The last procedure is the one usually adopted and it tends to produce variable results. The other two procedures will give significantly different results in locked wheel braking tests, although the results from traction tests should correspond fairly closely. Without knowing the highway conditions over which the studded tires will be used, it is not possible to state which of the three procedures will give the most representative result.

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Determination of Precrash Parameters from Skid Mark Analysis

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This paper presents the results of an experimental study to validate and improve the methods currently used in the reconstruction of accidents to determine precrash parameters from skid marks. This was accomplished by testing six vehicles, three cars and three trucks, that had a variety of tires and loadings on three differing types of pavements. Both severe (wheels locked) and moderate (no wheels locked) stops were made. Prebraking speed, the length of the skid marks produced, stopping distance, and a number of other variables of interest were measured for each stop. Analysis of the experimental data focused on repeatability of skid mark data, validity of the currently used skid mark length versus prebraking speed formula, accuracy of the various methods for measuring tire friction, and tire marks left by nonlocked wheels. The currently used skid mark length versus prebraking speed formula was found to be better for accident reconstruction when using test data from locked wheel stops than were either of two other formulas that were tried. Four methods for measuring tire friction were evaluated. Two of these methods, the American Society for Testing and Materials skid number and an estimate based on a standard table found in the literature, were shown to give incorrect results when used for heavy, air-braked trucks. For some conditions, stops for which none of the vehicle's wheels locked were found to produce tire marks that were longer than those produced during a locked wheel stop. The tire marks generated during nonlocked wheel stops look like light shadowy (visible when viewed along their length but not from directly above) skid marks. Accident investigators must be careful when using light skid marks in the formulas to determine prebraking speed from skid mark length to ensure that the skid marks were made by locked wheels. Otherwise, too high an estimate of the vehicle's prebraking speed may be obtained.

Skid marks have an important role in the National Highway Traffic Safety Administration's (NHTSA) effort to increase vehicular safety on our nation's roads. The study of skid marks left on pavement after an accident has occurred helps experts in accident reconstruction determine the course of events that led to the accident and the precrash parameters of the vehicles involved. These, in turn, help NHTSA develop countermeasures to prevent accidents from occurring and to protect the occupants of vehicles involved in collisions.

Reconstructionists use the analysis of skid marks to help identify impact locations, vehicle trajectories, wheel lockup patterns, deceleration, and prebraking speed. The last three of these important quantities are calculated by means of relatively simple formulas based on a field investigator's report of the number and length of skid marks observed and the type and condition of the pavement on which the accident occurred.

The formulas used by accident reconstructionists are theoretical formulas and in their derivation a number of assumptions are made. If any of these assumptions are invalid, it could lead to errors between what actually occurred and the results of the accident reconstruction. Also, accident investigators frequently use standard tables (1,2) to estimate the coefficient of friction that was acting between a vehicle's tires and the road. These tables need to be checked for possible errors due to differing vehicle types, loading, tire types, and pavement composition.

The overall goal of this study was to increase knowledge of skid marks and to improve the accuracy of formulas and tables that involve them that are used in accident reconstruction. This was done by studying a large number of skid marks produced under controlled experimental conditions. Specifically, this study concentrated on (a) the repeatability of stops that produce skid marks, (b) the validity of the formulas and tables used to relate skid mark length to prebraking speed, (c) the best method of determining the coefficient of friction between the tire and the road for use in skid mark analysis, and

Table 1. Types of vehicles tested.

Vehicle	Class	Tires	Lightly Loaded Weight	Gross Vehicle Weight Rating
1980 Chevette	Subcompact car	P155/80R13 Armstrong radials	2 520	2 850
1980 Chevette	Subcompact car	A78/13 Armstrong bias ply	2 520	2 850
1980 Malibu station wagon	Intermediate car	P195/75R14 Uniroyal radials	3 910	
1976 Ford LTD	Full-sized car	P230/R15 Michelin radials	5 000	6 430
1976 Ford LTD	Full-sized car	H78/15 Cooper bias ply	5 000	6 430
1977 Ford F-250	Pickup truck	7.50-16 Remington bias ply	4 920	6 900
1977 Ford F-7000	Straight truck	Front, 10.0-20F Goodyear Super Hi Milers bias ply; Rear, 10.00-20F Goodyear Custom Cross Rib Hi Milers bias ply	9 430	27 500
1973 IH Transtar-Fontaine	Tractor-semitrailer	Front and trailer, 10.00-20F Goodyear Super Hi Milers bias ply; Rear, 10.00-20F Goodyear Custom Cross Rib Hi Milers bias ply	30 050	80 500

Table 2. Severe braking test matrix.

Vehicle Loading	Tire Type	Road Surface	1980 Chevette	1980 Malibu Station Wagon	1976 Ford LTD	1977 Ford F-250	1977 Ford F-7000	1973 IH Transtar-Fontaine
LLW, curb weight plus 300 lb	Bias ply	VDA asphalt	X		X	X	X[a]	X[a]
		Tar and gravel chip	X		X			
		Skid pad concrete	X		X			
	Radial	VDA asphalt	X	X[b]	X[b]			
		Tar and gravel chip	X		X			
		Skid pad concrete	X		X[b]			
Half-loaded	Bias ply	VDA asphalt				X		
GVW, fully loaded	Bias ply	VDA asphalt				X	X[a]	X[a]
	Radial	VDA asphalt	X		X[b]			

Note: Each test condition was run five times at 10, 20, 30, 40, and 60 mph for a total of 25 runs.

