EFFECTIVENESS OF STUDDED TIRES

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This paper describes the results of tests of the locked-wheel stopping distances of four tire combinations on glare ice, on wet and dry asphaltic concrete, and on wet and dry portland cement concrete pavements. Identical cars with highway tread tires on four wheels, with plain snow tires on the rear wheels, with studded snow tires on the rear wheels, and with studded snow tires on four wheels were tested at speeds up to 50 mph and at temperatures from -5 to 33 F. On glare ice, snow tires gave no consistent improvement in stopping distance, compared with standard highway tires. Studded tires on the rear wheels resulted in a significant reduction in stopping distance, and studded tires on all four wheels resulted in a reduction in stopping distance that was more than twice the reduction with studs in the rear tires only. The improvements were greatest at ice temperatures near the freezing point. While the improvements decreased with decreasing ice temperatures, these improvements did not disappear at temperatures near -5 F, as suggested by earlier research. On asphalt pavements, no significant differences in stopping distances were found on either wet or dry surfaces. On concrete pavements, studded tires were found to give small but significant increases in stopping distances on both wet and dry surfaces.

•STUDDED TIRES have now been in common use in Canada for a number of years, and research on both the advantages and the disadvantages of their use has been proceeding throughout this period. However, it was only with the publication of a report by Smith and Shonfeld (1) that there came into existence any general recognition of the costs to the public of damage done by studded tires to street and highway pavements. These costs for highways in southern Ontario alone were estimated at $127 million over the next 9 years.

Recognition of these costs and other disbenefits leads directly to the question of the value of the studded tires to the general public. This value may lie in convenience, resulting from an increased ability to start up on a slippery surface, or in enhanced safety, resulting from improvements in stopping distances, in cornering ability, or in tractive effort.

A review of technical literature revealed that tests of studded tires have been carried out by a number of agencies, mainly by those in other countries but also including significant work by the Royal Canadian Air Force (2) in 1965. The Highway Research Board has published a number of reports on studded tires. Perhaps the most important single document on the subject is a study by the National Cooperative Highway Research Program (3). The Committee on Winter Driving Hazards of the National Safety Council has carried out tests of studded tires on ice annually since 1964 (4) and has published reports of its test results (5).

The majority of identified test results was concerned with stopping distance tests on glare ice, almost all at low speeds (principally 20 mph). There seemed little reason to

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suppose that results arrived at elsewhere (particularly those of the National Safety Council, whose tests are conducted in northern Wisconsin) would not be valid in Canada. However, there did appear to be a question as to whether stopping distances derived at 20 mph could properly be considered as representative of stopping distances at other more typical speeds.

Some of the published research indicated, without establishing beyond question, that cars with studded tires may require greater stopping distances on some pavement surfaces than those required by cars with standard highway tires. As a result of this background, the Canada Safety Council in February 1970 engaged the firm of Damas and Smith to carry out the research reported in this paper. From other published test results, it was concluded that there were discrepancies between empirical test results and theoretical stopping distances on ice. A purely empirical approach was chosen for the research.

TESTING PROGRAM AND EQUIPMENT

The performance of any car in braking or traction is dependent on a multitude of factors, including tires, vehicle suspension system, surface conditions, driver action, and system action (the latter constituting the interaction of these and a variety of other identifiable and unidentifiable factors). In the case of studded tires, the relative importance of some of these factors may change, while others may be added—the number of studs, their size, their pattern of arrangement, the material of which they are made, and their shape and protrusion.

It was concluded that the effects of some of these factors are minor and that other variables might be fixed at average or representative values, thus enabling limited testing to produce meaningful results. At the opposite extreme, there are important variables whose values may be entirely fortuitous, such as ice and air temperatures. Between these two types, other variables are controllable, and their values and effects are, in some cases, of prime importance. Speed is outstanding among these.

In designing the research, we concluded that the stopping tests required measuring the important uncontrollable variables, controlling and measuring the more important controllable variables, and, so far as possible, fixing all other factors at single values. Thus, the tire characteristics were fixed at an average value by selecting tires of a single construction type and by frequent checking of tread wear and pressures. Similarly, the combined effects of the vehicle suspension system were nominally fixed by the use of identical vehicles. Driver actions could be fixed or their effects minimized by the use of highly disciplined drivers following very simple directions that would leave little room for the exercise of personal characteristics.

