Enhancements to ConnDOT's Pavement Friction Testing Program

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16. Abstract

This report documents the work performed and results obtained for research conducted to enhance ConnDOT's pavement friction testing program. The program was enhanced with the purchase in 2005 of a new Dynatest 1295 Pavement Friction Tester. Upgrades from the previous tester included the addition of a high-speed laser to measure pavement macrotexture, and a global positioning system to track coordinates. A Circular Texture Meter was purchased in 2006 to compare to the high-speed laser. In 2007, the new friction tester was upgraded to a dual-sided system, enabling testing in either wheelpath. Speed gradients for various ConnDOT pavement surfaces were determined, the macrotexture of asphalt pavement designs used in Connecticut were characterized, the use of the International Friction Index was evaluated, and the effects of roadway geometry on friction measurements were studied. Deliverables include new and upgraded equipment, recommendations, tentative guidelines for evaluating friction at high wet accident sites in Connecticut, a procedure for handling friction test requests, and a draft policy statement.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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INTRODUCTION

This project was proposed for inclusion in the Connecticut State Planning and Research (SP&R) Work Program in May 2004 in order to address the Connecticut Department of Transportation's (ConnDOT's) need to upgrade its friction testing equipment *(1)*. At that time, a fifteen-year-old 1989 KJ Law Model 1290 pavement friction tester, with a retrofitted trailer (2000) was being used to perform pavement friction tests. Historically, ConnDOT pavement friction testers were replaced on a ten-year schedule.

This is the third and final report published for this project. The first report (CT-2243-1-10-1) titled "Historical Overview of Pavement Friction Testing in Connecticut" provides a concise historical reference for current and future employees *(2)*. It fits into the succession planning that should take place within a state highway agency prior to retirements and changes in employee responsibilities.

The second report (CT-2243-2-10-3) titled "Characterizing the Macrotexture of Asphalt Pavement Designs in Connecticut" presents results of ConnDOT's efforts to establish targets for pavement texture depth on high-speed facilities by characterizing the macrotexture of a few different ConnDOT hot-mix asphalt (HMA) pavement mixes *(3)*.

Equipment Upgrades

The project started on September 1, 2004, and a new Dynatest 1295 Pavement Friction Tester (Figure 1) was purchased in 2005. It is capable of performing dry or self-wetted locked wheel and peak incipient testing between 20 and 70 mph, while computing the dynamic friction number *(4)*. It uses an on-board computer to calculate this number from one or two Model 1270 two-axis force transducer(s) mounted to the trailer's axle assembly.

Upgrades from the previous tester include the addition of a High-Speed Selcom Optocator/SLS5000 Laser Sensor (Figure 2) for measuring pavement texture at high speeds (high-speed laser), and a Trimble Model AgGPS 33300-00 global positioning system (GPS) for tracking coordinates (longitude and latitude) (Figure 3).

FIGURE 1 Dynatest 1295 Pavement Friction Tester.

FIGURE 2 Housing for High-Speed Selcom Optocator/SLS5000 Laser Sensor.

FIGURE 3 Trimble Model AgGPS 33300-00 Global Positioning System.

For comparison to the aforementioned laser profiler, a Nippo Sangyo Co., Ltd. Circular Texture Meter (CTMeter) (Figure 4) was purchased in 2006. Pavement macrotexture profiles were measured with the CTMeter in accordance with ASTM Standard E 2157. The purpose of comparison was to determine if the high-speed laser profiler macrotexture measurements correlated well with the CTMeter measurements obtained in accordance with the above ASTM test method, and whether or not the high-speed laser profiler could provide viable results.

FIGURE 4 Nippo Sangyo Co., Ltd. Circular Track Meter purchased in 2006.

In August 2007, the Dynatest 1295 Pavement Friction Tester was upgraded from a single-sided to a dual-sided system. This entails that two Model 1270 two-axis force transducers are now mounted to the axle assembly of the trailer: one on the left side (driver’s side) and one on the right side (passenger’s side). The single-sided system could only measure friction in the driver’s side wheel path. The dual-sided system is capable of measuring pavement friction in either wheel path. This provides the operator with several choices. Pavement friction tests can be alternated between the left and right wheels, or tests can be performed exclusively with either the left or right wheel; however, tests cannot be performed with the left and right wheels simultaneously. A ribbed tire can be mounted on one side, and a smooth tire on the other, which allows ribbed and smooth tire tests to be performed without having to change tires. Alternatively, the same tire (ribbed or smooth) can be mounted on both wheels, allowing either ribbed or smooth tire friction measurements in both wheel paths.

Additional components include a computer and electronics (Figure 5), a 300-gallon water tank, and an Ohio State University water nozzle (Figure 6).

FIGURE 5 Inside the cab of the Dynatest 1295 Pavement Friction Tester purchased in 2005.

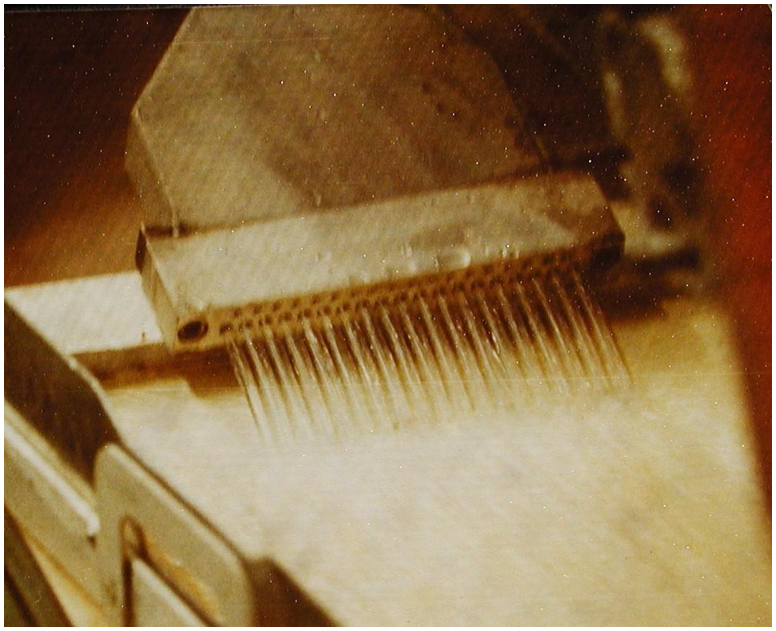

FIGURE 6 Ohio State Water Nozzle used to wet pavement in front of test tires.

Participation in Transportation Pooled Fund Study TPF-5(141)

In the fall of 2007, ConnDOT joined Transportation Pooled Fund Study TPF-5(141), "Pavement Surface Properties Consortium: A Research Program." The Virginia Department of Transportation is the lead agency and the contractor is Virginia Tech. The contract amount is over $720,000 and it has 100% SP&R approval *(5)*. This pooled-fund study complements ConnDOT's own SPR-2243 study because its objective is to enhance "the level of service provided by the roadway transportation system through optimized pavement surface texture characteristics." Study partners include the FHWA, Georgia, Mississippi, Pennsylvania, South Carolina and Connecticut. The pooling of technical expertise from these other state agencies and Virginia Tech has been extremely beneficial to Connecticut's own friction testing program thus far. Continued participation will help to address another need stated in the proposal *(1)*, "… to refine and implement the latest practices for the collection and analysis of skid resistance (pavement friction data)."

Study Objectives and Scope

The objectives of this study as stated in the proposal *(1)* were to (1) update friction number speed correction factors based upon pavement mix designs currently in use in Connecticut with an upgraded friction tester (hardware and software), (2) research relationships between texture and friction, (3) evaluate the potential use of the International Friction Index (IFI) in Connecticut, and, (4) implement the appropriate latest technology and procedures for pavement friction data request, collection and processing.

As discussed above, a CTMeter was purchased in 2006 in order to compare texture values measured with the CTMeter to the high-speed laser profiler. Accordingly, the scope of this report also includes a presentation of the laser profiler versus CTMeter macrotexture measurement comparisons performed at the Virginia Smart Road facility, as part of TPF-5(141). CTMeter measurements were taken with the ConnDOT instrument and also with Virginia Tech's CTMeter on twelve different pavement designs. This paper presents measurements taken with ConnDOT's CTMeter. Three CTMeter measurements were taken and averaged for each pavement design. These pavement designs encompassed a wide range of textures, from fine to coarse. The goal of these comparisons was to provide some validation of the laser profiler macrotexture measurements as they compared to the CTMeter measurements obtained in accordance with ASTM E 2157.

In observance of a Federal Highway Administration (FHWA) Technical Advisory entitled *Surface Texture for Asphalt and Concrete Pavements (6)*, another objective evolved to begin to establish targets for pavement texture depth on high-speed facilities by characterizing the macrotexture of different ConnDOT hot-mix asphalt (HMA) pavement mixes. The nominal maximum aggregate size for these designs ranged from 4.75-mm to 12.5-mm. Part of this effort to characterize pavement macrotexture is to begin taking the first steps in establishing texture depth targets for new and in-service pavement surfaces in Connecticut. The advisory states "providing adequate texture depth has been shown to improve pavement friction test results at high speeds and reduce crash rates on high speed facilities." The advisory suggests these targets be established by owner-agencies based upon project specific factors, such as roadway geometry *(6)*. This effort was largely presented in Report No. CT-2243-2-10-3 *(3)*, but is summarized in the conclusions of this final report as well.

LITERATURE REVIEW

A historical overview of pavement friction testing in Connecticut is presented in Report CT-2243-1-10-1 *(2)*. This effort will not be duplicated in this final report, but a literature review is presented below.

The *Guide for Pavement Friction (7)* defines pavement friction as "…the force that resists the relative motion between a vehicle tire and a pavement surface." They identified two modes of operation for the longitudinal dynamic friction process: free-rolling and constant-braked. In the free-rolling mode, something called the slip speed is zero. The slip speed is defined as "the relative speed between the tire circumference and the pavement". In the constant-braked mode, the slip speed approaches the vehicle speed.

Slip is more commonly referred to in terms of its percent ratio to the vehicle velocity. "A locked-wheel state is often referred to as a 100 percent slip ratio and the free-rolling state is a zero percent slip ratio." The peak friction that is reached during braking typically occurs between 10 and 20 percent slip *(7)*. Most new cars today are equipped with anti-lock brakes, which pump the brakes repeatedly in order to operate at or near this peak value. Pavement friction testers experience the entire cycle during the locked-wheel test, from free rolling to 100 percent slip. The reported friction number is an average of readings measured during 100 percent slip. Modern testers, such as the Dynatest Model 1295, also calculate the peak friction that occurs prior to lockup.