[a]All speeds were not used for safety reasons.
[b]Test condition was not run at 10 mph.

(d) the relation among the point of brake application, the onset of tire mark production, and the location of wheel lockup.

This paper summarizes the test program and procedures used. The principal results obtained from the testing are explained. The discussion of how to best measure the tire-road coefficient of friction outlined in this paper is presented in detail elsewhere (3). Details of the test program, test procedures, analytical methods used, and experimental results that were obtained are also contained elsewhere (4).

EXPERIMENTAL TESTING PROGRAM

During the summer of 1980, an experimental test program was conducted to supply the data needed to study the issues mentioned above. Three different types of tests were performed during the experimental program:

1. Severe braking tests in which the test driver applied the brakes of an instrumented test vehicle as rapidly and as hard as possible so as to cause rapid wheel lockup; this approximates panic braking such as might be done by a real driver when he or she becomes aware of an impending collision;
2. Moderate braking tests in which a servo-controlled brake actuator applied the brakes of an instrumented test vehicle at a predetermined constant level for which none of the wheels locked up to see if skid marks would be produced; and
3. Skid trailer tests, which measured peak and slide coefficients of friction for many of the tires used in this study, were performed on each of the different pavements used; the skid numbers of these pavements were also measured by using standard American Society for Testing and Materials (ASTM) test tires.

During the severe braking tests, the effect of changes in vehicle loading, tire type, and pavement type on the skid marks produced during a stop were studied for stops from five different initial speeds for each of six different types of vehicles. Table 1 gives the types of vehicles tested.

Tests were run with the vehicles (a) at lightly loaded weight (LLW), (b) fully loaded to gross vehicle weight rating (GVWR), and (c) half loaded (i.e., midway between the two other weights). Tests were conducted by using radial and bias ply tires on three test surfaces. The test surfaces used were the Transportation Research Center of Ohio (TRC) vehicle dynamics area (VDA), which is paved with asphalt, the TRC skid pad, which is paved with concrete, and a currently in-use public road, which is paved with a gravel chip and tar mixture laid over an asphalt road bed. Table 2 is a matrix of the severe braking tests.

Eight channels of data (only six for the F-7000) were strip-chart recorded for each stop. The data recorded were (a) distance traveled, (b) speed, (c) acceleration, (d) brake force or pressure applied, and (e) wheel rotational rate or lockup for each wheel. Also, the stopping distance (the distance from the beginning of the brake application until the vehicle reached a complete stop) and the prebraking speed were measured.

At the completion of each test stop, the skid marks produced during that stop were measured. This process begins by the measurer locating and marking the start and end of each skid mark. It is easy to

Table 3. Corrected stopping distances.

Vehicle	Loading	Surface	Tires	Nominal Speed (mph)	ASTM Skid No. at 40 mph	Slide Friction Coefficient at 40 mph for Nominal Load	Avg Corrected Stopping Distance (ft)	Long Corrected Stopping Distance (ft)	Short Corrected Stopping Distance (ft)	SE Corrected Stopping Distance (ft)	SE As Percentage of Avg Corrected Stopping Distance
Chevette	LLW	VDA	Bias ply	10			4.7	5.0	4.4	0.12	2.47
				20			17.4	18.1	16.7	0.27	1.54
				30			39.2	39.5	39.0	0.09	0.24
				40	81.1	0.848	69.4	70.3	68.3	0.34	0.48
				60			157.6	159.6	154.4	0.94	0.60
Chevette	LLW	Tar and gravel chip	Bias ply	10[a]			5.0	5.6	4.7	0.17	3.48
				20			20.1	22.5	17.7	0.81	4.00
				30			45.2	46.9	43.8	0.56	1.24
				40	60.8	0.714	80.2	86.6	75.2	2.12	2.64
				60			207.5	213.4	205.1	1.52	0.73
LTD	LLW	VDA	Radial	10			Not run				
				20			19.3	19.8	18.8	0.21	1.09
				30			45.6	46.9	45.0	0.36	0.78
				40	81.1	0.773	79.1	80.4	77.8	0.54	0.68
				60			167.7	170.2	165.0	0.85	0.51
Transtar-Fontaine	GVW	VDA	Bias ply	10			10.6	10.9	10.2	0.12	1.10
				20			33.0	34.2	30.4	0.69	2.08
				30			70.2	71.2	68.9	0.40	0.58
				40	81.1	0.566	119.3	121.7	116.1	0.93	0.78
				60			Not run				

Note: Five test runs were made at each nominal speed.
[a]Ten runs were made for this case.

locate the end of each skid mark because this is distinct and occurs where the test vehicle's wheels stopped. The start of the mark is harder to locate. The location of the start of the skid marks depends on the measurer's judgment. Therefore, to keep the results as consistent as possible, the same measurer was used throughout this study.

After the skid mark ends had been located, the length of each of the skid marks was measured with a tape measure, and the results were recorded. If the skid marks were curved, the path of the skid was followed as closely as possible to determine the true length of the mark.

During the moderate braking tests, the effect of changes in brake pedal force applied and road surface composition on the skid marks produced during a stop were studied. All test runs were made by stopping the subcompact passenger car from a single initial speed of 30 mph on several different pavements. All of these tests were run with the lightly loaded vehicle and radial tires.