Four identical cars (new 1970 Chevrolet sedans) were fitted with the following tire combinations and were used to carry out stopping distance tests on glare ice, on wet and dry asphaltic concrete, and on wet and dry portland cement concrete pavements:

1. Standard highway tread tires on all four wheels;
2. Plain snow tires on rear wheels and standard highway tread tires on front wheels;
3. Studded snow tires on rear wheels and standard highway tread tires on front wheels; and
4. Studded snow tires on all four wheels.

The cars came equipped with belted bias tires. The snow tires selected for testing were also belted bias tires taking 122 studs. The only criteria used in selecting these tires were that they should have the same construction as the tires fitted to the cars by the manufacturer and that they should be readily available. It was hoped that they would, therefore, be representative of what the public might buy if seeking a good quality tire.

It was recognized that snow tires are not particularly suitable for use on front wheels and that, if studded tires were to be used on all four wheels, different tread patterns for front and rear wheels would be desirable. It was known at the time that one manufacturer was producing a special tire for use with studs on the front wheels, but this tire was not available in Canada. Consequently, it was necessary to settle for snow tires on all wheels in order to have studs on all wheels.

During the course of testing, the tires were checked daily for loss of studs and any excessive wear in either the studs or the tires. In addition, several daily checks were made to ensure correct tire pressures and the fitness of the vehicles and of the various testing devices. Replacement of most of the test tires became necessary following the first set of tests on dry pavement. Marking devices were used to mark the point of brake application. All of these were connected to the brake-light circuit.

Ice tests were conducted on Lake Vernon near Huntsville, Ontario. Pavement tests were conducted at three sites, all of which were provincial highways, selected on the basis of pavement type, level profile, and ease of detouring traffic. Two of the sites had pavements with HL1 asphalt mixes, 40 percent traprock, and 5.6 to 5.8 percent asphalt. These pavements were 1½ and 2½ years old, with annual average daily traffic (AADT) volumes of 3,500 and 4,800 vehicles. The third site was constituted of a concrete slab construction with a concrete surface, was 2½ years old, and had AADT volumes of 600 vehicles.

The stopping-distance tests were conducted at three speeds—20, 35, and 50 mph. The car was driven slightly above the test speed and then allowed to decelerate to the required speed. It was then brought to a skidding stop by locking the wheels and holding the steering wheel firmly in a straight-ahead position. Two Ontario Provincial Police drivers were used in rotation, with each driver completing at least four runs of each test series in each car.

A total of 599 observations of stopping distances on glare ice was recorded, with surface temperatures ranging from -5 to 33 F. A total of 581 observations of stopping distances on wet and dry pavements was also recorded.

ANALYSIS OF TEST RESULTS

Stopping Distance on Glare Ice

Mathematical Model—It was assumed that stopping distance is a function of two main factors—ice temperature and the speed when brakes are applied. It was assumed that the effects of all other factors could be adequately expressed as random error in which the standard deviation is proportional to the braking speed.

The first model for regression analysis purposes was specified as follows:

$$D_i = B_0 + B_1V_i + B_2V_i^2 + B_3T_i + B_4T_i^2 + B_5V_iT_i + V_ie_i \tag{1}$$

where

i = 1, 2, . . . , n, the index number to identify sets of test factors;
D_i = distance to stop, ft;
T_i = temperature of ice, deg F;
V_i = velocity (speed) at which brakes are applied, mph; and
e_i = error, a random variable with a mean of zero and a standard deviation of σ.

The method of least-squares was used to fit the following regression equation to data for each of the four cars:

$$\overline{D}_i = b_0 + b_1V_i + b_2V_i^2 + b_3T_i + b_4T_i^2 + b_5V_iT_i \tag{2}$$

where the b's are unbiased estimates of the unknown B's in Eq. 1.

After carrying out the standard regression analysis of variance and rejecting terms that were not statistically significant, we found that each of the four car types had a different set of statistically significant terms. It was also found that the signs of terms were such that negative values of D were obtained by extrapolation to the left of the ranges $0 \le T \le 32$ and $20 \le V_i \le 50$. Because of these inconsistencies, it was decided to eliminate the constant term and additive terms in T_i and T_i^2.

