	94	0.49	0.28
26	1	0.454	14	RF	70	0.19	94	0.4	0.22
41	4	0.154	4	LRO	40	0.19	92	0.55	0.25
35	2	0.146	4	LRI	40	0.19	87	0.57	0.28
25	2	0.146	4	LRI	60	0.19	87	0.24	0.10
25	2	0.146	4	LRI	70	0.19	87	0.14	0.10
34	3	0.231	7	RRI	40	0.19	90	0.59	0.27
24	3	0.231	7	RRI	60	0.19	90	0.23	0.12
24	3	0.231	7	RRI	70	0.19	90	0.17	0.09
Water depth 0.02									
38	1	0.454	14	RF	40	0.02	94	0.68	0.53
28	1	0.454	14	RF	60	0.02	94	0.65	0.30
28	1	0.454	14	RF	70	0.02	94	0.57	0.24
43	4	0.154	4	LRO	40	0.02	92	0.64	0.26
37	2	0.146	4	LRI	40	0.02	87	-	-
29	2	0.146	4	LRI	60	0.02	87	0.37	0.15
29	2	0.146	4	LRI	70	0.02	87	0.26	0.12
32	3	0.231	7	RRI	40	0.02	90	0.66	0.29
31	3	0.231	7	RRI	60	0.02	90	0.34	0.16
31	3	0.231	7	RRI	70	0.02	90	0.24	0.12
44	5	0.261	8	RRO	40	0.02	94	0.59	0.27

[15] LFS – left front steer, RF, right front, LRO – Left rear drive outside, LRI - Left rear drive inside, RRI – right rear drive inside, RRO – right rear drive outside

Table 9 – Cornering stiffness and average peak lateral friction

		Water depth 0.11 inch								
		Average	Air							
		Tread Depth	Pressure	Cornering Stiffness			Avg. Peak Lateral			Friction
Tire		(32-inches)	(psi)	40	60	70	40	60	70	Speed (mph)
Right Front		14	94	914	782	686	0.7	0.54	0.40	
Left Front		14	73	-	888	-	-	0.46	-	
Right Drive Axle										
	Outside	8	94	-	569	-	-	0.26	-	
	Inside	7	90	936	546	352	0.5	0.24	0.15	
Left Drive Axle										
	Outside	4	92	-	542	-	-	0.23	-	
	Inside	4	87	976	489	280	0.49	0.24	0.12	
		Water depth 0.19 inch								
		Average	Air							
		Tread Depth	Pressure	Cornering Stiffness			Avg. Peak Lateral			Friction
Tire		(32-inches)	(psi)	40	60	70	40	60	70	Speed (mph)
Right Front		14	94	888	706	617	0.70	0.46	0.29	
Left Front		14	73	-	-	-	-	-	-	
Right Drive Axle										
	Outside	8	94	-	-	-	-	-	-	
	Inside	7	90	932	559	260	0.50	0.20	0.09	
Left Drive Axle										
	Outside	4	92	-	-	-	-	-	-	
	Inside	4	87	961	494	217	0.48	0.16	0.09	
		Water depth 0.02 inch								
		Average	Air							
		Tread Depth	Pressure	Cornering Stiffness			Avg. Peak Lateral			Friction
Tire		(32-inches)	(psi)	40	60	70	40	60	70	Speed (mph)
Right Front		14	94	998	936	891	0.74	0.61	0.51	
Left Front		14	73	-	-	-	-	-	-	
Right Drive Axle										
	Outside	8	94	-	-	-	-	-	-	
	Inside	7	90	1059	774	631	0.55	0.31	0.22	
Left Drive Axle										
	Outside	4	92	-	-	-	-	-	-	
	Inside	4	87	1099	734	571	0.54	0.30	0.20	

The cornering stiffness from the General Dynamics tire testing, as indicated in table 9, at 60 mph and 0.11 inches of water was entered into HVE's Force in the y-direction (lateral force) versus slip angle data since this is the only data used by SIMON and EDSMAC4 for cornering calculations. Table 9 also includes the average peak lateral friction from the testing as the tire turned from 0- to 15-degrees. The average peak friction was determined by assessing the graph and averaging about 100 observations from the highest value area in the plot. In some of the tests the peak lateral friction value was obtained at 2- to 5-degree angles, while in other tires the lateral friction appeared to be rising slightly at 15-degrees. It should be noted that the peak lateral friction value was similar to the peak longitudinal value. Eight plots of some of the TIRF tire data are included in the attachment.

SIMULATION

The accident was simulated in several parts. Initially the approach of the Suburban to the accident site was simulated in SIMON to calibrate the surface/tire interface (friction) with the deceleration observed in the vehicle's data recorder. Then the bus tires were adjusted to account for wear and the approach of the bus to the accident site was modeled in SIMON. The collision was simulated in EDSMAC4(14) and also in SIMON using DyMESH(15).

Simulating the Approach of the Suburban

The approach of the Suburban to the accident site was simulated using SIMON. The vehicle was driven to correspond with the Suburban's data recorder information. The weight of the passengers was entered as a part of the vehicle load initially[15]. The Suburban was started at 55.0 mph and the speed changed less than 0.6 mph higher or 0.2 mph lower on the approach to the accident site, until the brakes were applied. The Suburban was placed in third gear, as 4th gear was an overdrive which would have resulted in the need to change throttle and perhaps gear more often as the Suburban ascended and descended the hills in the simulation. In the simulation, the throttle was placed at 43- to 44-percent to maintain the 55 mph speed prior to the accident. However, the event data recorder indicated a throttle of 28% for the two seconds prior to braking. The Suburban required only minor corrections of the steering wheel on the approach (less than 1-degree). The approach simulation was 14.2 seconds in duration.

The Suburban tires' in-use factors were modified to 0.93 as it approached the accident. This resulted in speed reductions similar to that indicated in the event data recorder when braked at 35 pounds of pedal force. The brakes were applied over one second, starting 11.2 seconds into the simulation. This data was used as a basis with the tire data to model the bus approach and tire friction interface values. The calibrations of the corrected data recorder information with the simulation results are shown in table 10. The tires on the Suburban were larger than designed for by GM, so the speeds were increased by 2%.