The skid trailer tests used an ASTM skid trailer with ASTM tires to measure the skid numbers of each of the test surfaces used during this study. Peak and slide friction coefficients were also measured for each of the passenger car tires used on all of the test surfaces for which each particular tire was tested. Details of the skid trailer testing are given elsewhere (3).

Repeatability of Skid Mark Data

Two methods were used to check the consistency of the severe braking test data. First, the variability of the vehicle and the pavement was studied by looking at the distance the test vehicle took to stop for each test condition. Then, the consistency with which the measurer was able to mark the ends of the skid marks was analyzed. Before the stopping distances of test stops that were made from the same nominal prebraking speed but from slightly differing actual prebraking speeds could be compared, it was necessary to correct the stopping distances to account for the differing speeds. Corrected stopping distances were calculated for each run by means of Equation 1:

$$CSD = SD \cdot V_N^2 / V_A^2 \quad (1)$$

where

CSD = corrected stopping distance,
SD = actual stopping distance,
V_A = actual prebraking speed, and
V_N = nominal prebraking speed.

This formula was taken from the Society of Automotive Engineers recommended practice J-299, stopping distance test procedure. After they had been corrected, stopping distances for the same nominal speed could be compared directly.

Equation 1 was used to develop a table to summarize the corrected stopping distances of all of the more than 500 test stops that were made. This allowed comparison of the corrected stopping distances for varying loadings, pavements, and tires. Table 3 is a typical portion of this table. The last two columns of Table 3 give the amount of variability that was present in the testing. The next to last column contains the standard error in the corrected stopping distance (equal to the standard deviation divided by the square root of the number of trials), and the last column contains the standard error as a percentage of the average corrected stopping distance. To obtain some idea as to what the numbers in the last column mean for the five trials that were run for each test case, a standard error percentage of 1.14 percent means that 95 percent of the test values will be within 5 percent of the average value.

Analysis of the corrected stopping distances showed that the severe braking stops were repeatable. The average standard error as a percentage of the average corrected stopping distance was 1.75 percent. This indicates that 95 percent of all of the test stops had corrected stopping distances that were within 10 percent of the average value.

Significantly greater variability in stopping performance was observable for two sets of test conditions. For stops made from a nominal prebraking speed of 10 mph, the average standard error percentage was 3.14 percent. However, the maximum standard error for any of the 10-mph cases was 0.29

ft. Since the fifth wheel measures stopping distance with approximately this accuracy, this level of error is not significant. Testing on the tar and gravel chip pavement was also less consistent and repeatable. The average standard error percentage, for stops from all test speeds, was 3.10 percent on the tar and gravel chip pavement versus the 1.42 percent obtained for the other pavements. Corrected stopping distances were less consistent on the tar and gravel chip pavement due to variations in the composition and slickness of the surface. During the testing we noticed that the vehicle took longer to stop when a higher proportion of tar was present in the road.

Next, the consistency with which the measurer was able to measure the length of the skid marks produced during testing was checked. To determine the length of the skid marks on one side of the vehicle, the measurer must mark three points: the viewed from above (VFA) point, the viewed from ground level (VFGL) point, and the start of front marks (SFM) point. Determination of the precise location of the three points marked by the measurer was a difficult and somewhat subjective process because the skid marks tended to fade into the pavement. Although the same person was used as measurer throughout this program, there was clearly some run-to-run variability in the locations of the points chosen.

To determine the amount of variability inherent in the measurement process, the length of several sets of skid marks was measured every day for several days. By measuring the skid marks on a daily basis, enough time passed between each remeasurement so that the measurer could not remember the location of the marks from the previous day and had to relocate them. Data collected by measuring the length of eight skid marks produced during three stops on seven consecutive days was analyzed.

Skid marks decay with time. For the lightly traveled test surfaces that were used, this decay is very slow. To prevent this decay from biasing the analysis, linear regression was performed for each of the skid marks analyzed by using, as the model form,

$$S = C + Dn \quad (2)$$

where S is the skid mark length, n is the number of the measurement, and C and D are determined by regression. Only skid marks for which the 90 percent confidence interval on D included zero were then retained for analysis since these marks showed no significant decay with time.

The standard error, the standard error as a percentage of the average skid mark length, and the 95 percent confidence limits were calculated for each of the eight skid marks. The mark with the greatest variability had a 95 percent confidence limit of ±11.1 percent of its average length. On the average, the skid marks had a tight 95 percent confidence limit of ±3.8 percent of the average length. This indicates that the skid mark measurement process was repeatable.

Validity of the Skid Mark Length Versus Prebraking Speed Formula

A detailed analysis of the skid mark length data collected during the severe braking testing was conducted to either confirm the validity or else improve the existing prebraking speed versus skid mark length formulas. This was done by using the severe braking test data for performing regression analyses that determined values of coefficients in three model equations. The model equations have as their specific form,

$$S = A_1 V^2 \quad (3)$$

$$S = A_2 V^2 + C_2 \quad (4)$$

$$S = A_3 V^2 + B_3 V + C_3 \quad (5)$$

where

S = skid mark length,
V = prebraking speed, and
A_1, A_2, A_3, B_3, C_2, and C_3 = unknown coefficients, which were determined by regression.

Model 1 (Equation 3) has the same form as the standard skid mark length versus prebraking speed formulas. Model 2 (Equation 4) has the same form as the standard formulas would have if they were modified by assuming a constant distance between the start of braking and the onset of skid mark production. Model 3 (Equation 5) has the same form as the standard formulas would have if they were modified to account for a ramp brake application plus the traveling of a constant distance prior to the onset of skid mark production.