In the final analysis, the model was thus reduced to the following form:

$$D_i = B_1T_iV_i + B_2V_i^2 + V_ie_i \tag{3}$$

For standard regression analysis purposes, this can be rewritten as follows:

$$(D_i/V_i) = B_1T_i + B_2V_i + e_i \tag{4}$$

The error term V_ie_i in Eq. 3 has a mean of zero and a standard deviation of $V_i\sigma$, while the error term in Eq. 4 has a mean of zero and a standard deviation of σ.

Estimation Equation—As a result of the preceding mathematical model analysis, the following regression equation was fitted to the data, using stepwise linear regression analysis, for each of the four cars:

$$D_i = b_1T_iV_i + b_2V_i^2 \tag{5}$$

where b_1 and b_2 are unbiased estimates of the unknown parameters B_1 and B_2 in Eq. 4. The following equations resulted.

1. Highway tire, four wheels (n = 99):

$$\overline{D}_i = 0.108\,T_iV_i + 0.250\,V_i^2 \tag{6}$$

2. Highway tire front, snow tire rear (n = 103):

$$\overline{D}_i = 0.090\,T_iV_i + 0.258\,V_i^2 \tag{7}$$

3. Highway tire front, studded snow tire rear (n = 91):

$$\overline{D}_i = 0.057\,T_iV_i + 0.232\,V_i^2 \tag{8}$$

4. Studded snow tire, four wheels (n = 98):

$$\overline{D}_i = 0.019\,T_iV_i + 0.202\,V_i^2 \tag{9}$$

The residual sum of squares for D_i/V_i in Eq. 6 was 100.54. Addition of a linear term V_i in Eq. 6 would reduce the residual sum of squares to 98.95. The reduction, 1.59, is not statistically significant because $F_{1,96} = 1.59/(98.95/96) = 1.54$.

The residual sum of squares for D_i/V_i in Eq. 7 was 146.84. Addition of a linear term V_i in Eq. 7 would reduce the residual sum of squares to 109.78. The reduction, 37.06, is statistically significant at the $\sigma = 0.01$ (99 percent) significance level, because $F_{1,98} = 37.06/(109.78/100) = 33.8$. However, the addition of the term V_i would yield a negative sign that is not acceptable when extrapolated.

The residual sum of squares for D_i/V_i in Eq. 8 was 45.46. Addition of a linear term V_i in Eq. 8 would reduce the residual sum of squares to 44.67. The difference, 0.79, is not statistically significant because $F_{1,86} = 0.79/(44.67/88) = 1.56$.

The residual sum of squares for D_i/V_i in Eq. 9 was 34.88. Addition of a linear term V_i in Eq. 9 would reduce the residual sum of squares by an insignificant amount.

Data Variations—In total, 599 tests were run on glare ice. However, the results of a number of tests were not used in the analysis. These were classified a priori as unsuitable because conditions changed during the tests (e.g., faults occurred in the ice) or because the accuracies of measurements were doubtful (e.g., thermometer readings of ice temperature were affected by local melting). The numbers of tests rejected and used for analysis were as follows:

Car	Total	Rejected	Used
Highway tire, four wheels	152	53	99
Snow tire, rear only	172	69	103
Studded snow tire, rear only	137	46	91
Studded snow tire, four wheels	138	40	98

After braking speed and ice temperature effects were accounted for, a good deal of variation in stopping distances remained. Such variations are the result of a multitude

of factors not controlled in the tests and not included in the mathematical model. As noted in Eq. 1 or 2, the variations were described as values of a random variable $V_i e_i$, where e_i has a mean of zero and a standard deviation of σ. A sample standard deviation, s, was computed as an estimate of σ in each of the four cases, and the following results were compiled:

Car	s	$V_i s$	$2V_i s$
Highway tire, four wheels	1.018	$1.018V_i$	$2.036V_i$
Snow tire, rear only	1.206	$1.206V_i$	$2.412V_i$
Studded snow tire, rear only	0.716	$0.716V_i$	$1.432V_i$
Studded snow tire, four wheels	0.603	$0.603V_i$	$1.206V_i$

One would expect about 95 percent of all data points D to fall within the limits $D_i \pm 2V_i s$. About 95 percent of all the points used in the analysis did fall inside these two sigma limits. Plots of the data points and the upper and lower limits are shown in Figures 1, 2, 3, and 4.