Table 10- Simulation of the Suburban Braking versus the Corrected data recorder

Simulation Time (seconds)	Simulation Speed (mph)		Data Recorder Time (Seconds)	Data Recorder Speed (mph)	2% Correction for tire size	Difference Simulation minus Corrected
			-5	54	55.08	
			-4	54	55.08	
11.2	54.94		-3	54	55.08	-0.14
12.2	49.98		-2	47	47.94	2.04
13.2	41.62		-1	40	40.8	0.82
14.2	33.84					

[15] The passenger weight for the SUV could have been added separately as a payload in SIMON but when changing back to EDSMAC4 the load would have had to be added to the vehicle weight, since this load was minor and changed CG only slightly, it was left in the vehicle weight for SIMON.

Simulating the Approach of the Dina Motorcoach

This portion of the simulation was conducted to determine the speed at which the bus could approach the hill prior to the loss-of-control and to then match the marks left by the bus during the loss-of-control. The bus tires had to be adjusted using the in-use-factor to produce friction levels similar to that of the testing at General Dynamics. The in-use factors will be discussed first.

Initially in the simulations the bus could not accelerate to over 62 to 63 mph on the approach, based on the manufacturers data on the transmission, engine and rear end. This necessitated additional conversations with the bus owner that resulted in the changing of the gear ratio and the maximum engine speed based on work conducted by the bus owner on these components. In SIMON the passenger load and loads for suitcases are added as a payload prior to the activation of the event. Similarly the brake adjustments are entered prior to the initiation of the event.

Adjusting Friction for the Bus Tires

In HVE, the friction between the tires and the roadway is the product of the surface friction multiplier (entered for each surface during building of the environment) multiplied by the friction for the tire model (tires are selected while building the vehicle model). The ASTM smooth tire tests at 50 mph were initially used as the friction multiplier for the surface. The ASTM tests were conducted with 0.02 inches of water depth. Additional adjustments for friction were made using the in-use factor of the tires to adjust for speed, tires and water depth, based on the General Dynamics data.

By proportion, the slide friction for the bus tire (0.48)[16], ratio to a 1.0 surface friction value compared to a calculated 0.0768 slide friction for the tested 0.16 ASTM test surface (lowest average value) in the area of loss of control (see equation 4).

$$\frac{0.48 \text{ (slide friction)}}{1.0 \text{ (surface friction value)}} = \frac{X \text{ (calculated surface friction value)}}{0.16 \text{ (ASTM scene friction in right wheel)}}$$

(equation 4)

Next the tested tire data for the 60 mph test with 0.11[17]inches of water depth was multiplied by the ratio of the test tire friction times the ratio of the actual surface divided by the test tire surface divided by the calculated surface friction value as follows:

$$\text{In-use factor} = \frac{\text{Test tire friction (0.29[18] for front left) x } \dfrac{\text{0.16 (ASTM road low)}}{\text{0.12 (Tire surface)}}}{\text{calculated friction value (0.0768)}}$$

(Equation 5)

In-use factor = 5.03 (This was too high a value to enter in HVE as the friction charts became erratic, so the ASTM

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[16] Firestone bus tires were modeled as Michelin XZA tires, where the slide value is 0.48 at 40 mph and 6,625 pounds. The slide friction is the value of Fx/Fz at 100% longitudinal slip achieved during the test at the given load and speed on a particular surface. This is the value of friction at which a tire stops rotating and slides on a surface leaving behind a skid mark or tiremark.

[17] The 60 mph speed was based on preliminary simulations of the accident. The 0.11 water depth was chosen, because that was the depth that could be calculated and the fact that the tires would quickly move from the ruts and obtain a higher friction value.

[18] See Table 8 for tire friction slide values from the General Dynamics testing.

Table 11 – In-use Factor calculated for wheels

		Tread depth	60 mph	In-use		Peak Longitudinal
Tire In-use Factors			0.11 water	Factor	Divide by 2	Friction From TireTesting
Tire			Slide Friction	Value	(Pavement doubled)	60 mph 0.11in.
Right Front		15/32	0.29	5.03	2.515	0.52
Left Front		14/32	0.27	4.69	2.345	0.50
Right Drive axle						
	Outside	5/32	0.12	2.08		0.23
	Inside	6/32	0.13	2.		0.27
	Average		0.125	2.17	1.085	
Left Drive axle						
	Outside	3/32	0.12	2.08		0.21
	Inside	2/32	0.12	2.08		0.27
	Average		0.12	2.08	1.04	
Right tag		5/32	0.12	2.08	1.04	
Left tag		8/32	0.165	2.86	1.43	

values were doubled and the In-use factors were halved). Similarly the other In-use factors for the tires were calculated as indicated in table 11.

To check the approach cited above, the In-use Factor for all the wheels were assigned a value of 2.515 and the bus was stopped by applying 35 pounds of force at the brake pedal[19] in a SIMON simulation as the bus approached the beginning of the tiremarks. The forward acceleration for the 2 seconds that the bus remained in the lane were summed and averaged to be 0.27, which is very close to the 0.29 that was targeted for this type of tire[20].

Simulating the Bus Approach

The approach of the bus was simulated for 28.1 seconds. The bus was started at 63 mph, in 5th gear and the throttle was held constant at 20% for 23.4 seconds, until the brakes were applied. The speed of the bus decreased from 63 mph initially to 62.5 mph 3.3 seconds into the simulation, increased to 65.4 mph 15 seconds into the simulation, and then decreased on the uphill prior to the loss-of-control to 61.2 mph before the brakes were initially applied. The speeds of the bus after the brakes were applied are indicated in table 12. At 23.0 seconds the brakes were initially applied, and the brakes were at 15 pounds of brake pedal force 0.5 seconds later. About 2.2 seconds later (25.7 seconds in the simulation) the brake pressure was increased from 15 pounds of force to 35 pounds of force over a half second

[19] Based on vehicle testing, with these slippery surfaces, applying more brake pressure resulted in little or no difference in the deceleration rate because most of the available friction was being used at this force.

[20] In this area the surface was a 0.16 in the right wheel path and a 0.20 in the left wheel path with an ASTM smooth tire. Only the right dual wheel appeared to lock in the simulation and leave tiremarks. The highest deceleration was 0.28, which occurred about 35% of the time.

(brakes were at 35 pounds at 26.2 seconds into the simulation).