Smooth- and Ribbed-Tires for Friction Testing

Either an AASHTO M 261, "Standard Tire for Pavement Frictional-Property Tests" or an AASHTO M 286, "Smooth-Tread Standard Tire for Special-Purpose Pavement Frictional-Property Tests" can be used for conducting the tests. While the AASHTO nomenclature for the smooth tire suggests a different status for the smooth tire by saying it's for "special-purpose" tests, the ASTM counterpart standards give both tires equal status *(8)*: ASTM E 524, "Standard Smooth Tire for Pavement Skid-Resistance Tests" and ASTM E 501, "Standard Rib Tire for Pavement Skid-Resistance Tests."

The ribbed tire has been the standard test tire used in Connecticut for friction testing since the inception of the friction testing program in Connecticut in 1970. Initially, it was used because it was considered the standard test tire by ASTM. Early on, ASTM chose the ribbed tire as the standard because it was believed that it was less sensitive to the water flow rate and therefore results would be more reproducible. The ribbed tire continued to be used as the standard tire in Connecticut even after the smooth tire was given equal status in 1990. This was largely due to inertia. ConnDOT engineers were comfortable with making decisions based upon ribbed tire friction test values, and historical results were readily available. The smooth tire was used on occasion upon request or for research purposes.

In the 1970s, Ganung and Kos *(9)* performed smooth-tire testing during a research study to identify and evaluate wet-weather high-hazard locations in Connecticut. The study was conducted because they had found during inventory testing between 1973 and 1974 that measured ribbed-tire friction values were frequently high in areas showing high percentages of wet-weather accidents *(9)*. They were surprised by these experiences, so they decided to perform smooth-tire friction tests "to determine if these apparently hydroplaning-prone areas could be delineated by this means." Their rationale was that a smooth tire "will experience dynamic hydroplaning with a much smaller quantity of water than will the standard ASTM E501 ribbed test tire." They felt that the smooth tire would be a better "indicator of pavement conditions conducive to hydroplaning in very heavy rain."

They coupled these smooth-tire measurements with smooth-tire measurements obtained previously and found that "…low smooth-tire numbers are quite common throughout the State, with values ranging from the mid twenties to as low as three or four." Counterpart ribbed-tire values did not always correspond to these low smooth-tire values, as instances of ribbed-tire values in the fifties were not unusual. They also found a "good correspondence between low smooth-tire skid numbers and accident experience", and that ribbed tire values did not correspond well to accident experiences *(9)*. This is significant because the ribbed tire values did not always correspond with low smooth-tire values. If low smooth-tire values do in fact correspond to accident experiences as Ganung and Kos suggested and ribbed-tire values do not, then the smooth tire should be the standard test tire – not the ribbed tire.

In their conclusions, Ganung and Kos *(9)* stated "Inventory tests on the Merritt Parkway indicated that 95 percent of the wet weather accidents occurred where smooth tire skid numbers were 15 or lower, and only five percent took place with values above 15." They did not find any accidents that appeared to be related to dynamic hydroplaning for areas that had smooth-tire friction values greater than about 25. Perhaps consideration should be given to setting an intervention level for smooth-tire friction values of less than 15.

Ganung and Kos *(9)* attempted to relate smooth-tire friction values at a fixed speed with ribbed-tire speed gradients, but were unsuccessful. They were also unable to develop a rigorous association between friction values and texture depths.

Ultimately, because the majority of the smooth-tire friction values measured during their study were below 30, Ganung and Kos *(9)* recommended that the then existing friction testing inventory system be expanded to include smooth-tire testing in order to determine descriptive statistics.

Other Research, Smooth- and Ribbed-Tires for Friction Testing

In 1992, Transportation Research Record (TRB) 1348 was published. This publication included work, sponsored by the Pennsylvania Department of Transportation, by Henry and Wambold *(10)* who wrote a paper titled "Use of Smooth-Treaded Test Tire in Evaluating Skid Resistance." They recommended that both tires be used for project-level surveys. In circumstances for which only one tire can be used, they recommended the smooth tire because "it is sensitive to macro- and microtexture whereas the ribbed tire responds primarily to the microtexture."

The Illinois Department of Transportation performed smooth- and ribbed-tire friction testing during the 1980's. An overview of their work is also presented in TRB Record 1348 by Hall et al *(11)*. They presented tentative guidelines for evaluating friction at high wet-pavement accident sites in two tables. The first table was for accident sites before 1987 with ribbed-tire values only, and the second table was for accident sites after 1987 incorporating both ribbed- and smooth-tire friction values. For instances where ribbed-tire values were less than or equal to 30 or smooth-tire values were less than 15, their tentative guideline was "Friction is probably a factor contributing to wet-pavement accidents." When ribbed-tire values were greater than 30 and smooth-tire values were between 15 and 25, or ribbed-tire values were between 31 and 35 and smooth-tire values were greater than 25, the guideline was "Uncertainty exists as to whether pavement friction is the primary factor." Finally, for instances where ribbed-tire values were greater than or equal to 36 and smooth-tire values were greater than 25, their guideline was "Probably some condition other than pavement friction may be the primary factor causing wet pavement accidents."

The Indiana Department of Transportation recently upgraded their friction testing program and investigated using the smooth tire. In a 2003 published report titled "Upgrading the INDOT Pavement Friction Testing Program," they recommended the standard smooth tire for network level pavement friction testing. They also recommended a minimum smooth-tire friction value of 20 at 40 mph for network pavement inventory friction testing. They felt that this requirement would be economically reasonable *(12)*.

Personnel at the National Aeronautics and Space Administration (NASA) Langley Research Center's Landing and Impacts Dynamic Branch provided a summary of their ribbed- and smooth-tire friction values in TRB Record 1348. Yager *(13)* reported that the smooth tire was "more sensitive to variations in speed, surface texture, and contaminants than the ASTM E501 rib-tread tire." He also pointed out that the smooth tire is not influenced by tire wear.

THE EFFECT OF ROADWAY GEOMETRY ON FRICTION MEASUREMENTS

Tangent versus Nontangent Sections

On October 17, 2007, the pavement friction tester was brought to the Consumer Union Test Track in Colchester, Connecticut. The track was constructed with a ConnDOT 9.5-mm hot-mix asphalt mix. In order to compare friction tests performed on nontangent versus tangent sections, Research personnel brought a transit and laid out horizontal curves of 24 (radius=239 ft) and 28 degrees (radius=205 ft). A 28 degree of curvature was the sharpest curve at which the tests could be safely performed at or slightly above 30 mph. Next, pavement friction tests were performed along the nontangent sections and compared to tests performed on the same pavement along straight tangents. The left test wheel (drivers-side) was used for all of the tests. The tests were performed in such a manner that the test wheel always traveled along the above radii.

It should be noted that the nontangent sections surveyed for this study were along relatively flat pavement. Actual highway horizontal curves of 24 and 28 degrees would typically be superelevated. Superelevated curves provide the skid trailer with greater traction for banking.

Tables 1-6 below present friction test values of the same pavement measured along a right-hand 28 degree curve (Table 1), right-hand 24 degree curve (Table 2), and along straight tangents. The straight tangents were measured through three different gates in order to capture as much of the same pavement as that tested along the curves. Results for each gate are presented in Tables 3-5.

The average FN_{40R} value for the right-hand 28 degree curve was 57.7, and the standard deviation was 0.7 (Table 1). When the degree of curvature was reduced to 24 degrees, the average right-hand curve value was 56.3 and the standard deviation was 1.6 (Table 2). The overall average value for the three straight tangent gates was 55.0, and the overall standard deviation was 1.4 (Tables 3 through 5). FN_{40R} tended to increase slightly with the degree of curvature.

TABLE 1 Friction Test Values Measured on 28° Right Hand Horizontal Curve

Test Number	FN_{act}	Average Speed	FN_{40R}
1	62.0	32.8	58.4
2	60.1	34.3	57.3
3	58.7	36.3	56.9
4	59.6	37.1	58.2
5	59.6	36.9	58.1
Average	**60.0**	**35.5**	**57.7**
Minimum	**58.7**	**32.8**	**56.9**
Maximum	**62.0**	**37.1**	**58.4**
Standard Deviation	**1.2**	**1.9**	**0.7**

TABLE 2 Friction Test Values Measured on 24° Right Hand Horizontal Curve

Test Number	FN_{act}	Average Speed	FN_{40R}
1	60.3	37.5	59.1
2	59.4	38.8	58.8
3	56.9	40.5	57.2
4	56.0	40.1	56.1
5	55.1	38.5	54.4
6	56.4	38.2	55.5
7	55.8	38.4	55.0
8	56.0	39.9	56.0
9	55.4	39.5	55.2
10	57.3	39.9	57.3
11	55.9	38.2	55.0
Average	**56.8**	**39.0**	**56.3**
Minimum	**55.1**	**37.5**	**54.4**
Maximum	**60.3**	**40.5**	**59.1**
Standard Deviation	**1.7**	**1.0**	**1.6**

TABLE 3 Friction Test Values Measured on Straight Tangent, Gate 1

Test Number	FN_{act}	Average Speed	FN_{40R}
1	54.8	40.5	55.1
2	54.6	40.4	54.8
3	53.7	39.5	53.5
4	54.0	40.7	54.4
5	56.6	41.2	57.2
Average	**54.7**	**40.5**	**55.0**
Minimum	**53.7**	**39.5**	**53.5**
Maximum	**56.6**	**41.2**	**57.2**
Standard Deviation	**1.1**	**0.6**	**1.4**

TABLE 4 Friction Test Values Measured on Straight Tangent, Gate 2

Test Number	FN_{act}	Average Speed	FN_{40R}
1	53.8	41.0	54.3
2	54.2	40.3	54.4
3	55.4	39.7	55.3
4	53.6	40.0	53.6
5	52.9	40.6	53.2
Average	**54.0**	**40.3**	**54.1**
Minimum	**52.9**	**39.7**	**53.2**
Maximum	**55.4**	**41.0**	**55.3**
Standard Deviation	**0.92**	**0.51**	**0.79**

TABLE 5 Friction Test Values Measured on Straight Tangent, Gate 3

Test Number	FN_{act}	Average Speed	FN_{40R}
1	57.8	39.8	57.7
2	57.1	39.7	57.0
3	55.8	39.4	55.5
4	55.7	40.7	56.1
5	53.6	40.5	53.9
Average	**56.0**	**40.0**	**56.0**
Minimum	**53.6**	**39.4**	**53.9**
Maximum	**57.8**	**40.7**	**57.7**
Standard Deviation	**1.6**	**0.6**	**1.5**

Instead of comparing the means (averages) of these datasets, which are really point representations, interval estimates of each were compared next. In the case presented in Figure 7, the degree of plausibility is specified by a 98% confidence interval. This provides some reliability to a range within which FN_{40R} lies.