Test Results—Equations 6, 7, 8, and 9 all have the same form. If ice temperature is fixed, the stopping distance is a parabolic function of braking speed. If braking speed is fixed, the stopping distance is a straight-line function of ice temperature. Plots of stopping distance versus ice temperature for cars traveling at fixed speeds of 20, 35, and 50 mph are shown in Figure 5. Plots of stopping distance versus speed for cars traveling on glare ice at fixed temperatures of 0 and 30 F are shown in Figure 6. Figure 5 shows that at 20 mph the stopping distance required for cars with the different tire combinations is almost the same at temperatures slightly below 0 F. This fact has also been reported in other research (4). However, at higher speeds, the stopping distances are still significantly different at temperatures below 0 F. It is evident that, at the three speeds tested and within the temperature range observed, the cars with studded snow tires required less distance to stop than those without. Also evident is the fact that the studded snow tires become more effective with increasing (higher)

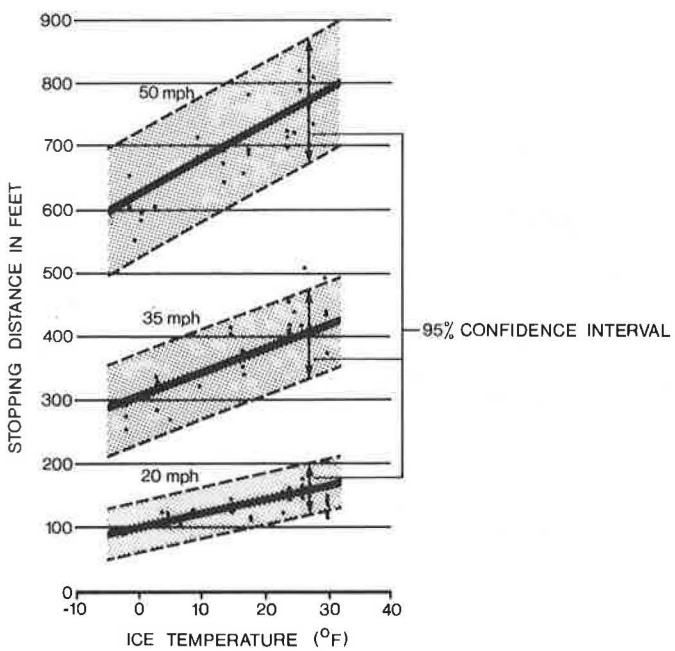

Figure 1. Stopping distance versus ice temperature for car with highway tires on four wheels.

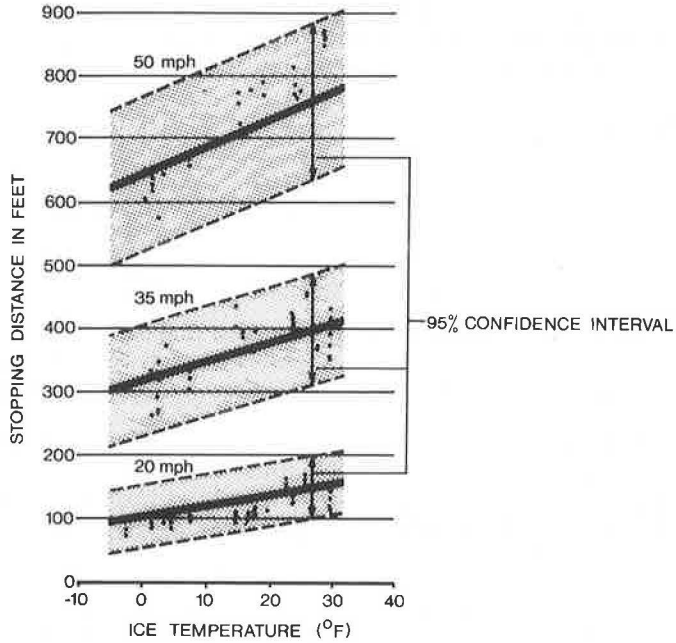

Figure 2. Stopping distance versus ice temperature for car with snow tires on rear wheels only.