Table 12 – Speed of the bus after braking initiated

Simulation Time (seconds)	Bus Speed (MPH)
23	61.2
24	60.2
25	57.8
26	54.6
27	48.0
28	41.7

Steering was minimal on the approach: -0.5 to +1-degrees at the steering wheel. As the bus approached the accident site it was steered to the right from 22 to 24.4 seconds about 3.5-degrees at the steering wheel. Between 24.4 seconds and 24.8 seconds the bus steering was increased with 70-degrees steer to the left, that was increased 0.3 seconds later to 180 degrees to the left. The 180-degrees left steer was held about 0.45 seconds and then the bus was steered right about 180-degrees per 0.5 seconds until it was steered right 450-degrees (1.25 turns right) just prior to impact with the Suburban[21].

With these speeds, braking and steering inputs, the bus followed the physical evidence very closely (see figure 2). This indicates that the bus driver may have slowed initially, steered hard to the left and then braked hard prior to entering the median and then steered hard to the right. This seems very consistent with the driver's statement.

Assessing the Role of Various Factors Using HVE

A perturbation analysis, using the SIMON approach, looked at the effect had the tires been the same as the right front, the same as the drive wheels, the brake adjustments were the same – all 1-inch, if the ABS had been working on the tag axle, and if all wheels were equipped with working ABS. For these simulations there was no steering corrections and the brakes were applied initially at 15 pounds approaching the tiremarks and then increased after 2-seconds to 35 pounds.

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[21] The witnesses in the bus reported that the bus driver was thrown from his seat in the median. In the simulation the bus was initially steered right as the left wheel went over the centerline. The steering wheel was at 0-degrees when the left front tire was about 4 feet from the median yellow lane line. The steering wheel was to the right 180-degrees when the wheels were in the middle of the shoulder, was at 360-degrees to the right on the downward embankment and was at 450-degrees to the right as the front left metal of the bus body began to dig into the ground and the front wheel suspension was being compressed by the upward slope out of the median. SIMON does not currently take the vehicle body contacts with the ground into account. However, the peak G as the bus was starting to dig into the surface was 0.67 G's and about 0.63 seconds later was about 1.14 G's of which 1.03 G's was vertical. It is probable that the bus driver began to leave his seat after the steering wheel was at 450-degrees to the right as the front of the bus began to dig in and the vertical G-forces approached 1.0 G's. Then it is not known if the wheels plowing in the dirt and ascending the other lanes stayed at 450-degrees by themselves due to external forces, or slowly returned to neutral steering, but the impact with the Suburban occurred about 1 second after the 450-degrees was obtained and the driver started to leave his seating area. The steering in the simulation was held at 450-degrees right steer to match the tiremarks.

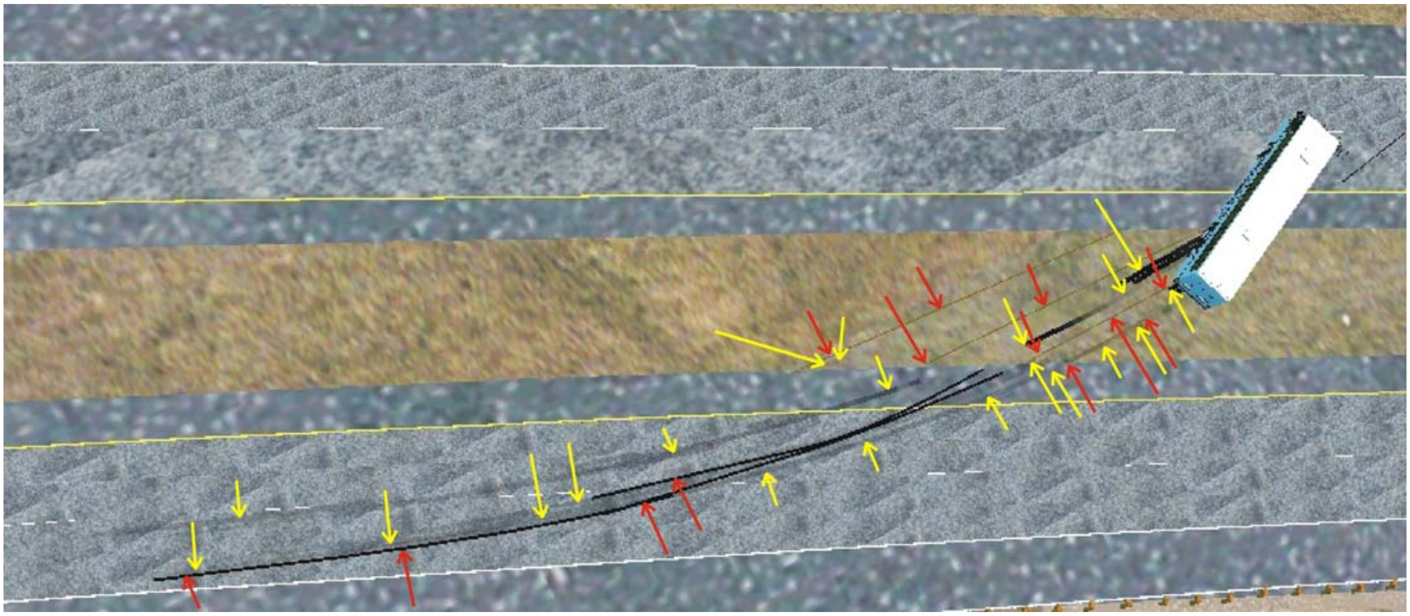

Figure 2 – Comparison of physical evidence to simulation tire marks for the SIMON bus approach (Red arrows point to evidence and yellow arrows point to simulation tiremarks.)