Separate regression analyses were performed for each of the 22 different combinations of vehicle type, tire type, pavement type, and loading that were tested. Regressions were performed for the skid marks left by each of the vehicle's individual wheels as well as for the average length from combinations of wheels. The numbers that follow were found by using the four-wheel average skid mark length. Similar results were obtained, however, for the regressions that were performed by using each of the individual wheel's skid marks.

Tables 4 and 5 give the results of the regressions by using the four-wheel average skid mark length for each of the three models. For the IH Transtar-Fontaine rig, for which the four-wheel average length was not used because this rig had more than four wheels, the regressions performed with the left front wheel and with the left leading tractor tandem data are given.

Table 4 contains the coefficient of determination (R^2) that was calculated for each model for the various test conditions. The lowest value of the coefficient of determination that was obtained for any of the models for any set of test conditions was 0.9784. For more than two-thirds of the cases shown, R^2 was above 0.9950 and 85 percent of the cases had it above 0.9900. These are extremely high values for the coefficient of determination and indicate that all three models could closely fit the experimental data. However, because R^2 was so large for all of the test cases, it was inadequate to determine which model was most accurate. This is because a model with more terms in it, such as model 3, normally accounts for more of the variation in the data. It may, however, be less useful for accident reconstruction than is a model with fewer terms in it such as model 1. To see how much more accurate the models that contained more terms actually were, the mean square error was studied.

The mean square error, which is the second measure of goodness of fit given in Table 4, is an estimate of the deviation of the regression curve from the actual data. It was analyzed by taking the average of the mean square errors for each model for all of the test cases given in Table 4. Also looked at was the influence of vehicle type, tire type, vehicle loading, and pavement composition on model accuracy. This was done by computing the average mean square error for selected subsets of the test conditions.

The average values of the mean square error that were found for all of the test cases were 28.01 for model 1, 20.08 for model 2, and 17.50 for model 3. This indicates that model 3 was the most accurate, followed by models 2 and 1, respectively. However, the improvement in accuracy between models was not great. The mean square error is the normalized sum of the squares of the residuals. The square root of the average values given shows that model 1 has a root mean square deviation between the model's predicted skid mark length and the actual skid mark length of slightly over 5.25 ft versus slightly under 4.25 ft for model 3. Given an average skid mark length of approximately 50 ft, this improvement of about 1 ft in accuracy is not significant.

A look at the individual test cases shows large case-to-case variations in the mean square error for the differing models. For some test conditions model 3 is significantly more accurate than model 1, with improvements in the deviation between the predicted and actual skid mark lengths of up to 5.25 ft occurring. There does not, however, seem to be any way of predicting in advance when this improvement will occur.

Table 4. Goodness of regression fits.

				Model 1		Model 2		Model 3	
Vehicle	Loading	Surface	Tires	R^2	Mean Square Error	R^2	Mean Square Error	R^2	Mean Square Error
Chevette	LLW	VDA	Bias ply	0.9993	3.95	0.9995	1.55	0.9997	1.01
	LLW	VDA	Radial	0.9990	5.05	0.9985	4.11	0.9986	4.07
	LLW	Skid pad	Bias ply	0.9989	6.06	0.9986	3.67	0.9986	3.82
	LLW	Skid pad	Radial	0.9990	4.63	0.9990	2.34	0.9991	2.23
	LLW	Tar and gravel chip	Bias ply	0.9889	111.99	0.9886	64.79	0.9946	32.22
	LLW	Tar and gravel chip	Radial	0.9859	151.39	0.9784	129.02	0.9845	96.88
	GVW	VDA	Radial	0.9971	16.99	0.9939	17.72	0.9939	18.50
Malibu	LLW	VDA	Radial	0.9988	8.04	0.9968	8.74	0.9986	8.65
LTD	LLW	VDA	Bias ply	0.9990	5.94	0.9978	6.19	0.9979	6.04
	LLW	VDA	Radial	0.9993	5.35	0.9983	5.25	0.9989	3.59
	LLW	Skid pad	Bias ply	0.9990	6.50	0.9979	6.77	0.9980	6.87
	LLW	Skid pad	Radial	0.9985	12.29	0.9960	12.48	0.9967	11.02
	LLW	Tar and gravel chip	Bias ply	0.9969	31.00	0.9937	30.95	0.9940	30.85
	LLW	Tar and gravel chip	Radial	0.9917	69.25	0.9844	67.79	0.9849	65.75
	GVW	VDA	Radial	0.9891	129.63	0.9902	55.23	0.9939	36.41
F-250	LLW	VDA	Bias ply	0.9983	8.91	0.9964	9.30	0.9965	9.47
	Half	VDA	Bias ply	0.9955	26.46	0.9968	10.29	0.9987	4.56
	GVW	VDA	Bias ply	0.9975	16.76	0.9977	8.52	0.9978	8.39
F-7000	LLW	VDA	Bias ply	0.9952	16.13	0.9899	14.15	0.9934	9.68
	GVW	VDA	Bias ply	0.9987	17.02	0.9988	6.62	0.9989	6.63
Transtar-Fontaine	LLW	VDA	Bias ply[a]	0.9973	3.14	0.9926	3.43	0.9928	3.69
	LLW	VDA	Bias ply[b]	0.9953	3.23	0.9877	3.39	0.9911	2.72
	GVW	VDA	Bias ply[a]	0.9984	7.97	0.9971	5.02	0.9971	5.31
	GVW	VDA	Bias ply[b]	0.9988	4.54	0.9967	4.57	0.9967	4.84

[a]Results for left front wheel. [b]Results for left leading tractor tandem wheel.