Now, compare the 24 degree right-hand curve interval to the tangent intervals. It can be seen that the 24 degree right-hand interval shares a large part of all three of the tangent intervals. Thus, at a 98% confidence level, it appears that tests conducted along a right-hand 24 degree curve compare well to tests along straight tangents.

The 28 degree right-hand curve shares a large part of the Tangent-Gate 3 interval, part of the Tangent-Gate 1 interval, but does not share any of the Tangent-Gate 2 interval. Considering the above, tests conducted along a right-hand 28 degree curve compare fairly well to tests along straight tangents. Perhaps Tangent-Gate 3 was most representative of the pavement tested along the 28 degree right-hand curve.

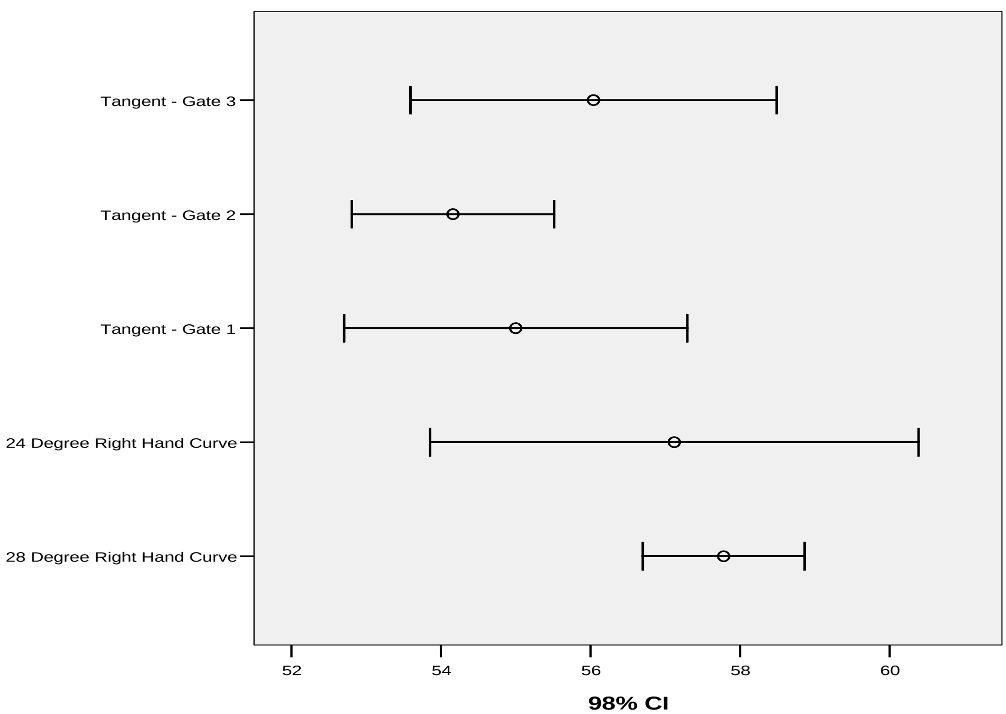

FIGURE 7 Simple Error Bar Defined at 98% Confidence Interval for Mean FN_{40R} Values.

Related Literature

Research at the Turner-Fairbank Research Center, published in 1983, was conducted to investigate methods for performing pavement friction tests on nontangent roadway sections *(14)*. They indicated that, in addition to the degree of curvature, the test speed is limited by the roadway design and geometrics, such as superelevation. They recommended limiting the centrifugal force in the trailer's horizontal plane to approximately 0.3 to 0.4 g's during locked wheel tests along horizontal curves. This limiting g-force was determined during dry conditions in order to keep the unlocked wheel on firm dry pavement, since the locked wheel has little capacity to provide restraining side force to keep the trailer from jack-knifing. They recommended that a Hi-g alarm be installed to activate system abort circuits in the electronics of the tester when the horizontal force on the trailer exceeds 0.3 g's. Finally, they found no significant differences in FN accuracy when comparing straight tangent versus nontangent sections of the same pavement as long as they conformed to the above criteria.

Positive (uphill) versus Negative (downhill) Grades

On September 17, 2007, friction tests were performed on Route 66 in Marlborough in order to compare tests performed going uphill versus downhill on the same pavement. It wasn't the same exact pavement because traffic would have to be stopped in order to perform tests traveling in the opposing direction of traffic, but they were performed at approximately the same mileposts on the same route. In order to set-up a truly valid experiment, a section of pavement would have to be put on a hypothetical turntable, such as those used in rail yards, in order to eliminate any directional polarization between tests uphill versus downhill. This way, the texture of the pavement would be approached from the same direction. Of course, it would not be practical or economical to carryout such an experiment.

Two hills were compared: one between approximately 18.6 and 18.8 miles (5 to 7% grade) and the other between 19.3 and 19.6 miles (6.5 to 7% grade). For the section between 18.6 and 18.8 miles, the average FN_{40R} value going uphill in the westbound direction was 51.8 (see Table 7), while the average FN_{40R} value going downhill in the eastbound direction was 46.1 (see Table 8). For the section between 19.3 and 19.6 miles, the average FN_{40R} value was 47.0 going uphill in the eastbound direction (Table 9), and the average FN_{40R} going downhill in the westbound direction was 46.6 (Table 10). Thus, one section compared well, while the other did not compare very well.

TABLE 6 Route 66 WB, Approximate Grade = 5% to 7.0% (Uphill)

Pass			Test	Milepost	Speed	FN_{act}	FN_{40R}
1	1		81	18.826	39.1	51.1	50.7
	2		82	18.776	39.0	54.6	54.1
	3		83	18.726	39.3	50.6	50.3
	4		84	18.676	39.3	51.0	50.7
	Total	Mean			**39.2**	**51.8**	**51.4**
		Minimum			39.0	50.6	50.3
		Maximum			39.3	54.6	54.1
		Std. Deviation			0.1	1.9	1.8
2	1		105	18.784	39.6	52.4	52.2
	2		106	18.734	40.5	52.9	53.2
	3		107	18.684	39.0	50.6	50.1
	4		108	18.634	40.5	52.6	52.9
	Total	Mean			**39.9**	**52.1**	**52.1**
		Minimum			39.0	50.6	50.1
		Maximum			40.5	52.9	53.2
		Std. Deviation			0.7	1.0	1.4
3	1		134	18.789	39.2	52.1	51.7
	2		135	18.739	40.2	53.1	53.2
	3		136	18.689	40.5	50.3	50.6
	4		137	18.639	40.2	52.0	52.1
	Total	Mean			**40.0**	**51.9**	**51.9**
		Minimum			39.2	50.3	50.6
		Maximum			40.5	53.1	53.2
		Std. Deviation			0.6	1.2	1.1

TABLE 7 Route 66 EB, Approximate Grade = -5% to -7.0% (Downhill)

Pass			Test	Milepost	Speed	FN_{act}	FN_{40R}
1	1		85	18.676	39.6	46.6	46.4
	2		86	18.726	40.5	43.8	44.1
	3		87	18.776	40.1	45.5	45.6
	4		88	18.826	40.0	46.4	46.4
	Total	Mean			**40.1**	**45.6**	**45.6**
		Minimum			39.6	43.8	44.1
		Maximum			40.5	46.6	46.4
		Std. Deviation			.4	1.3	1.1
2	1		113	18.693	40.4	48.0	48.2
	2		114	18.743	41.1	45.3	45.8
	3		115	18.793	40.7	45.0	45.4
	4		116	18.843	40.0	44.9	44.9
	Total	Mean			**40.6**	**45.8**	**46.1**
		Minimum			40.0	44.9	44.9
		Maximum			41.1	48.0	48.2
		Std. Deviation			.5	1.5	1.5
3	1		145	18.652	40.9	46.0	46.5
	2		146	18.702	40.5	48.3	48.6
	3		147	18.752	39.5	45.6	45.4
	4		148	18.802	39.8	45.9	45.8
	Total	Mean			**40.2**	**46.5**	**46.5**
		Minimum			39.5	45.6	45.4
		Maximum			40.9	48.3	48.6
		Std. Deviation			.6	1.2	1.4

TABLE 8 Route 66 EB, Approximate Grade = 6.5% to 7.0% (Uphill)

Pass			Test	Milepost	Speed	FN_{act}	FN_{40R}
1	1		90	19.280	39.3	48.8	48.5
	2		91	19.330	39.9	48.5	48.5
	3		92	19.380	40.6	46.9	47.2
	4		93	19.430	40.7	45.9	46.3
	5		94	19.480	40.1	47.2	47.3
	6		95	19.530	40.6	44.2	44.5
	7		96	19.580	37.8	44.7	43.6
	Total	Mean			**39.9**	**46.6**	**46.5**
		Minimum			37.8	44.2	43.6
		Maximum			40.7	48.8	48.5
		Std. Deviation			1.0	1.8	1.9
2	1		117	19.281	40.4	50.1	50.3
	2		118	19.331	39.7	50.6	50.5
	3		119	19.381	41.1	48.1	48.7
	4		120	19.431	40.2	46.5	46.6
	5		121	19.481	40.5	46.0	46.3
	6		122	19.531	40.5	44.3	44.6
	7		123	19.581	41.2	46.2	46.8
	Total	Mean			**40.5**	**47.4**	**47.7**
		Minimum			39.7	44.3	44.6
		Maximum			41.2	50.6	50.5
		Std. Deviation			.5	2.3	2.2
3	1		149	19.285	39.4	49.3	49.0
	2		150	19.335	41.0	48.7	49.2
	3		151	19.385	40.5	45.4	45.7
	4		152	19.435	39.8	46.2	46.1
	5		153	19.485	40.2	46.9	47.0
	6		154	19.535	40.6	44.8	45.1
	7		155	19.585	40.8	44.2	44.6
	Total	Mean			**40.3**	**46.5**	**46.7**
		Minimum			39.4	44.2	44.6
		Maximum			41.0	49.3	49.2
		Std. Deviation			.6	1.9	1.8