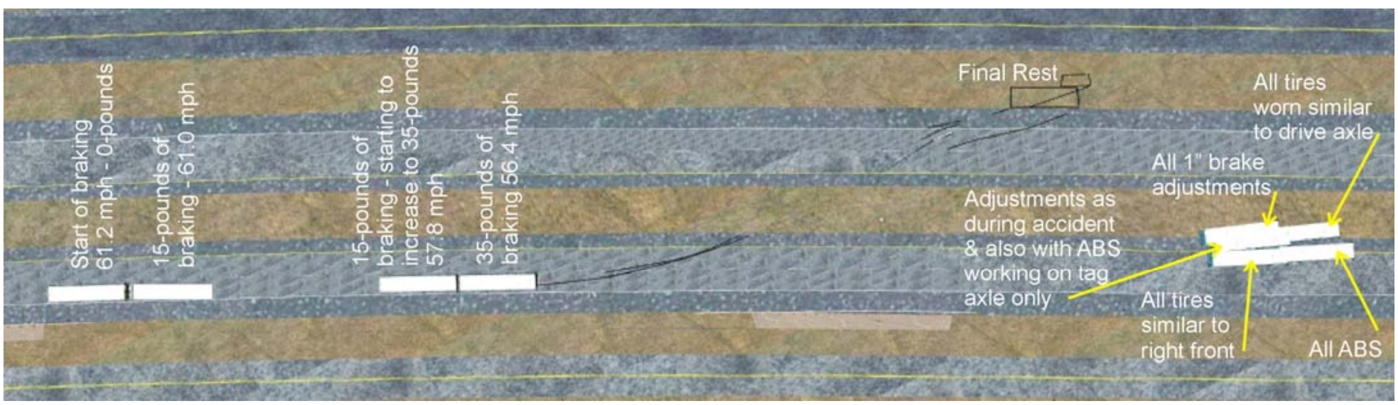

Figure 3 - Comparison of braking with no steering at the accident site with various conditions

Figure 3 shows where the bus started its braking sequence and where the bus would have stopped with these various conditions relative to the final rest position after the accident. If the tag axle ABS had been working, it would have had no effect according to the simulation. If the bus had ABS on all wheels it would have stopped in the left lane and would not have drifted further to the left into the median as in some of the other simulations, but the bus would have taken a longer distance to stop. If all the wheels were the same as the right front tire, the bus would have stopped quicker than the other conditions and in the left lane. If the brakes were all adjusted to 1-inch, the bus would have stopped beyond the shoulder of the pavement further in the median than any or the other vehicle conditions. If all the tires had been as bad as the worse tire on the drive axle the bus would have run off into the median further than any of the other combinations and would have traveled almost as far as the ABS equipped bus. These simulations show that the differential friction on the pavement would have caused the bus to move left, even with similar tires or ABS, without steering correction, but the bus would not have gone into the southbound lanes and struck the Suburban without significant steering input by the bus driver.

One witness, in a Ford 4-wheel 1-ton truck, indicated that a Lincoln-Continental was stopped about 70 feet north of the top of the crest vertical curve, but he also said the bus missed his truck by 10 feet when he was in the right lane. A witness estimated the rear of the stopped vehicles, and a similar bus was moved forward until the driver could see the stop signals. The distance from the bus to the stopped vehicle, over the crest of the hill, was about 767 feet. From the crest of the vertical curve, to where the bus began to leave a tiremark in the right lane was about 114 feet based on the simulation. Another witness indicated that from the start of the tiremark to where the last car stopped was about 350 feet. The bus, in the various simulation scenarios stopped, over 425 feet from the beginning of the mark. Thus it was very likely that the bus would have run into the rear of the vehicles if it had not swerved to the left.

The Collision

EDSMAC4 was used to simulate the collision based on the data from the bus and Suburban approach, which were simulated using SIMON. EDSMAC4 is a 2-dimensional program so the bus and Suburban would not roll during impact or post-impact in EDSMAC4. The SIMON simulation for the bus approach was simulated at 0.00333-second increments to allow the bus position relative to the Suburban to be changed slightly. After about 50 iterations, the EDSMAC4 version that replicated the tiremarks the best was chosen. In this simulation the Suburban rotates about 100-degrees and goes across the roadway, over the shoulder and up the concrete wall. At the top of the concrete wall the velocity of the Suburban is low (4 to 5 mph) and the Suburban turns and slides down the wall into the area where the bus, which was on its side would have been contacted in the top of its roof at about 10 mph. The speed of the Suburban at initial impact was 32.7 mph, which would indicate that the Suburban braked another full second beyond that indicated on the pre-crash data recorder[22]. The speed of the bus was 39.8 mph at impact, indicating that the bus continued to slow as it spun-out and crossed the median. In this event, the left front tire of the Suburban was blown starting at 0.1 seconds and lasting for 0.1 seconds. The left front wheel was also deformed inward and rearward as indicated by the Safety Board mapping.

The EDSMAC4 data indicated that the total delta-V for the Suburban during impact was about 57.8 mph and for the bus was about 15.9 mph. From impact to separation, the Suburban had a velocity change in the longitudinal direction of 51.3 mph, which compares closely to the 48.71 mph delta-V recorded in the Suburban's data

[22] The last speed indicated on the recorder can be as much as 1 second before the impact. Thus if the vehicle braked at the same deceleration rate as the previous two seconds, the speed at collision is within 1 mph of the speed that would be expected.

recorder[23]. The EDSMAC4 simulation indicated that the vehicles were in contact for about 0.12 seconds. The Suburban's data recorder could only hold 0.15 seconds of data post-impact, and the first 0.04 seconds did not indicate a reduction in speed for the Suburban, leaving only 0.110 seconds of crash data, which may explain why the simulation delta-V in the longitudinal direction was slightly higher than the recorded data. The simulation data also includes the lateral component of delta – V, which helps to show in this case that the recorded delta-V is below that which should be expected because the bus struck the Suburban at an angle.

In addition, SIMON's newest feature, DyMESH was used to try to simulate the accident in 3-dimensions. A small 1.2-second segment was obtained after numerous unsuccessful attempts. The event kept terminating due to excessive loads on the wheels as the bus rolled and seemed to vault coming out of the ditch, with the bottom of the bus rubbing along hood level of the Suburban. The starting positions of the vehicles relative to each other were varied numerous times in an attempt to have a more successful run. While the event was not totally successful, it did highlight that the Suburban probably spun around the front of the bus and the rear struck the side of the bus. In the DyMESH simulation, the Suburban struck the bus at the front axle, while in a combined EDSMAC4, SIMON and EDVSM simulation, the Suburban struck the bus behind the front tire, similar to areas with physical evidence. The DyMESH simulation also highlighted that the bus may have been partially airborne after emerging from the median and could have hit the Suburban higher in the area of the hood initially. At the end of the simulation the bus had rolled about 21-degrees. Additionally, the change in velocity for the Suburban during contact of the vehicles was 55.5 mph, which compares favorably to the 57.8 mph for the EDSMAC4 simulation. In the longitudinal direction, the Suburban's data recorder indicated 48.7 mph, EDSMAC4 indicated 51.3 mph and SIMON indicated 45.8 mph.