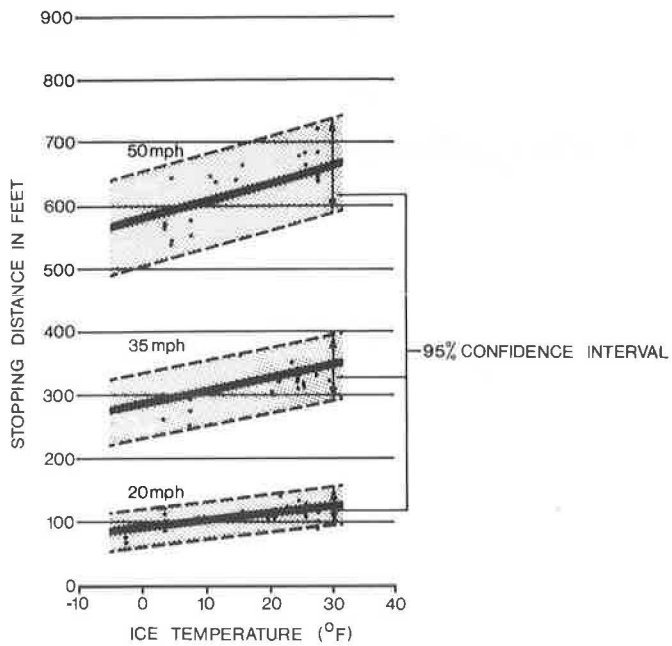

Figure 3. Stopping distance versus ice temperature for car with studded snow tires on rear wheels only.

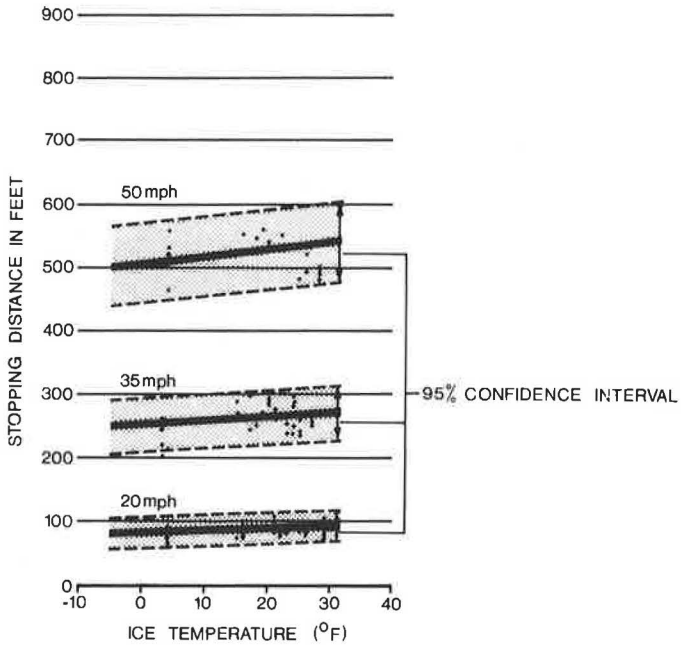

Figure 4. Stopping distance versus ice temperature for car with studded snow tires on four wheels.