TABLE 9 Route 66 WB, Approximate Grade = -6.5% to -7.0% (Downhill)

Pass			Test	Milepost	Speed	FN_{act}	FN_{40R}
1	1		73	19.574	40.3	47.6	47.8
	2		74	19.524	42.1	44.9	46.0
	3		75	19.474	41.7	45.5	46.4
	4		76	19.424	40.9	45.0	45.5
	5		77	19.374	40.6	45.1	45.4
	6		78	19.324	40.2	48.6	48.7
	7		79	19.274	39.5	47.5	47.3
	Total	Mean			**40.8**	**46.3**	**46.7**
		Minimum			39.5	44.9	45.4
		Maximum			42.1	48.6	48.7
		Std. Deviation			0.9	1.5	1.2
2	1		97	19.560	40.8	44.6	45.0
	2		98	19.510	39.9	44.9	44.8
	3		99	19.460	39.6	47.0	46.8
	4		100	19.410	39.3	45.9	45.6
	5		101	19.360	40.7	46.9	47.3
	6		102	19.310	41.7	46.0	46.9
	7		103	19.260	41.1	47.5	48.1
	Total	Mean			**40.4**	**46.1**	**46.3**
		Minimum			39.3	44.6	44.8
		Maximum			41.7	47.5	48.1
		Std. Deviation			0.9	1.1	1.2
3	1		127	19.562	39.6	44.5	44.3
	2		128	19.512	39.1	47.1	46.7
	3		129	19.462	39.5	46.9	46.7
	4		130	19.412	40.5	46.0	46.3
	5		131	19.362	39.8	47.0	46.9
	6		132	19.312	39.9	47.2	47.2
	7		133	19.262	40.8	48.7	49.1
	Total	Mean			**39.9**	**46.8**	**46.7**
		Minimum			39.1	44.5	44.3
		Maximum			40.8	48.7	49.1
		Std. Deviation			0.6	1.3	1.4

98% Confidence intervals are plotted in Figure 8 below for each dataset. It can be seen with some degree of reliability, that the hill from 18.6 to 18.8 miles had different FN_{40R} values for uphill versus downhill datasets. On the other hand, the hill from 19.3 to 19.6 miles had similar FN_{40R} values.

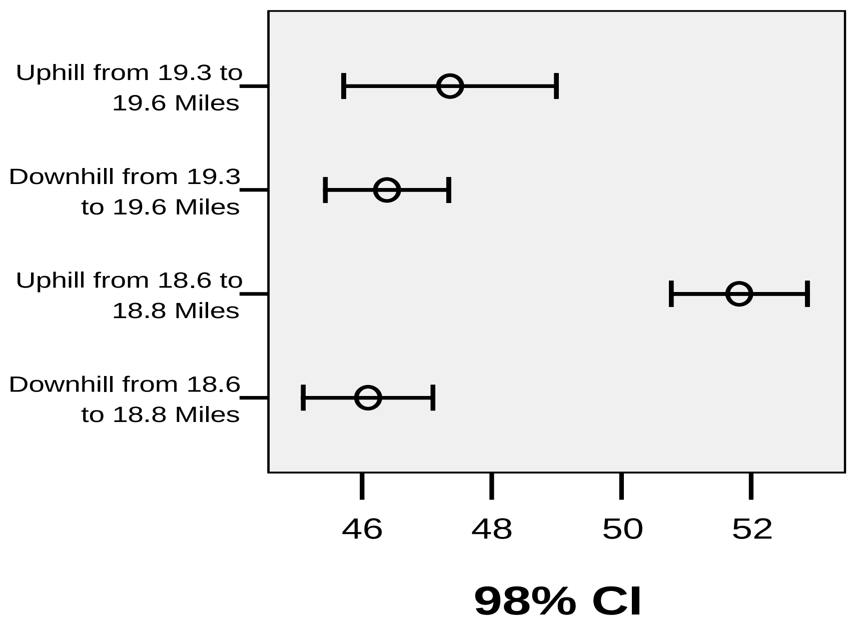

FIGURE 8 98% Confidence Intervals for FN_{40R} values.

SPEED GRADIENTS FOR PAVEMENT FRICTION TESTING

The speed gradient tests were performed at three speeds in increments of 10 mph as specified in AASHTO T 242 and ASTM E 274: 30 mph, 40 mph, and 50 mph. They were performed for four different ConnDOT hot-mix asphalt mixes (HMA): Class 1, Superpave 12.5 mm, Superpave 9.5 mm, and #4 (4.75-mm HMA). In addition, speed gradient tests were performed on portland cement concrete (PCC) diamond ground pavements.

For each site, tests were performed in such a manner as to allow speed gradients to be calculated at five or six different mileposts. This was accomplished performing interval testing at the same mileposts during three passes each at 30, 40, and 50 mph. This proved to be worthwhile because the speed-gradient slopes at the individual mileposts corresponded better than combining them and determining a speed-gradient slope for the entire site.

Class 1 HMA

Four different sites were evaluated for Class 1 HMA. Speed-gradient slopes were evaluated two ways as described above: at individual mileposts and combined for individual sites. Table 11 below presents speed-gradient slopes and R^2 values for each milepost tested. The average R^2 value for all of these Class 1 relationships at individual mileposts was quite high at 0.87. Contrast this to the average R^2 value presented in Table 12 for individual sites (all mileposts combined), which was 0.69.

The average speed-gradient slope for Class 1 HMA from Table 11 below was negative 0.40, and the standard deviation was +/-0.09. The average speed-gradient slope for each site was within one standard deviation of the overall average (-0.40 +/- 0.09), as they ranged from negative 0.33 to negative 0.47 (see Table 11). 63 percent of the speed gradients for individual mileposts were within one standard deviation, and all of the individual milepost values were within two standard deviations (between -0.22 and -0.58). Figures 9 through 18 provide scatter plots and linear trend lines for each site, for both individual mileposts and for entire sites (mileposts combined).

TABLE 10 Class 1 HMA Speed Gradient Slopes and R^2 Values by Milepost

Route	Dir.	Year Paved	Milepost	Speed Gradient Slope	R^2
3	SB	2001	4.83	-0.27	0.70
3	SB	2001	4.89	-0.24	0.68
3	SB	2001	4.95	-0.45	0.91
3	SB	2001	5.01	-0.32	0.56
3	SB	2001	5.07	-0.36	0.72
3	NB	2001	4.78	-0.52	0.93
3	NB	2001	4.84	-0.32	0.69
3	NB	2001	4.9	-0.35	0.90
3	NB	2001	4.96	-0.30	0.81
3	NB	2001	5.02	-0.38	0.96
3	NB	2001	5.08	-0.31	0.60
16	EB	1997	0.62	-0.37	0.91
16	EB	1997	0.7	-0.41	0.92
16	EB	1997	0.78	-0.56	0.99
16	EB	1997	0.86	-0.53	0.99
16	EB	1997	0.94	-0.44	0.98
16	EB	1997	1.02	-0.51	0.99
15	SB	1996	65.39	-0.32	0.94
15	SB	1996	65.31	-0.54	0.97
15	SB	1996	65.23	-0.50	0.99
15	SB	1996	65.15	-0.49	0.98
15	SB	1996	65.07	-0.51	0.98
173	NB	2002	0.68	-0.38	0.96
173	NB	2002	0.75	-0.40	0.97
173	NB	2002	0.82	-0.38	0.97
173	NB	2002	0.89	-0.45	0.64
173	NB	2002	0.96	-0.30	0.79
Average				**-0.40**	**0.87**

TABLE 11 Class 1 HMA Speed Gradient Slopes and R^2 Values by Site

Route	Dir.	Year Paved	Speed Gradient Slope, Average of Mileposts for Site	Speed Gradient Slope, Combined Data for Site	R^2, Average of Mileposts for Site	R^2, Combined Data for Site
3	SB	2001	-0.36	-0.34	0.75	0.66
3	NB	2001	-0.33	-0.36	0.79	0.75
16	EB	1997	-0.47	-0.48	0.96	0.69
15	SB	1996	-0.47	-0.48	0.97	0.87
173	NB	2002	-0.38	-0.39	0.87	0.48
Average			**-0.40**	**-0.41**	**0.87**	**0.69**

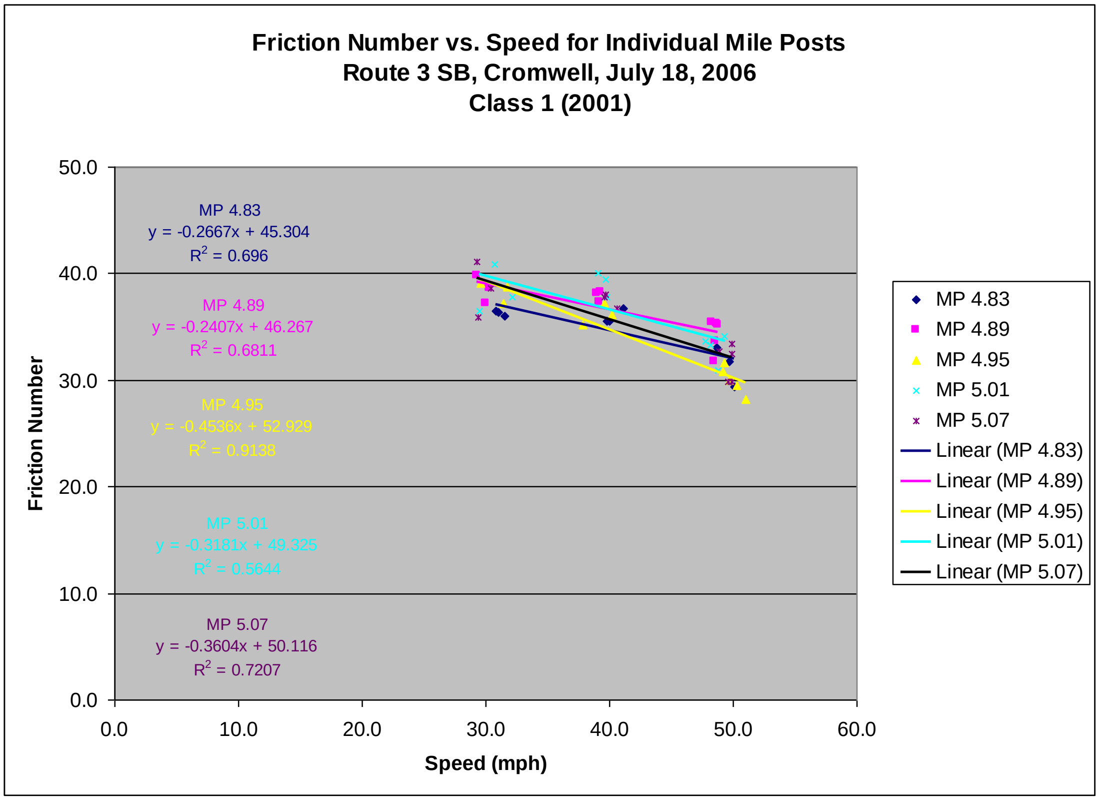

FIGURE 9 Speed gradients at individual mileposts for Route 3 SB Class 1 pavement in Cromwell.