SIMON may not have been as successful as desired for the collision, due to the complexity of the vehicles, and the override of the bus onto the Suburban while rolling. This greatly exceeded the suspension capabilities of the vehicles, even when the suspension and tire properties were increased to maximum values.

As mentioned earlier in the paper, after the EDSMAC4 collision and separation, the position and velocity of the bus were used to initiate a SIMON event during the bus rollover and the position and velocity of the Suburban were used to initiate an EDVSM event for the Suburban as it spun and went up the concrete embankment. These events matched the physical evidence well[24].

CONCLUSIONS

This wet pavement accident was a complex accident with low and split coefficients of friction on the roadway, and with worn tires on the rear axles. The simulation was run prior to tire testing based on limited, old commercial tire testing data and after tire testing at

[23] The recorder measures only in the longitudinal direction.

[24] For more information see Vehicle Dynamics Simulation Study, Docket 56493, Item 74

General Dynamics. As better friction data became available, the results of the simulation matched the physical evidence much more closely. The data available from the Suburban's crash data recorder helped to calibrate the surfaces. The SIMON program was needed to model the complex approach of the bus with changing frictional properties. After several SIMON events were executed with various conditions such as good tires, uniform brake adjustments, ABS and others aspects, the relative roles of each of the factors could be approximated. In the simulations, the overall factor in the loss-of-control was the driver's large left steering event. EDSMAC4 helped to determine the speed of the bus at impact and therefore provided a target for the SIMON run.

The EDSMAC4 event was enhanced with the data from the Suburban's crash data recorder. The crash data recorder helped to define the Suburban's speed prior to the crash and the severity in the x-direction. In using crash data recorder data, if the tire size is changed the speed must be adjusted. The reconstructionist must also be aware that the current GM data recorders provide data in the longitudinal direction only, and the last reported speed prior to the crash could be up to one second before the crash.

As now designed, HVE does not allow individual tire values to be assigned for each tire when there are dual tires on the wheel, instead the values of the two-tires have to be averaged. This may result in slight differences in results, by diminishing the effect of lower values consistently on the same side of the wheels. In the future, the tire modules need to allow for the entry of more complex data.

The data developed using the TIRF for these commercial tires on a slippery surface, and the data developed by Blythe[14] for automobiles highlights that at today's Interstate speeds of 60 mph or more, when there is more than 0.10 inch of water depth, even tires with tread depths several 32nds of an inch more than that required by States or the Federal Motor Carrier Safety Regulations (FMCSR) can reduce the available friction to less than 0.10. This is the equivalent of trying to operate on ice. A greater effort is needed to inform the public to slow down during rain. This could be accomplished through public announcements, or through technology. Using today's technology either variable speed limits could be posted using rain intensity data or the vehicle itself could detect water depths and recommend speeds or even regulate speeds.

Currently the FMCSRs require tires on the front of a commercial vehicle to have 4/32-inch of tread and the rear axles are required to have 2/32-inch of tread. The Blythe study and the simulations conducted as part of this study show that a vehicle may yaw or veer off the roadway more with tires with different properties, and especially with the tires with less treads on the rear axle(s).

Testing a wet pavement surface with a passenger car may provide insufficient data when trying to simulate or reconstruct an accident that involves a commercial vehicle at high speeds and varying tread depths. In this case, the split coefficient of friction on the roadway between the wheel paths and the traffic lanes would not have been observed without smooth tire testing using an ASTM skid trailer.