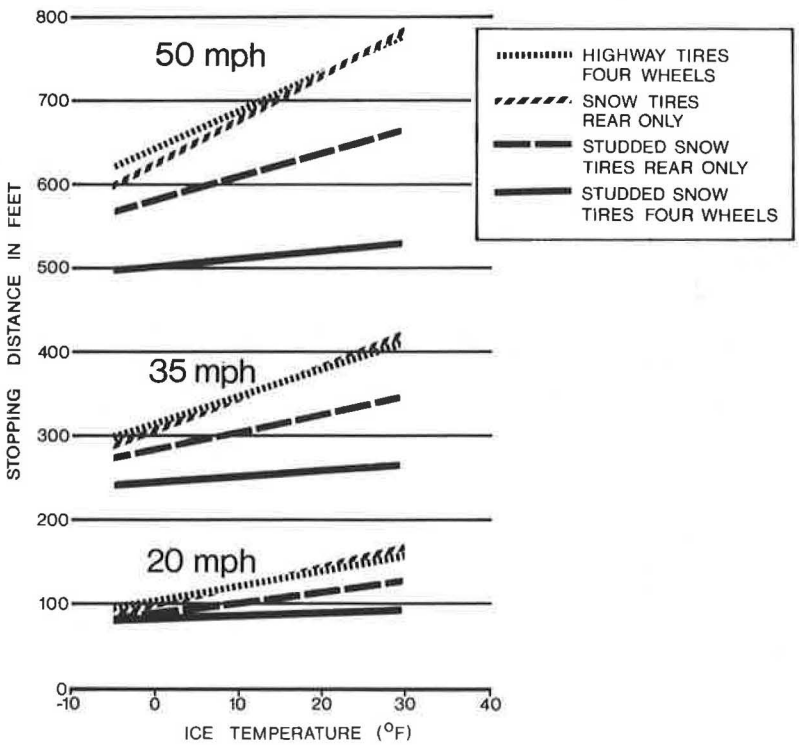

Figure 5. Stopping distance versus ice temperature for four cars traveling at 20, 35, and 50 mph.

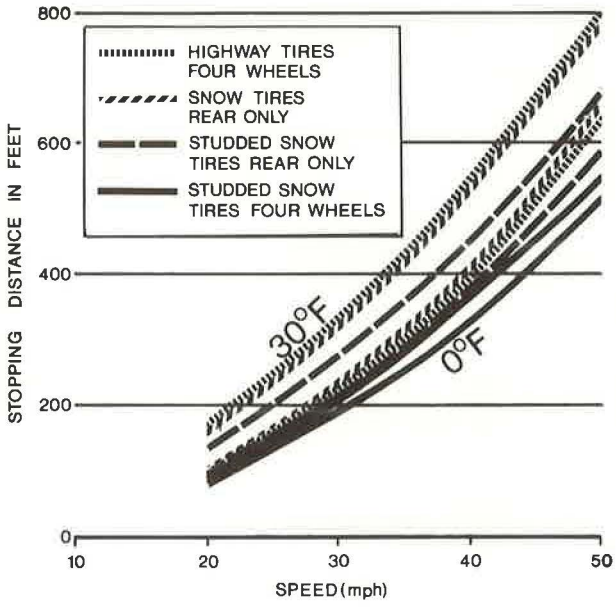

Figure 6. Stopping distance versus speed for cars traveling on glare ice.

temperature. It is also clear that the addition of studs in the front tires more than doubles the benefits from studs in the rear tires alone and that this enhanced benefit increases with speed. Figure 6 shows that the improvements in stopping distances with studded tires are materially greater at higher speeds.

Stopping Distance on Pavement

With few exceptions, at least eight test runs were completed for each test series. Initially all tests were conducted with the viewpoint that the variation in stopping distance would be different for each pavement surface. However, pairwise student t-tests at the 95 percent probability level showed that the two asphalt surfaces were from the same population of data. Therefore, the results of tests on the two asphalt surfaces were combined and are shown in Figure 7, while the results of the tests on the portland cement concrete surfaces are shown in Figure 8.

Figure 7 shows that, on the asphalt surfaces tested, the stopping distance does not materially depend on the type of tire. Figure 8, however, does show appreciable differences in stopping distances of the various cars under both wet and dry conditions of concrete. The ranking of the cars is in reverse order to that on the glare ice. It must be concluded, therefore, that, within the limits of the test conditions, studded tires increase the stopping distance on either wet or dry concrete surfaces and that this disadvantage increases with the use of studs on all four wheels.

The sample averages, $\overline{D}_i$, and variances, s_i, were computed for each test series. These are given in Table 1. The standard errors of estimated means, $s_{\overline{D}_i} = \sqrt{s_i^2/n}$, and the corresponding number of tests, n, are given in Table 2.

Significance tests were also made to determine whether the wet pavement tests differed from the dry pavement tests at the 95 percent probability level. This analysis showed that, while no significant difference could be determined at the lowest speed on the asphalt surface, the wet pavement test results were different from the dry pavement test results when all three speeds are taken into account.