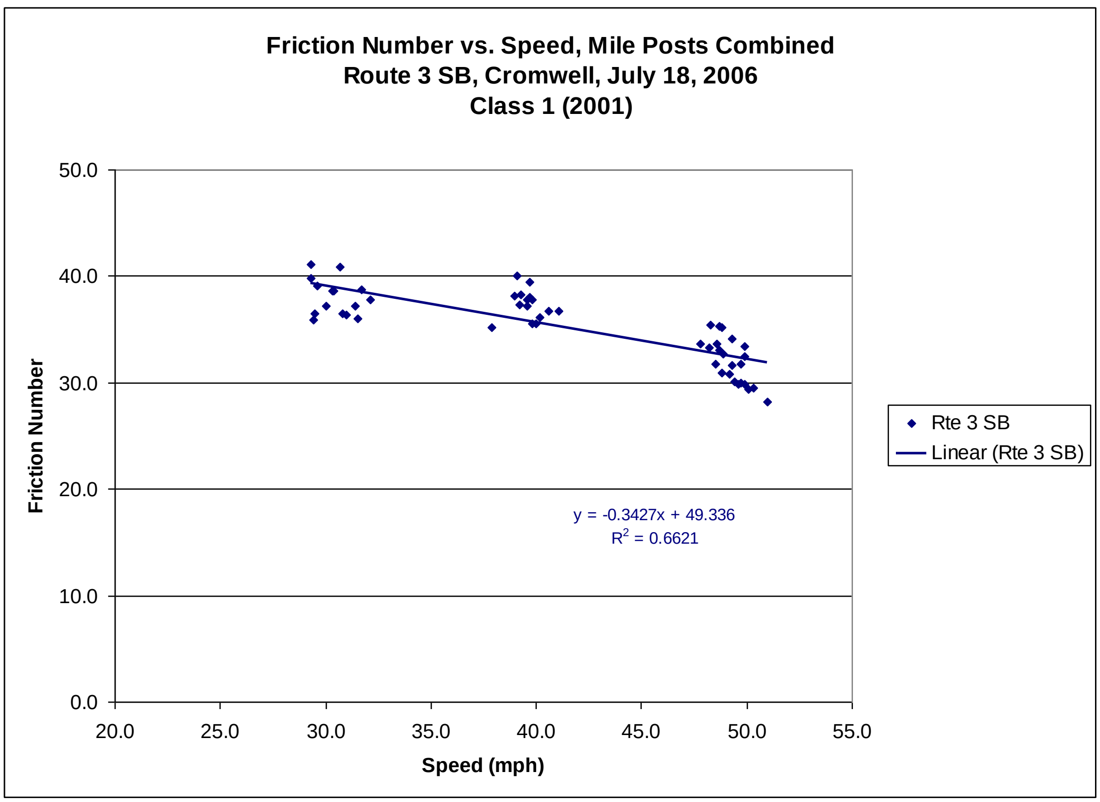

FIGURE 10 Speed gradients combined for Route 3 SB Class 1 pavement in Cromwell.

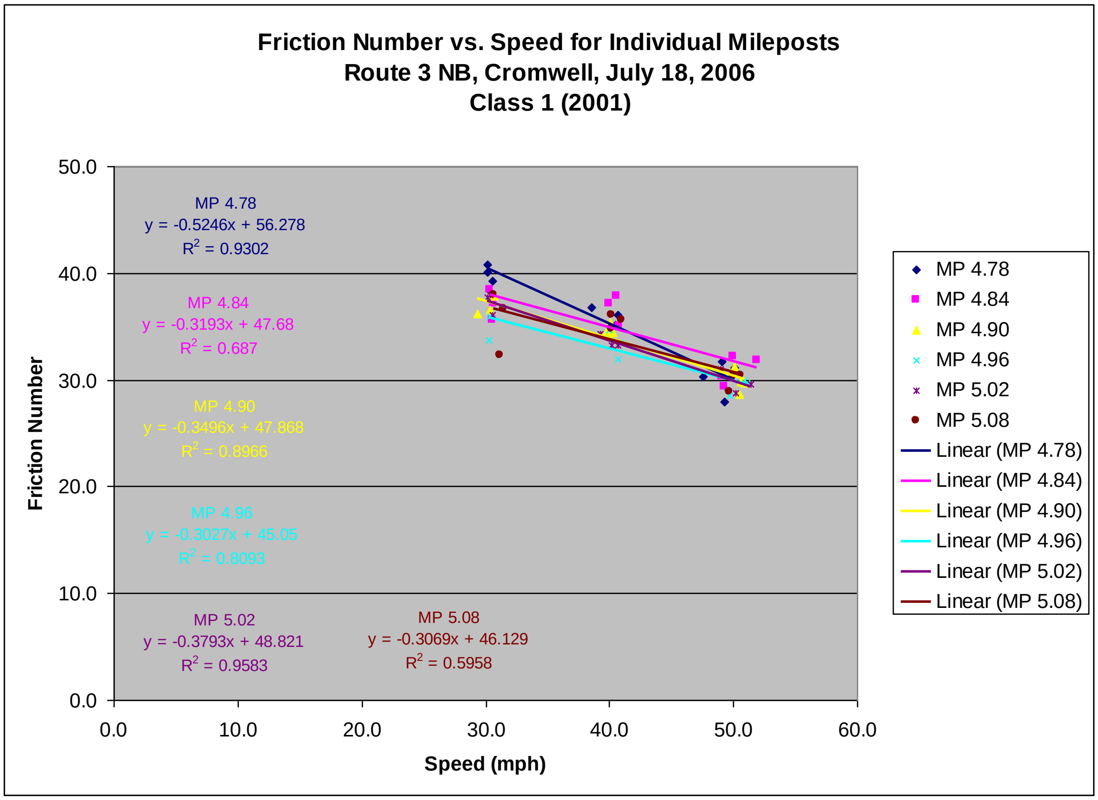

FIGURE 11 Speed gradients at individual mileposts for Route 3 NB Class 1 pavement in Cromwell.

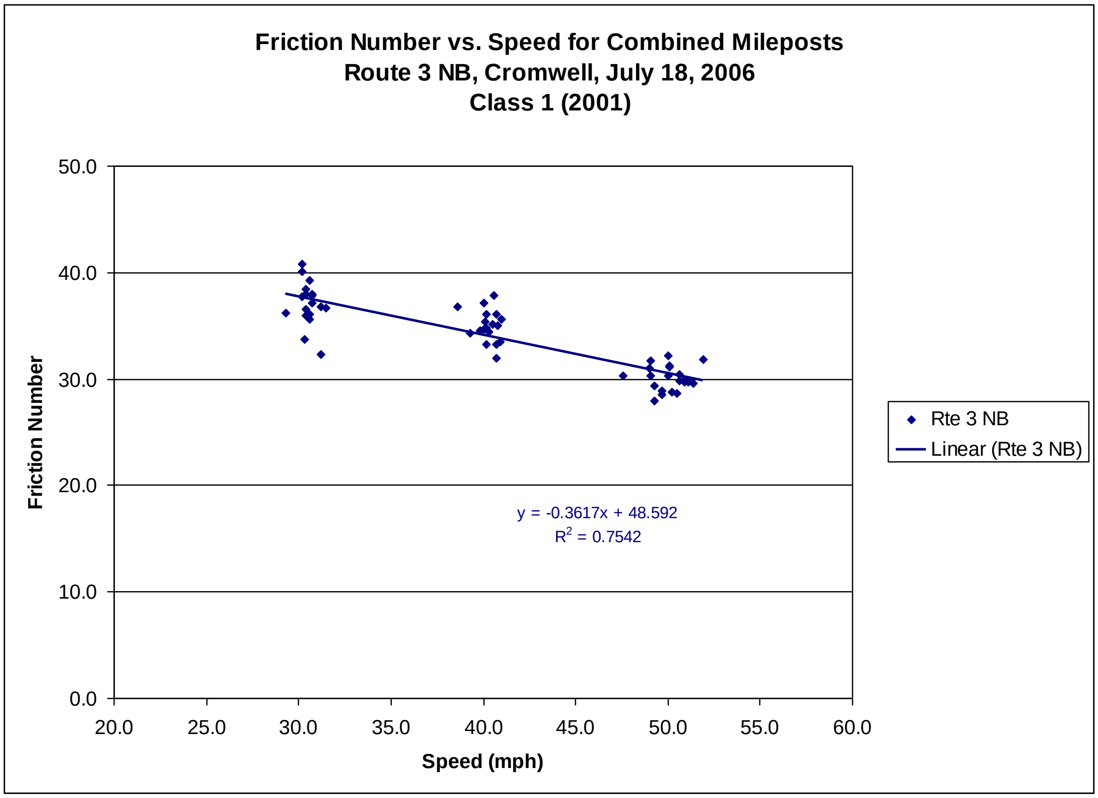

FIGURE 12 Speed gradients combined for Route 3 NB Class 1 pavement in Cromwell.