ACKNOWLEDGEMENTS

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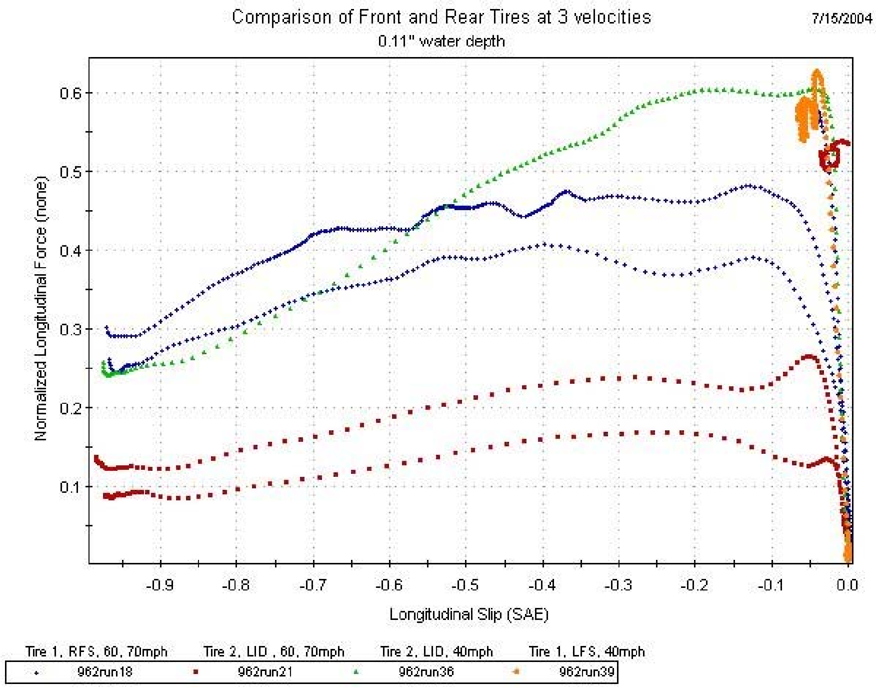
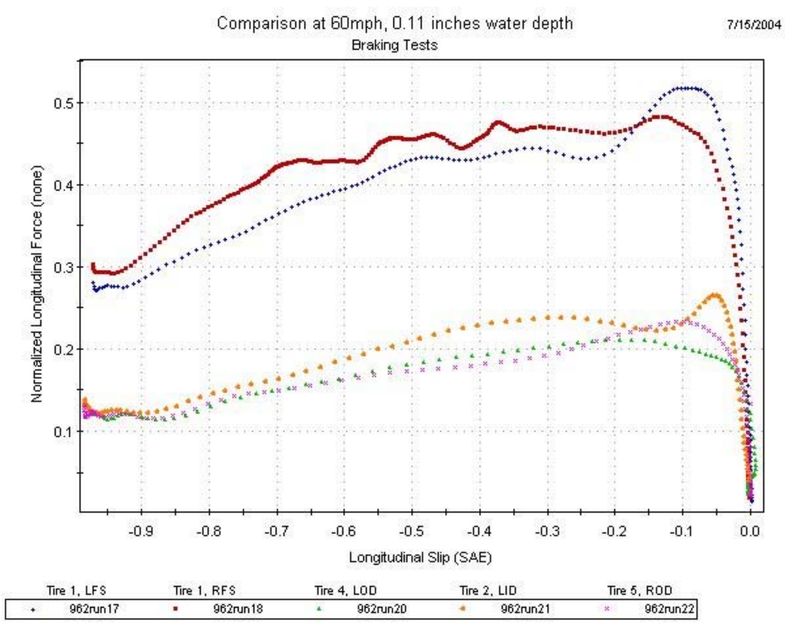
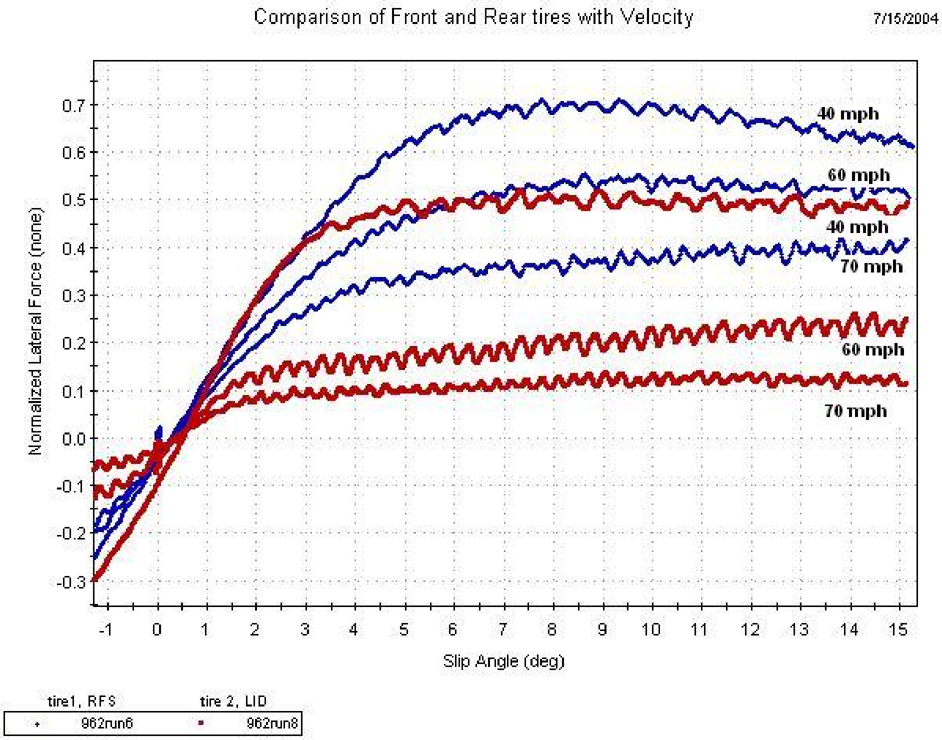
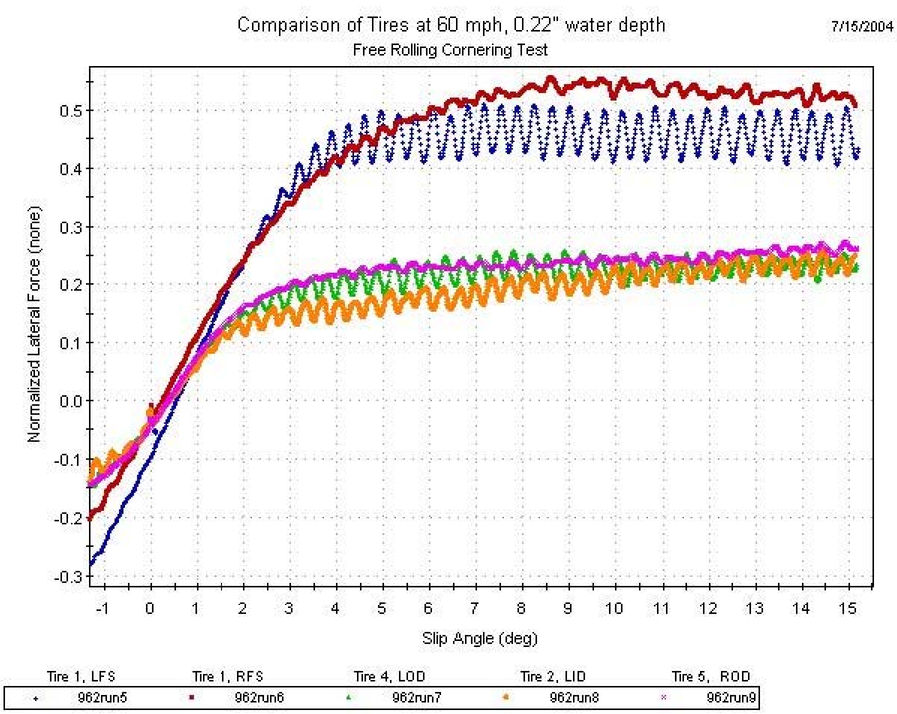
Attachment – Plotted General Dynamics TIRF data






Comparison of Front and Rear tires with Velocity
7/15/2004
40 mph
60 mph
40 mph
70 mph
60 mph
70 mph
Normalized Lateral Force (none)
Slip Angle (deg)
tire1, RFS
tire 2, LID
962run6
962run8