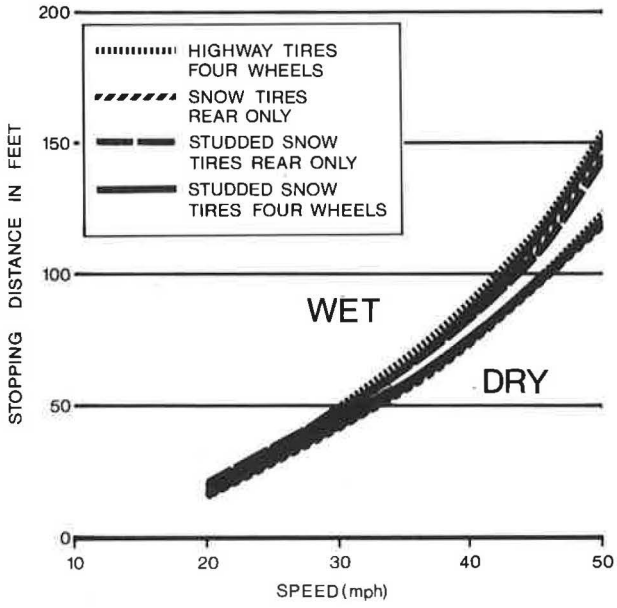

Figure 7. Stopping distance versus speed for cars traveling on asphalt pavement.

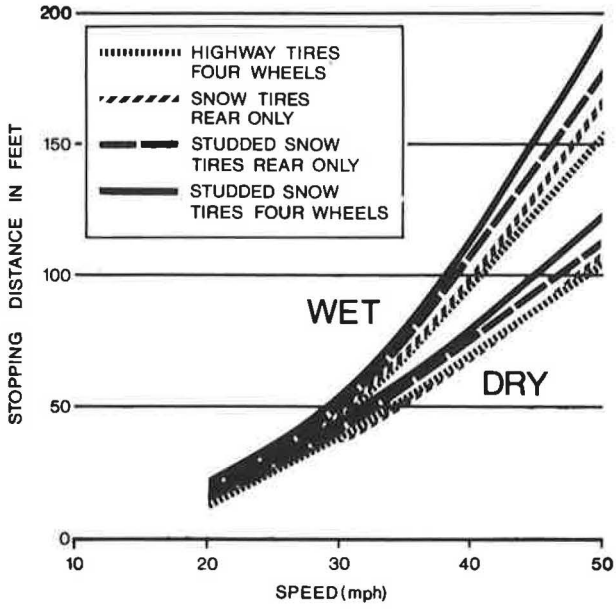

Figure 8. Stopping distance versus speed for cars traveling on concrete pavement.

TABLE 1

MEANS AND VARIANCES OF PAVEMENT TESTS

Pavement Type	Speed (mph)	Statistic	Highway Tires on Four Wheels	Snow Tires on Rear Wheels	Studded Snow Tires on Rear Wheels	Studded Snow Tires on Four Wheels
Dry asphalt	20	$\overline{D}_i$	17.50	15.20	17.60	17.50
		s^2	6.27	2.43	3.18	1.73
	35	$\overline{D}_i$	57.80	55.10	57.10	56.80
		s^2	42.16	20.73	15.05	20.33
	50	$\overline{D}_i$	121.10	117.70	117.10	116.10
		s^2	35.26	19.30	8.38	19.32
Wet asphalt	20	$\overline{D}_i$	17.80	15.70	18.50	17.40
		s^2	8.93	2.52	6.80	1.85
	35	$\overline{D}_i$	66.50	61.80	60.80	62.40
		s^2	62.00	13.00	20.16	5.72
	50	$\overline{D}_i$	150.90	148.00	141.80	148.60
		s^2	118.92	133.93	49.53	42.80
Dry concrete	20	$\overline{D}_i$	14.00	16.00	16.30	18.50
		s^2	12.28	1.42	1.00	2.00
	35	$\overline{D}_i$	53.00	50.30	56.80	58.30
		s^2	35.28	1.28	10.14	16.42
	50	$\overline{D}_i$	104.90	105.50	115.30	121.90
		s^2	45.00	29.71	8.71	9.57
Wet concrete	20	$\overline{D}_i$	14.70	17.50	18.60	22.80
		s^2	4.25	0.85	3.77	5.00
	35	$\overline{D}_i$	69.30	70.50	76.90	81.10
		s^2	139.50	23.71	33.66	152.42
	50	$\overline{D}_i$	153.50	165.60	177.10	195.00
		s^2	48.60	337.42	67.66	445.00