Table 5. Coefficients determined by regression.

				Model 1,	Model 2		Model 3		
Vehicle	Loading	Surface	Tires	A_1	A_2	C_2	A_3	B_3	C_3
Chevette	LLW	VDA	Bias ply	0.0413	0.0422	-2.237	0.0448	-0.199	0.626
	LLW	VDA	Radial	0.0390	0.0396	-1.500	0.0412	-0.121	0.258
	LLW	Skid pad	Bias ply	0.0392	0.0401	-2.333	0.0406	-0.040	-1.742
	LLW	Skid pad	Radial	0.0380	0.0389	-2.232	0.0406	-0.121	-0.485
	LLW	Tar and gravel chip	Bias ply	0.0523	0.0563	-10.068	0.0763	-1.508	11.722
	LLW	Tar and gravel chip	Radial	0.0537	0.0565	-7.491	0.0766	-1.521	14.640
	GVW	VDA	Radial	0.0415	0.0414	0.121	0.0415	-0.003	0.159
Malibu	LLW	VDA	Radial	0.0410	0.0424	-3.474	0.0429	-0.044	-2.694
LTD	LLW	VDA	Bias ply	0.0409	0.0408	0.117	0.0386	0.168	-2.316
	LLW	VDA	Radial	0.0437	0.0433	0.925	0.0362	0.594	-9.584
	LLW	Skid pad	Bias ply	0.0427	0.0428	-0.194	0.0412	0.118	-1.896
	LLW	Skid pad	Radial	0.0435	0.0430	1.320	0.0361	0.571	-8.815
	LLW	Tar and gravel chip	Bias ply	0.0494	0.0500	-1.641	0.0461	0.304	-6.086
	LLW	Tar and gravel chip	Radial	0.0478	0.0489	-2.952	0.0440	0.368	-8.278
	GVW	VDA	Radial	0.0512	0.0567	-14.151	0.0818	-2.111	23.979
F-250	LLW	VDA	Bias ply	0.0389	0.0389	-0.016	0.0373	0.125	-1.807
	Half	VDA	Bias ply	0.0414	0.0438	-5.830	0.0525	-0.650	3.555
	GVW	VDA	Bias ply	0.0420	0.0435	-4.125	0.0459	-0.178	-1.524
F-7000	LLW	VDA	Bias ply	0.0573	0.0595	-2.683	0.0790	-1.026	8.145
	GVW	VDA	Bias ply	0.0773	0.0802	-5.214	0.0831	-0.188	-2.773
Transtar-Fontaine	LLW	VDA	Bias ply[a]	0.0621	0.0621	0.058	0.0671	-0.210	1.946
	LLW	VDA	Bias ply[b]	0.0469	0.0478	-0.567	0.0300	0.746	-7.270
	GVW	VDA	Bias ply[a]	0.0707	0.0683	2.950	0.0689	-0.033	3.306
	GVW	VDA	Bias ply[b]	0.0613	0.0605	2.633	0.0603	0.013	4.598

[a]Results for left front wheel. [b]Results for left leading tractor tandem wheel.

To show the effects of pavement composition and variability on model accuracy, the average mean square error was calculated for each test surface. The results are given in the first three lines of Table 6. All of the models most accurately fit the experimental data for the testing on the skid pad; the VDA data ran a close second. Much poorer accuracy was obtained on the tar and gravel chip road. Note that this result is consistent with the greater variability in stopping performance on this surface that was pointed out earlier. Even on this surface, despite the relatively large improvements in mean square error from model 1 to model 3, the improvement in average root mean square skid mark length error was only about 2 ft, which is not significant.

Table 6 also gives the results of average mean square error calculations, which were made to determine the effect on model accuracy of tire type, vehicle loading, and vehicle type. The fourth and fifth lines of the table show that higher accuracy, and hence more consistent experimental data, was obtained with bias-ply tires than with radial tires. Since vehicles at GVW were only tested on the VDA, it was decided that this result should not be compared with the average mean square error from all of the LLW tests because these include the data from the highly variable tar and gravel chip surface. Comparison of the average mean square error from the GVW stops with that from the LLW stops, which were made on the skid pad or VDA, shows that the models less accurately fit the GVW data. Most of this increase in mean square error is attributable to the peculiar stopping behavior of the loaded Ford LTD.

Comparisons of model accuracy among passenger cars, pickup trucks, and the air-braked trucks was also made by using only the skid pad and VDA data. This revealed that the highest accuracy was obtained for the air-braked vehicles followed by the pickup truck, with the passenger cars third. This order was something of a surprise because the time delays that are inherent in air brakes were expected to result in less-consistent data. Also, it was anticipated that, due to these delays, model 3 would be by far the best for the air-braked vehicles. Instead, only a small improvement, which amounted to 0.5 ft in the average root mean square skid mark length error, was obtained.

For all three models, theoretical analysis of the assumed deceleration versus time curves and integration to determine stopping distance shows that the coefficient of sliding friction (U_s) is related to the coefficient of the velocity squared term (A_1, A_2, or A_3) by the equation

$$U_s = 1/2gA_i \qquad (6)$$

where g is the acceleration due to gravity. The complete theoretical analysis is contained elsewhere (4). From Equation 6, along with the values of A_1, A_2, and A_3 in Table 5, values of the slide friction coefficient have been calculated for each of the test conditions. These values are given in Table 7 along with results from two of the methods

Table 6. Average value of mean square error of selected test conditions.