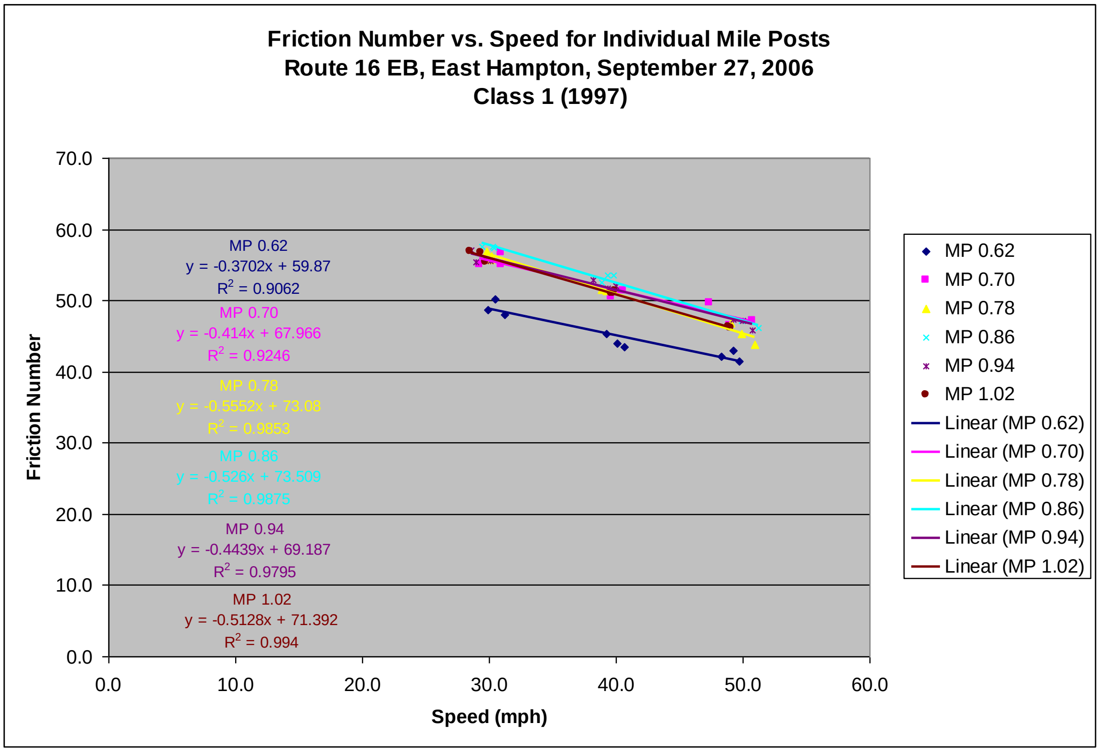

FIGURE 13 Speed gradients at individual mileposts for Route 16 EB Class 1 pavement in East Hampton.

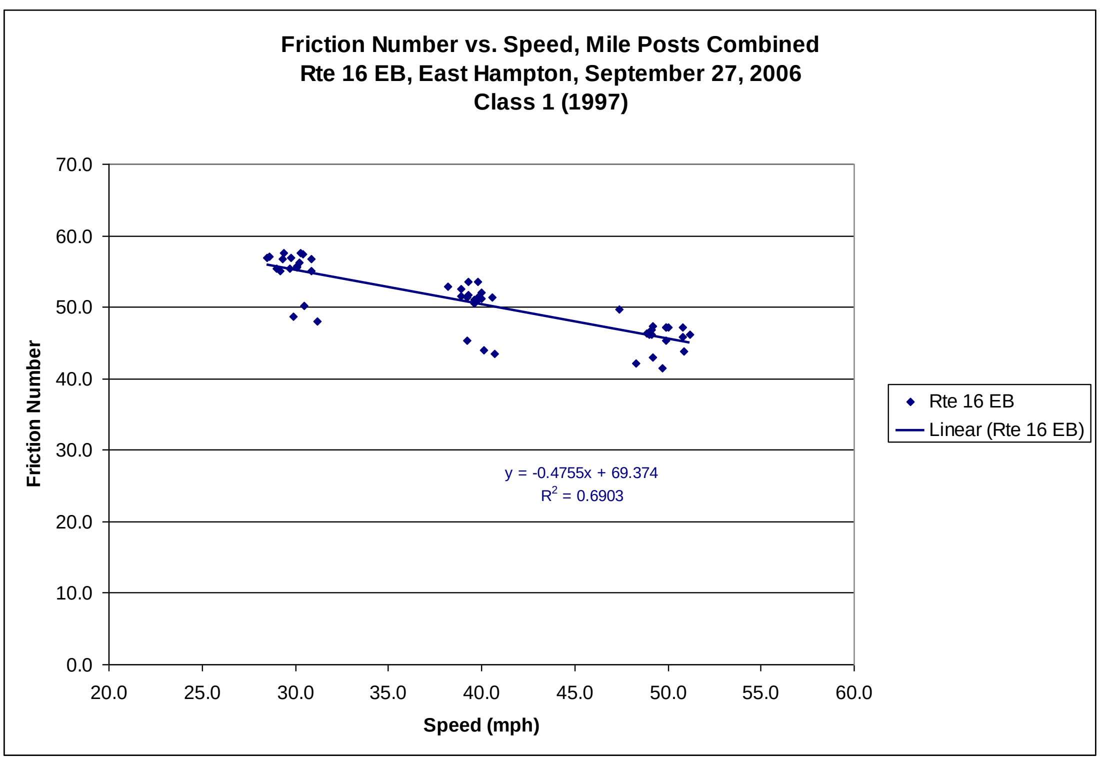

FIGURE 14 Speed gradients combined for Route 16 EB Class 1 pavement in East Hampton.

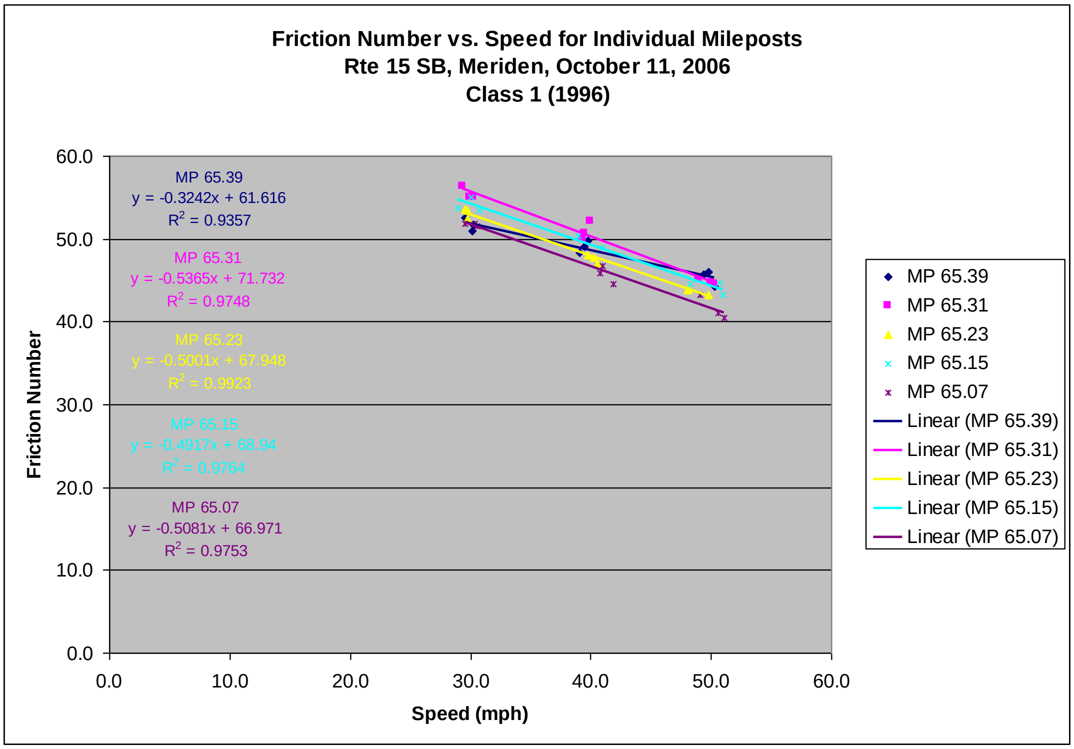

FIGURE 15 Speed gradients at individual mileposts for Route 15 SB Class 1 pavement in Meriden.

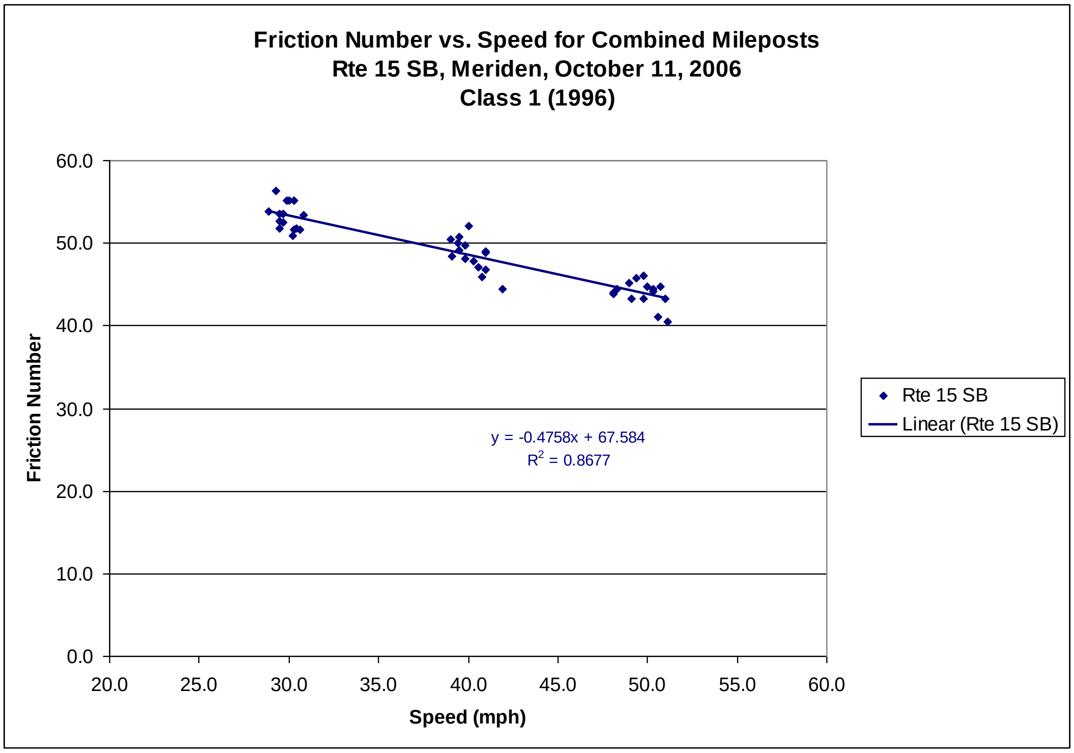

FIGURE 16 Speed gradients combined for Route 15 SB Class 1 pavement in Meriden.