Comparison of Tires at 60 mph, 0.22" water depth
7/15/2004
Free Rolling Cornering Test
Normalized Lateral Force (none)
Slip Angle (deg)
Tire 1, LFS
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Tire 5, ROD
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962run6
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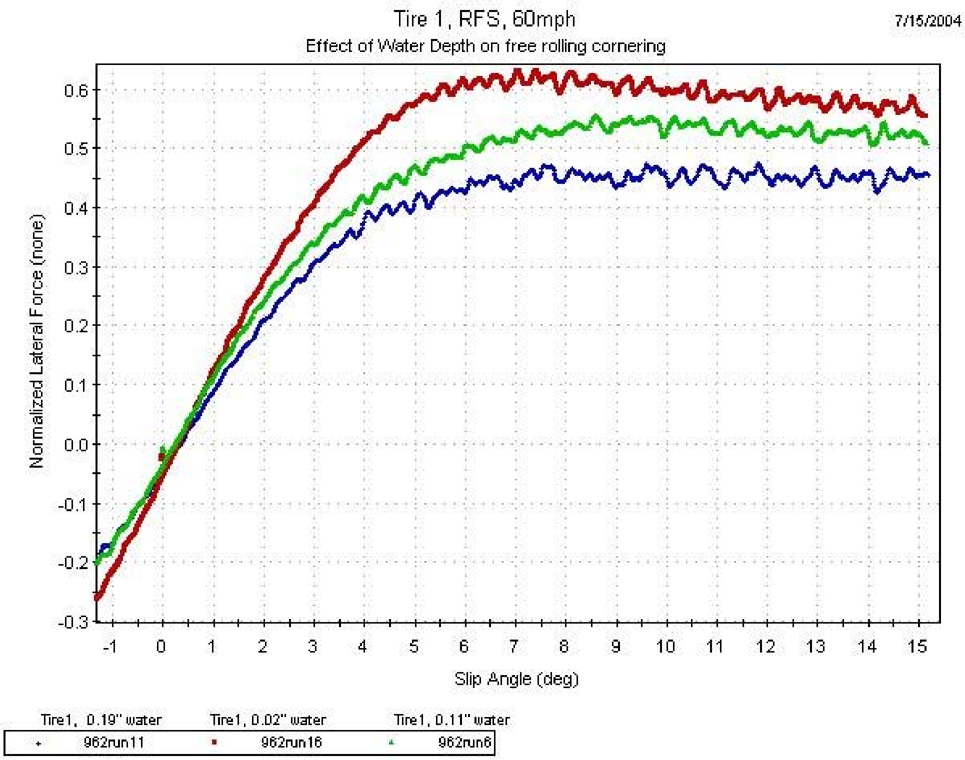
962run8
962run9


Tire 1, RFS, 60mph
7/15/2004
Effect of Water Depth on free rolling cornering
Normalized Lateral Force (none)
Slip Angle (deg)
Tire1, 0.19" water
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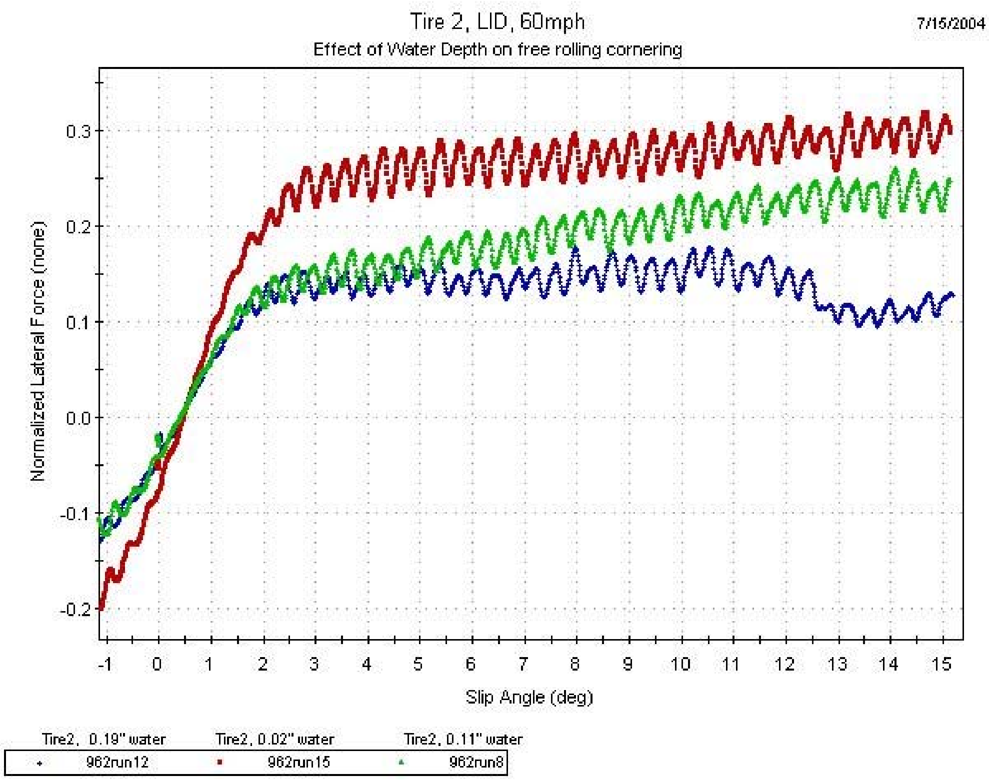
Tire1, 0.02" water
962run16
Tire1, 0.11" water
962run6