Test Condition	Model 1	Model 2	Model 3
Tar and gravel chip road	90.91	73.14	56.43
Skid pad	7.37	6.32	5.99
VDA	17.44	10.26	10.64
Bias ply tires	17.97	11.95	11.52
Radial tires	44.74	33.63	27.46
Vehicle at LLW	26.64	22.00	17.57
Vehicle at LLW and on skid pad or VDA	6.86	6.25	5.61
Vehicle at GVW	32.15	16.28	13.35
Passenger car tests	37.87	27.77	21.86
Passenger car tests on skid pad or VDA	18.58	11.28	9.29
Pickup truck tests	17.38	9.37	7.47
Air-braked truck tests	8.67	6.20	5.49

Note: Values are the average of the mean square error for all tests run with the specified test conditions.

Table 7. Calculated and measured slide friction coefficients.

				Calculated Slide Friction Coefficients			Measured Slide Friction Coefficients		
							ASTM Skid No.	95 Percent Confidence Limits of Measured	
Vehicle	Loading	Surface	Tires	Model 1	Model 2	Model 3		Low	High
Chevette	LLW	VDA	Bias ply	0.809	0.792	0.746	81.1	0.819	0.877
	LLW	VDA	Radial	0.856	0.843	0.811	81.1	0.841	0.869
	LLW	Skid pad	Bias ply	0.852	0.833	0.823	79.1	0.793	0.843
	LLW	Skid pad	Radial	0.879	0.859	0.823	79.1	0.777	0.827
	LLW	Tar and gravel chip	Bias ply	0.639	0.593	0.438	60.8	0.653	0.775
	LLW	Tar and gravel chip	Radial	0.622	0.591	0.436	60.8	0.616	0.768
	GVW	VDA	Radial	0.805	0.807	0.805	81.1	0.841	0.869
Malibu	LLW	VDA	Radial	0.815	0.788	0.779	81.1	0.779	0.833
LTD	LLW	VDA	Bias ply	0.817	0.819	0.865	81.1	0.782	0.798
	LLW	VDA	Radial	0.764	0.771	0.923	81.1	0.746	0.800
	LLW	Skid pad	Bias ply	0.782	0.780	0.811	79.1	0.771	0.815
	LLW	Skid pad	Radial	0.768	0.777	0.925	79.1	0.720	0.756
	LLW	Tar and gravel chip	Bias ply	0.676	0.668	0.725	60.8	0.494	0.686
	LLW	Tar and gravel chip	Radial	0.699	0.683	0.759	60.8	0.486	0.608
	GVW	VDA	Radial	0.652	0.589	0.408	81.1	0.779	0.833
F-250	LLW	VDA	Bias ply	0.859	0.859	0.896	81.1		
	Half	VDA	Bias ply	0.807	0.763	0.636	81.1		
	GVW	VDA	Bias ply	0.795	0.768	0.728	81.1		
F-7000	LLW	VDA	Bias ply	0.583	0.561	0.423	81.1	0.554	
	GVW	VDA	Bias ply	0.432	0.416	0.402	81.1	0.539	
Transtar-Fontaine	LLW	VDA	Bias ply[a]	0.538	0.538	0.498	81.1	0.588	
	LLW	VDA	Bias ply[b]	0.712	0.699	1.113	81.1	0.588	
	GVW	VDA	Bias ply[a]	0.472	0.489	0.485	81.1	0.566	
	GVW	VDA	Bias ply[b]	0.545	0.552	0.554	81.1	0.566	

[a] Results for left front wheel. [b] Results for left leading tractor tandem wheel.

that were used to measure the slide friction coefficient.

The last three columns of Table 7 give measured slide friction values. Of these, the third from last column shows the ASTM skid number at 40 mph of the test pavement. For the passenger cars, the last two columns contain the lower and upper bounds, respectively, of the 95 percent confidence interval of the skid-trailer-measured tire-road slide friction coefficient. This friction coefficient was measured by mounting the tire of interest on the skid trailer, loading the trailer so as to approximate the normal load on the tire when it is mounted on the vehicle, and determining the slide friction coefficient at 40 mph. For large trucks, the next to last column contains the measured slide friction coefficient for the combination of tires mounted on each vehicle and the last column is blank because no information was available on the spread of these values.

Generally good agreement was obtained for the passenger car tests between the calculated and measured values of the friction coefficient. More than one-third of the values were inside the 95 percent confidence interval and three-fourths of the values were within 10 percent of these limits. The calculated values agreed best for model 1, followed by model 2, and model 3; however, the improvement between models was small. Similarly, for the pickup truck data, for which the friction coefficients of the actual pickup truck tires were not measured, model 1 provides the values that best agree with the measured ASTM 40-mph skid number. For the air-braked trucks, the skid number is generally well above the calculated friction coefficients. Reasonable agreement (half of values within 10 percent, all values within 20 percent), however, was obtained between the measured values and the values calculated by model 1. Values calculated from models 2 and 3 did not agree as closely.