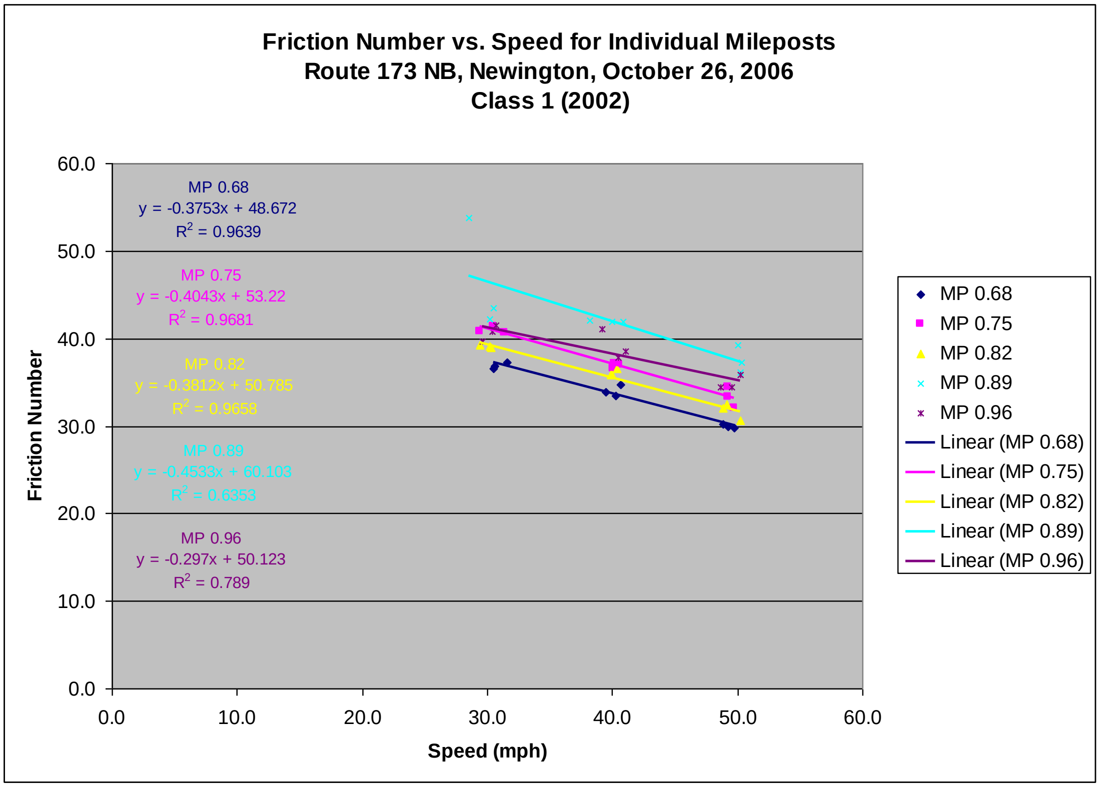

FIGURE 17 Speed gradients at individual mileposts for Route 173 NB Class pavement in Newington.

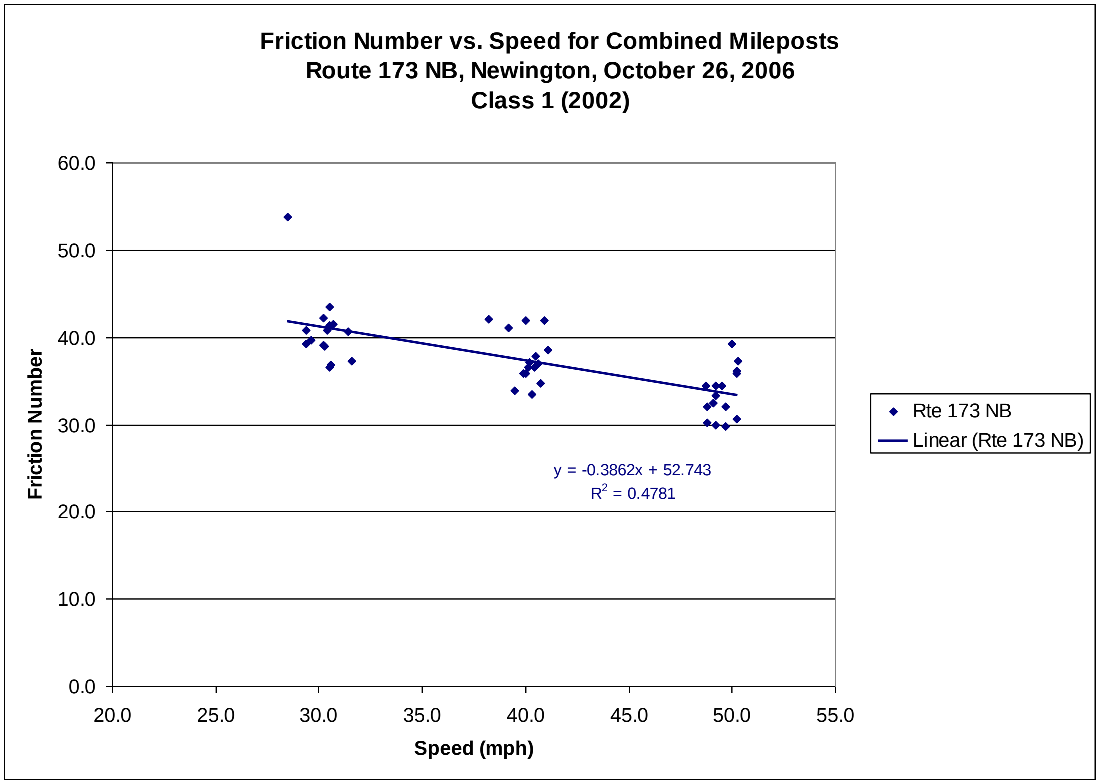

FIGURE 18 Speed gradients combined for Route 173 NB Class 1 pavement in Newington.

Figure 19 below presents a simple error bar chart, where the bars represent 98% confidence intervals (CI) for each location. That is to say, there is 98 percent likelihood that the range of values represented by the bars includes the population mean for each location. The red vertical line represents the speed gradient currently used by ConnDOT (-0.50) for calculating FN_{40R}. The green vertical line is located at the average speed gradient for the individual sites (negative 0.40). It can be seen that the red vertical line falls within the 98% CI for only two of the five locations. Therefore, for the Class 1 HMA, negative 0.50 wouldn't be the most representative speed gradient for calculating FN_{40R}.

What would the consequences be of using -0.50 when the actual gradient is -0.40 for example? Let's calculate FN_{40R} for a FN value of 40 measured at 30 mph. Using -0.50, FN_{40R} would be 35.0. Using a more representative speed gradient of -0.40 in this hypothetical scenario, FN_{40R} would be 36.0. A more conservative FN_{40R} value was calculated in this instance. Now, let's calculate FN_{40R} for a FN value of 40 measured at 50 mph. Using -0.50 in this case, FN_{40R} would be 45. Next, using -0.40, FN_{40R} would be 44. A non-conservative FN40R value was calculated in this case.

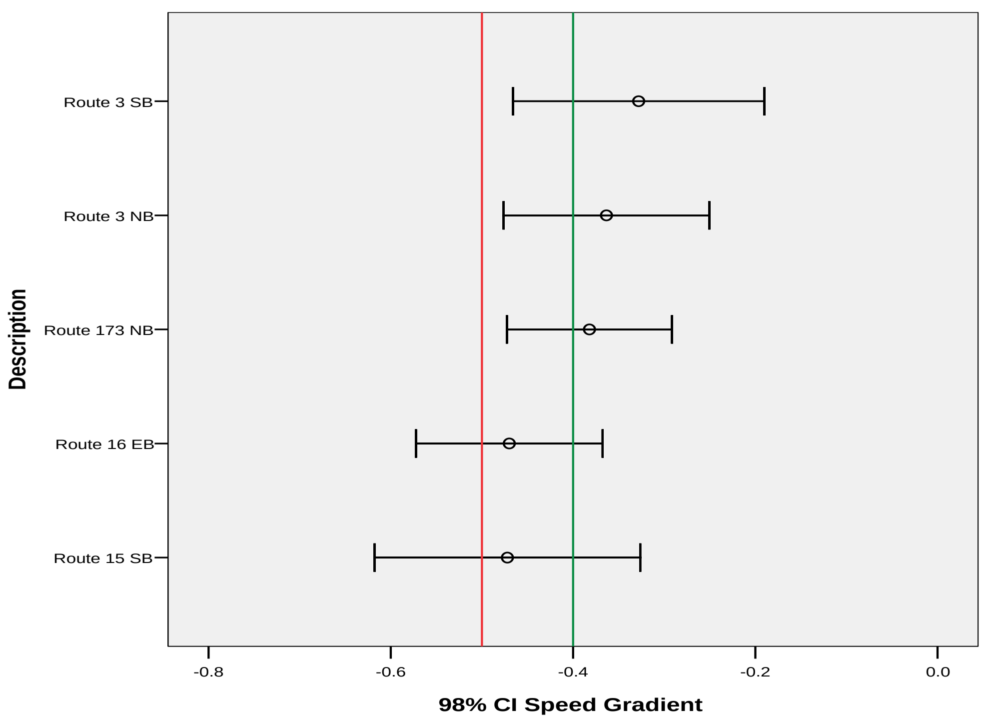

FIGURE 19 98% Confidence intervals for speed gradients for Class 1 pavements.

12.5-mm Superpave HMA

Speed-gradient slopes were determined for four different sites for the Superpave 12.5-mm HMA. These included Route 411 in Rocky Hill EB and WB, Route 15 NB in Berlin, Route 94 in Hebron, and Interstate 691 in Meriden. Trend line data for each milepost are presented in Table 13. Figures 20 through 29 provide scatter plots and linear trend lines for each site, for both individual mileposts and for entire sites.

The average speed-gradient slope for individual mileposts was -0.50, and the standard deviation was +/- 0.10. Therefore, the actual average gradient (-0.50) was equal to the assumed value (-0.50) used to calculate FN_{40R}. The values ranged between -0.35 and -0.67. 60 percent of the values were within one standard deviation of the mean (-0.40 to -0.60), and all of the values were within two standard deviations of the mean (-0.30 to -0.70). The average R^2 value was 0.93, so there was a strong linear tendency between friction numbers and speed for the individual mileposts.