Tire 2, LID, 60mph
7/15/2004
Effect of Water Depth on free rolling cornering
Normalized Lateral Force (none)
Slip Angle (deg)
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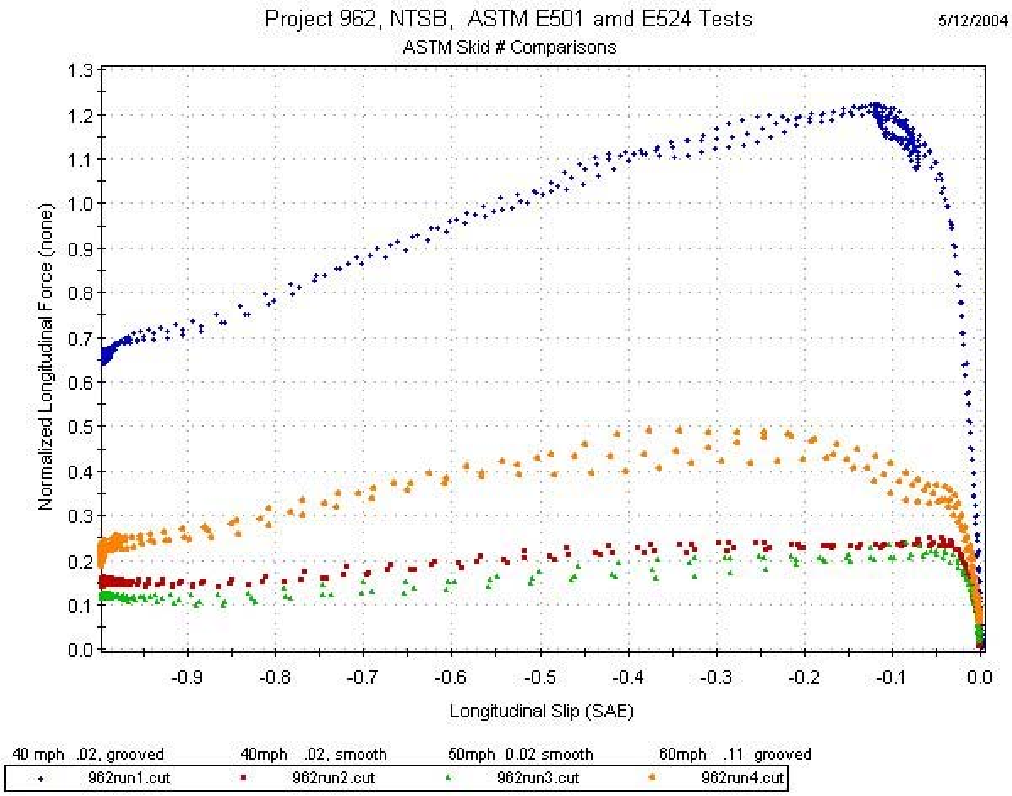
962run12
Tire2, 0.02" water
962run15
Tire2, 0.11" water
962run8


Project 962, NTSB, ASTM E501 amd E524 Tests
5/12/2004
ASTM Skid # Comparisons
Normalized Longitudinal Force (none)
Longitudinal Slip (SAE)
40 mph .02, grooved
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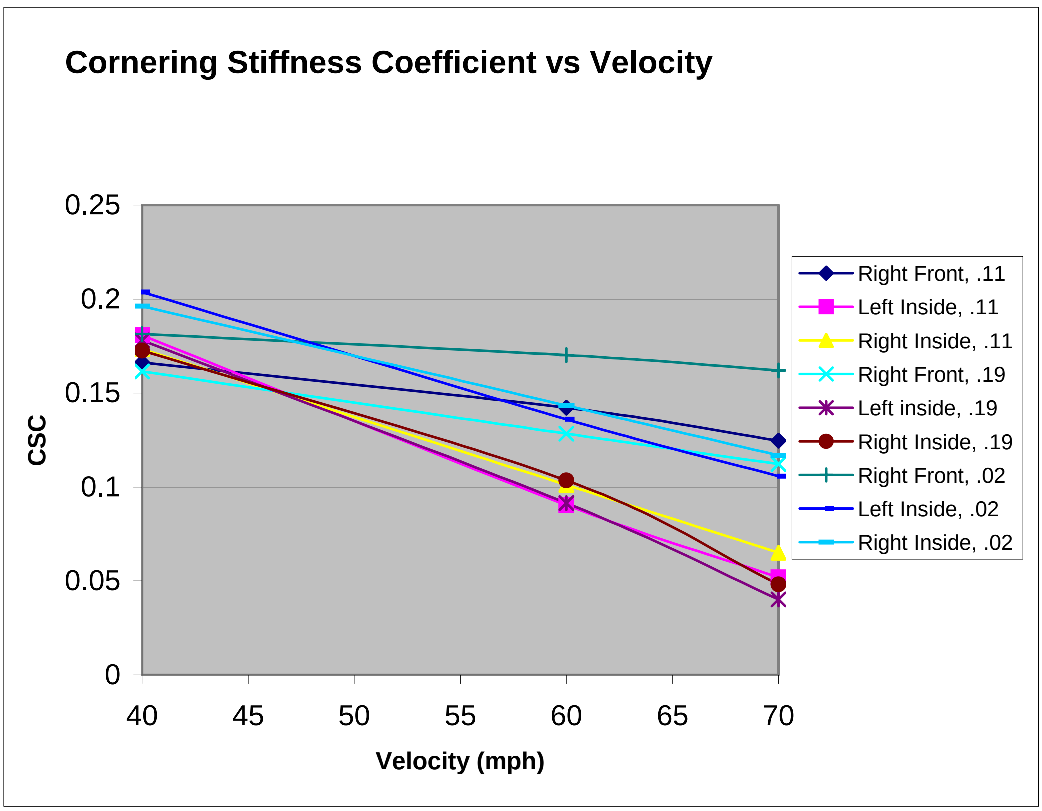
40mph .02, smooth
962run2.cut
50mph 0.02 smooth
962run3.cut
60mph .11 grooved
962run4.cut


Cornering Stiffness Coefficient vs Velocity
CSC
Velocity (mph)
Right Front, .11
Left Inside, .11
Right Inside, .11
Right Front, .19
Left inside, .19
Right Inside, .19
Right Front, .02
Left Inside, .02
Right Inside, .02

Tire Drag

Tire Drag Run	Tire	Tread Depth 32nds inch	Pressure (psi)	Water depth (inches)	Load (pounds)	Speed (mph) 40	60	70
						Estimated drag force (lbs)		
17	LF	14	73	0.11	5500	21	123	-
18	RF	14	94	0.11	5500	44	107	144
19	RF	14	94	0.11	5500	53	111	154
20	LOD	4	92	0.11	5400	86	147	-
21	LID	4	87	0.11	5400	40	131	170
22	ROD	8	94	0.11	5400	80	137	-
23	RID	7	90	0.11	5400	44	127	174
24	RID	7	90	0.19	5400	46	187	254
25	LID	4	87	0.19	5400	50	179	247
26	RF	14	94	0.19	5500	61	167	214
27	RF	14	94	0.02	5500	31	53	64
28	RF	14	94	0.02	5500	29	60	65
29	LID	4	87	0.02	5400	28	64	76
31	RID	8	90	0.02	5400	35	74	83