The values of B_3 given in Table 5 vary from test case to test case, with a low value of -2.111 and a high value of 0.746. From theoretical analysis (4), B_3 is one-half the time it takes for the brakes to apply (i.e., one-half the time it takes the deceleration to rise from zero to the steady state value). Therefore, it should change only slightly from test case to test case for a given vehicle and it should always, for all vehicle speeds, be positive. However, as was just pointed out, the value of B_3 varies considerably for a given test vehicle. Furthermore, for more than one-half of the cases in Table 7, B_3 is negative. Calculation of the average value of B_3 for all 24 cases in the table yields -0.21, a negative value. Although tests for significance of B_3 showed that for some cases B_3 was probably significant and for others it was not, these facts lead one to suspect that B_3 is probably actually zero and show that the time needed for the brakes to apply does not significantly affect skid mark lengths. Even for the air-braked trucks, whose brakes come on relatively slowly due to pneumatic delays, four of the six B_3 values are negative, which indicates that brake apply times did not influence the results.

The constant terms in the model equation also show considerable variation--C_2 ranged between -14.151 and 2.950 and C_3 ranged between -9.584 and 23.979. Because these terms are due to the tire having to travel some distance after the onset of braking before producing skid marks, it is expected that C_2 and C_3 should always, for all vehicle speeds, be negative. The large positive values of C_3 that were determined for some sets of test conditions are thought to be mathematical artifacts that indicate that model 3 is not valid. Excluding the cases with large positive values, C_2 and C_3 are generally quite small, with occasional sets of test conditions for which large negative values were found. There does not seem to be any consistent pattern to allow one to predict when the large negative values will occur.

To summarize the above discussion, model 3 provides, in general, a slightly more accurate fit to the experimental data than does either model 1 or 2. For some cases, it is significantly more accurate, but these cases cannot be predicted in advance. However, study of the slide friction coefficients that are calculated from each model shows that model 1's are in slightly better agreement with the measured values than are either of the other models'. Furthermore, study of B_3, C_2, and C_3 reveals that it was impossible to predict their values and that there are discrepancies between their experimentally measured values and skid mark theory.

Overall, model 1, which is the currently in-use skid mark length versus prebraking speed formula, was confirmed by the data. The attempt to find a usable, better formula failed because, although models 2 and 3 more accurately fit the experimental data, the problems of predicting B_3, C_2, and C_3 make them unsuitable for practical, real-world use. Therefore, model 1 is the best formula that can be developed for use in accident reconstruction.

The above analysis also points out the inadvisability of using the ASTM 40-mph skid number for prebraking speed versus skid mark length calculations that involve heavy trucks. Considerable additional analysis was performed with the severe braking test data to evaluate several methods of measuring the tire-road slide friction coefficient. The methods evaluated were as follows:

1. Estimation of the friction coefficient based on the pavement type and condition; Baker has a table that can be used to make this estimate (1);
2. Measurement of the ASTM skid number of the pavement at 40 mph (omitting water) and use of that as an estimate of the friction coefficient;
3. Measurement of the tire-road slide friction coefficient with a skid trailer by the same type of test that is used to measure skid number, except that the actual tire is used instead of a standard ASTM one and the loading is changed to approximate the actual load on the tire when on the vehicle; a larger skid trailer is used for heavy truck tires; and
4. A severe braking stop from a specified prebraking speed by using the actual vehicle and tires, measurement of the length of the skid marks produced, and calculation of the friction coefficient from the theoretical skid mark length-prebraking speed formula; as is pointed out by Hutchinson and others (5), due to financial constraints, this method can be used only rarely in an actual field investigation.

A complete description of the evaluation of these friction measuring methods is contained elsewhere (3). To summarize the major result of these evaluations, all four methods for measuring tire friction provide acceptable estimates for passenger cars and pickup trucks. However, for heavy trucks, only methods 3 and 4 provide acceptable estimates of the tire-road friction. Methods 1 and 2 yield friction coefficients that are too high.

TIRE MARKS WITH UNLOCKED WHEELS

The testing found that a wheel frequently begins to produce skid marks before it locks up. (Technically, these are scuff marks but, since their appearance was similar to that of skid marks, the term skid mark is used in this paper.) In fact, for some runs, a wheel produced skid marks during most of the stop despite failure to lock up at any time during the stop.

The experimental observations mentioned above raised the possibility that the moderate braking of a vehicle (i.e., braking with none of the wheels locked at any time during a stop) could still cause skid marks to be left. Depending on the amount of brake pedal force that had to be applied to leave marks and on the corresponding magnitude of the resulting vehicle deceleration, these skid marks could be longer than those left by severe (panic type) braking. This would create problems when using the standard skid mark length versus prebraking speed formulas. These equations assume severe braking and would, for a moderate braking stop, predict that the vehicle was going faster than it actually was. Therefore, it is important to know whether or not longer skid marks can be produced during a moderate braking stop from a given speed than during a severe braking stop from the same speed. Furthermore, if this should prove to be the case, then it is important to know if there is some distinguishing feature of the scuff marks that allow one to know when the severe braking formulas are valid.

To study this question, a number of moderate braking tests were run by using the lightly loaded 1980 Chevette with radial tires. All test stops were made from a nominal prebraking speed of 30 mph by applying a constant, predetermined force to the brake pedal with a servo-controlled brake actuator. Most of the testing was performed on the three surfaces used previously. A few tests were run on a number of other surfaces to see if they would yield similar results.