TABLE 2

NUMBER OF TESTS AND STANDARD ERRORS OF ESTIMATED MEANS

Pavement Type	Speed (mph)	Statistic	Highway Tires on Four Wheels	Snow Tires on Rear Wheels	Studded Snow Tires on Rear Wheels	Studded Snow Tires on Four Wheels
Dry asphalt	20	n	16	16	16	16
		$s_{\overline{D}_i}$	0.63	0.39	0.45	0.33
	35	n	16	16	16	16
		$s_{\overline{D}_i}$	1.62	1.14	0.97	1.13
	50	n	16	16	16	16
		$s_{\overline{D}_i}$	1.48	1.10	0.72	1.10
Wet asphalt	20	n	16	16	16	16
		$s_{\overline{D}_i}$	0.75	0.40	0.65	0.34
	35	n	16	16	16	16
		$s_{\overline{D}_i}$	1.97	0.90	1.12	0.60
	50	n	16	16	16	16
		$s_{\overline{D}_i}$	2.73	2.89	1.76	1.63
Dry concrete	20	n	8	8	8	8
		$s_{\overline{D}_i}$	1.24	0.42	0.35	0.50
	35	n	8	8	8	8
		$s_{\overline{D}_i}$	2.10	0.40	1.13	1.43
	50	n	8	8	8	8
		$s_{\overline{D}_i}$	2.37	1.93	1.04	1.09
Wet concrete	20	n	9	8	10	8
		$s_{\overline{D}_i}$	0.69	0.33	0.61	0.79
	35	n	9	8	10	8
		$s_{\overline{D}_i}$	3.94	1.72	1.84	4.36
	50	n	6	8	10	7
		$s_{\overline{D}_i}$	2.85	6.49	2.60	7.95

CONCLUSIONS

On the basis of the test procedures and conditions outlined in this report and to the extent that the tires and vehicles used in testing may be considered typical, the following conclusions may be reached:

1. On glare ice, snow tires give no consistent improvement in stopping distance, compared to standard highway tires. They appear to be slightly better at ice temperatures near the freezing point, slightly worse at ice temperatures near zero.
2. On glare ice, studded tires on only the rear wheels result in a significant reduction in stopping distance compared with standard highway and snow tires.
3. On glare ice, studded tires on all four wheels result in a reduction in stopping distance that is more than twice the reduction with studs on the rear tires only.
4. On glare ice, the improvements in stopping distance due to studs are greatest at ice temperatures near the freezing point.
5. On glare ice, the improvements in stopping distance due to studs, while decreasing with decreasing ice temperature, do not disappear at temperatures in the vicinity of -5 F, as suggested by earlier research. While the differences in stopping distance at 20 mph are very small, differences at higher speeds are still very significant at this temperature.
6. On dry asphalt surfaces, the type of tire and the presence or absence of studs make almost no difference in the stopping distance.
7. On wet asphalt surfaces, the type of tire and the presence or absence of studs make no significant difference in the stopping distance.
8. On both dry and wet concrete surfaces, studded tires on the rear wheels only result in a small but significant increase in stopping distance compared to that required with standard highway tires.
9. On both dry and wet concrete surfaces, studded tires on all four wheels result in an increase in stopping distance compared to that required with standard highway tires, but this increase is less than twice that resulting from studded tires on the rear wheels only.

REFERENCES

1. Smith, P., and Shonfeld, R. Pavement Wear Due to Studded Tires and the Economic Consequences in Ontario. Highway Research Record 331, 1971, pp. 54-79.
2. Salois, J. L. A., and Cousins, A. R. Evaluation—Studded Tires. Central Experimental and Proving Establishment, Royal Canadian Air Force, Rept. 1782, 1965.
3. Rosenthal, P., Haselton, F. R., Bird, K. D., and Joseph, P. J. Evaluation of Studded Tires: Performance Data and Pavement Wear Measurement. NCHRP Rept. 61, 1969.
4. Passenger Car and Friction Trailer Tests. Committee on Winter Driving Hazards, National Safety Council, final repts., 1965, 1966.
5. Winter Test Report. Committee on Winter Driving Hazards, National Safety Council, final repts., 1967, 1968.