The skid marks produced were generally much lighter than the ones produced during severe braking. As a result, it was normally impossible to distinguish between the front and rear wheel skid marks. Therefore, the entire length of the skid mark on the right and left sides was measured and recorded. It was then necessary to subtract the wheelbase of the vehicle (8.0 ft) from the measured length to determine the rear-wheel skid mark lengths.

The first set of moderate braking tests was run on the VDA asphalt. For this set, the Chevette was braked from 30 mph by pedal forces ranging from 30 to 100 lbs (it takes about 150 lbs to lock wheels). Even at the low pedal force of 40 lbs, noticeable skid marks were left.

The table below gives the corrected average skid mark lengths obtained from these tests versus the brake pedal force used to generate them. The test vehicle was a Chevette, LLW, run on VDA asphalt at a nominal speed of 30 mph and equipped with radial tires.

Pedal Force (lb)	Corrected Avg Skid Mark Length (ft)
40	88.1
50	71.7
60	62.5
70	55.8
80	55.2
90	51.7
100	40.8
∿300	31.6

The corrected average skid mark length is the average of the left and right skid mark lengths after they have had the wheelbase of the vehicle subtracted from them and are corrected for speed differences by means of Equation 1, with skid mark length substituted for stopping distance. This length increased as the applied brake pedal force decreased from the low of 31.6 ft that was obtained for the severe braking stops in an average of five stops to a high of 88.1 ft for an applied force of 40 lbs. This indicates a possible problem in using skid marks to determine prebraking vehicle speed. Specifically, if an accident investigator were to interpret the skid marks that were produced during the stop with 40-lb pedal force as having been produced during a severe braking stop, subsequent reconstruction would predict a prebraking vehicle speed of approximately 50 mph compared with the 30 mph that the vehicle actually was going.

There was a difference in darkness and intensity of the unlocked wheel, moderate braking skid marks as compared with the locked wheel, severe braking ones in that the moderate braking left only light, shadow-type marks. Normally, during severe braking, a light area occurs at the very beginning of the skid mark that is hard to see when looking directly down at the mark. To see this shadow properly, you have to look along the length of the skid mark from some distance away.

The moderate braking skid marks on the VDA asphalt are like these shadows in that they were just barely visible from directly above, but they are very clear from far away. The entire length of these marks is the shadow, with no dark portion such as normally appears in a locked wheel stop. To demonstrate this difference in appearance, Figures 1 and 2 show moderate braking skid marks, generated during a stop with 80-lb pedal force, next to severe braking skid marks. The moderate braking skid marks are to the right of the picture in Figure 1, and the light set are in the foreground in Figure 2. As Figure 1 shows, when viewed along their length, the moderate and severe braking skid marks are both dark. However, when viewed from above and to the side (as in Figure 2), the moderate braking marks are much lighter.

Unlocked wheel, relatively low deceleration stops produced long visible skid marks on two of the five other pavements tested on. On the basis of this testing, it is impossible to say just how much of a problem nonlocked wheel skid marks may cause for skid mark theory. At least for some pavements, it is possible to create longer skid marks with wheels that are braked so as to merely retard their motion than with locked wheels. It is not clear how prevalent this phenomenon is.

Since all of the nonlocked wheel skid marks were visible only as shadows (i.e., visible only when viewed along their length), the standard skid mark formulas are valid as long as the investigator only uses them for nonshadow skid marks. Any skid mark that is visible only as a shadow may be due to a nonlocked wheel for which the standard formulas are incorrect.

CONCLUSIONS

A number of results of interest to accident investigators and reconstructionists were developed during this study. First, the variability of stopping performance during severe braking stops of the type that leave dark skid marks was considered. This variability was found to be small for tests that were conducted on TRC's test pavements but increased to approximately 15 percent for tests on the tar and gravel chip public road. Testing during this project, with the hard and fast brake applications that were used, gave the minimum speed for producing a skid mark of a given length. Greater stopping vari-

Figure 1. Skid marks from moderate (left) and severe (right) braking viewed lengthwise.

Figure 2. Side view of skid marks from moderate (bottom) and severe (top) braking.

ability will be present in an actual accident situation. This is why a maximum value for the prebraking speed cannot be predicted from skid marks.

The process of measuring skid marks was found to be repeatable provided the measurements were made carefully. Less than a 5-percent error was typically made. Regression analyses were performed to see how well the currently used skid mark length versus prebraking speed formulas and two modified forms of the currently used formulas fit the experimental data. These analyses showed that the currently used formulas provided an excellent fit to the test data. Furthermore, neither of the modified formulas were able to explain the test data better.

Four methods of measuring the tire-road slide friction coefficient for use in skid mark analysis were evaluated. All four methods provided acceptable results for passenger cars and pickup trucks. However, for heavy trucks, only two of the four methods gave acceptable results--calculation of the friction from a stop and the skid-trailer-measured tire-road friction. The other two methods produced friction coefficients that were too high for trucks, which resulted in predicted speeds well above the actual ones.

Early in this study we found that wheels that did not lock during a stop could still produce long scuff marks, similar in appearance to skid marks. In fact, for some pavements stops for which none of the vehicle's wheels locked were found to produce tire marks that were longer than those produced during a locked wheel stop. The tire marks generated during nonlocked wheel stops look like light shadowy (visible when viewed along their length but not from directly above) skid marks. Accident investigators must be extremely careful when using light skid marks in the formulas to determine prebraking speed from skid mark length to ensure that the skid marks were made by locked wheels. Otherwise, too high an estimate of the vehicle's prebraking speed may be obtained.

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