TABLE 12 Speed Gradients and R^2 values by milepost on 12.5-mm Superpave pavements.

Route	Direction	Year	Milepost	Speed Gradient Slope	R^2
411	EB	2005	1.50	-0.45	0.92
411	EB	2005	1.60	-0.48	0.76
411	EB	2005	1.70	-0.59	0.89
411	EB	2005	1.80	-0.62	0.92
411	EB	2005	1.90	-0.41	0.71
411	WB	2005	1.35	-0.48	0.97
411	WB	2005	1.45	-0.62	0.88
411	WB	2005	1.55	-0.53	0.95
411	WB	2005	1.65	-0.53	0.99
411	WB	2005	1.75	-0.45	0.78
15	NB	2004	72.22	-0.35	0.92
15	NB	2004	72.28	-0.35	0.95
15	NB	2004	72.34	-0.37	0.94
15	NB	2004	72.40	-0.43	0.95
15	NB	2004	72.46	-0.35	0.95
94	EB	2005	8.67	-0.65	0.98
94	EB	2005	8.73	-0.67	0.99
94	EB	2005	8.79	-0.67	0.97
94	EB	2005	8.85	-0.62	0.96
94	EB	2005	8.91	-0.55	0.92
I-691	EB	2003	4.52	-0.53	0.97
I-691	EB	2003	4.44	-0.56	0.98
I-691	EB	2003	4.36	-0.43	0.95
I-691	EB	2003	4.28	-0.43	0.95
I-691	EB	2003	4.20	-0.46	0.98
Average				**-0.50**	**0.93**

TABLE 13 Speed Gradients and R^2 values by site on 12.5-mm Superpave pavements.

Route	Dir.	Year Paved	Speed Gradient Slope, Average of Mileposts for Site	Speed Gradient Slope, Combined Data for Site	R^2, Average of Mileposts for Site	R^2, Combined Data for Site
411	EB	2005	-0.51	-0.51	0.84	0.61
411	WB	2005	-0.52	-0.52	0.91	0.84
15	NB	2004	-0.37	-0.37	0.94	0.86
94	EB	2005	-0.63	-0.63	0.96	0.93
I-691	EB	2003	-0.48	-0.49	0.97	0.88
Average			**-0.50**	**-0.50**	**0.92**	**0.82**

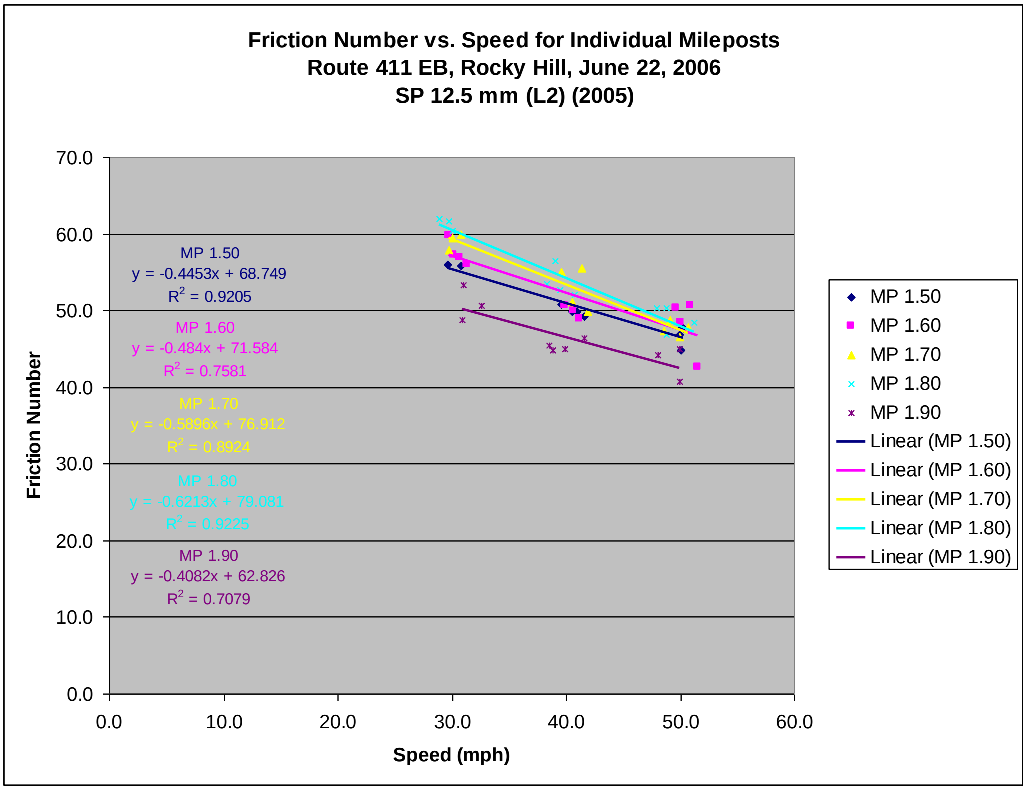

FIGURE 20 Speed gradients at individual mileposts for Route 411 EB SP 12.5-mm pavement in Rocky Hill.

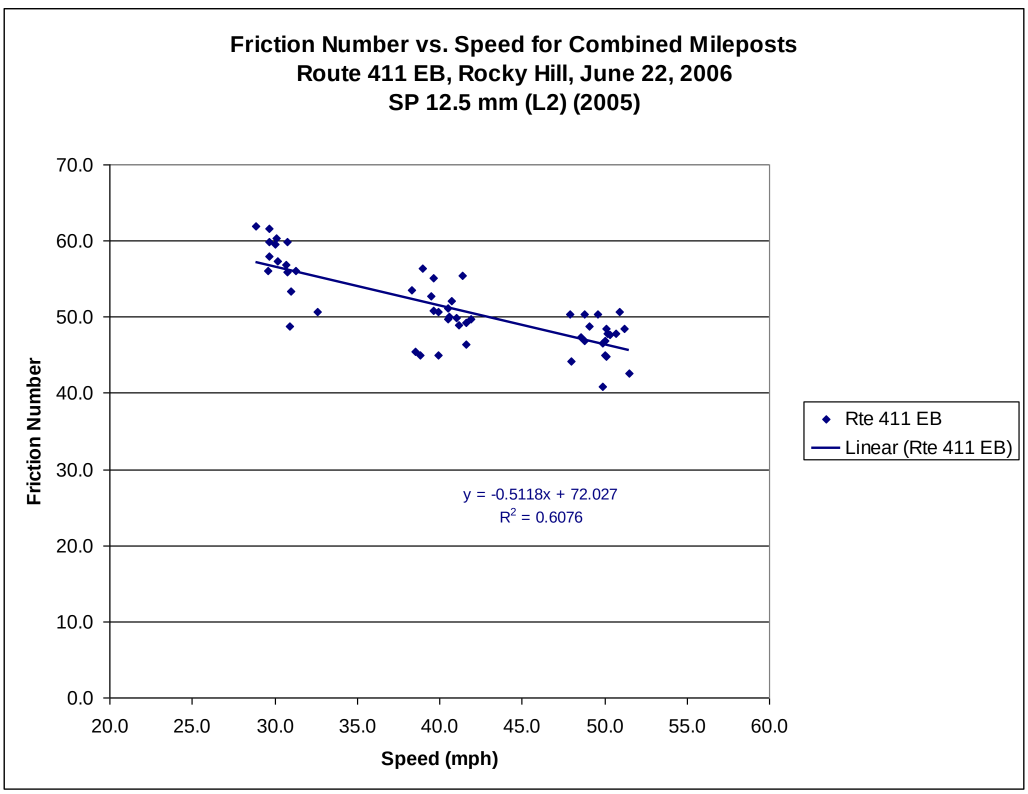

FIGURE 21 Speed gradients combined for Route 411 EB SP 12.5-mm pavement in Newington.

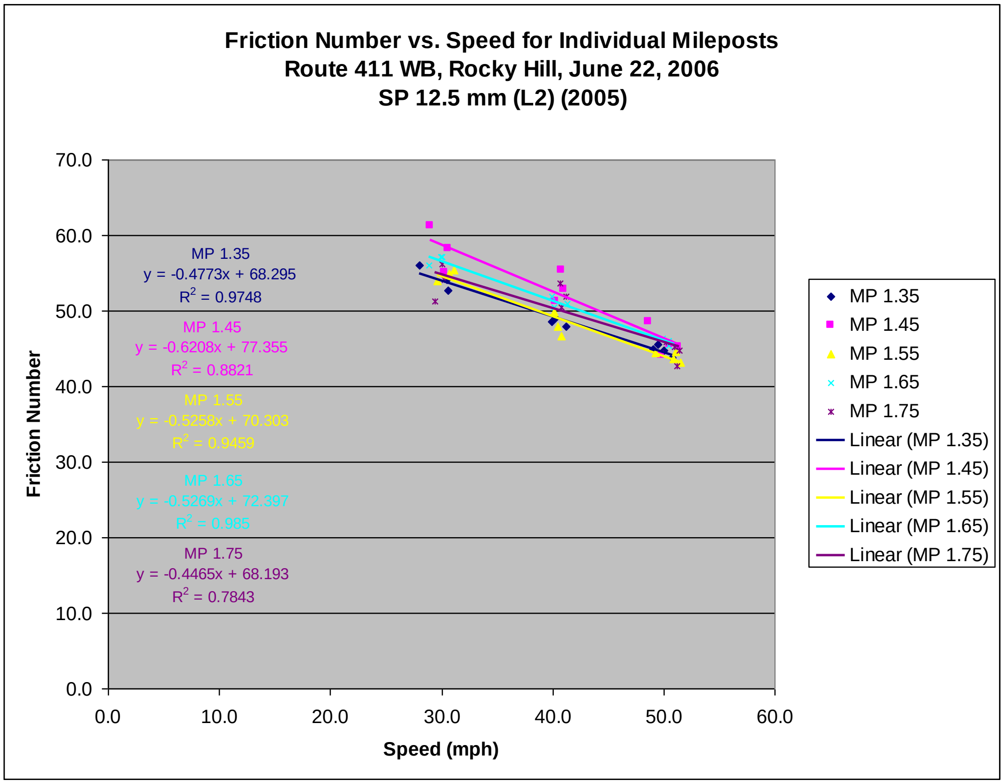

FIGURE 22 Speed gradients at individual mileposts for Route 411 WB SP 12.5-mm pavement in Rocky Hill.

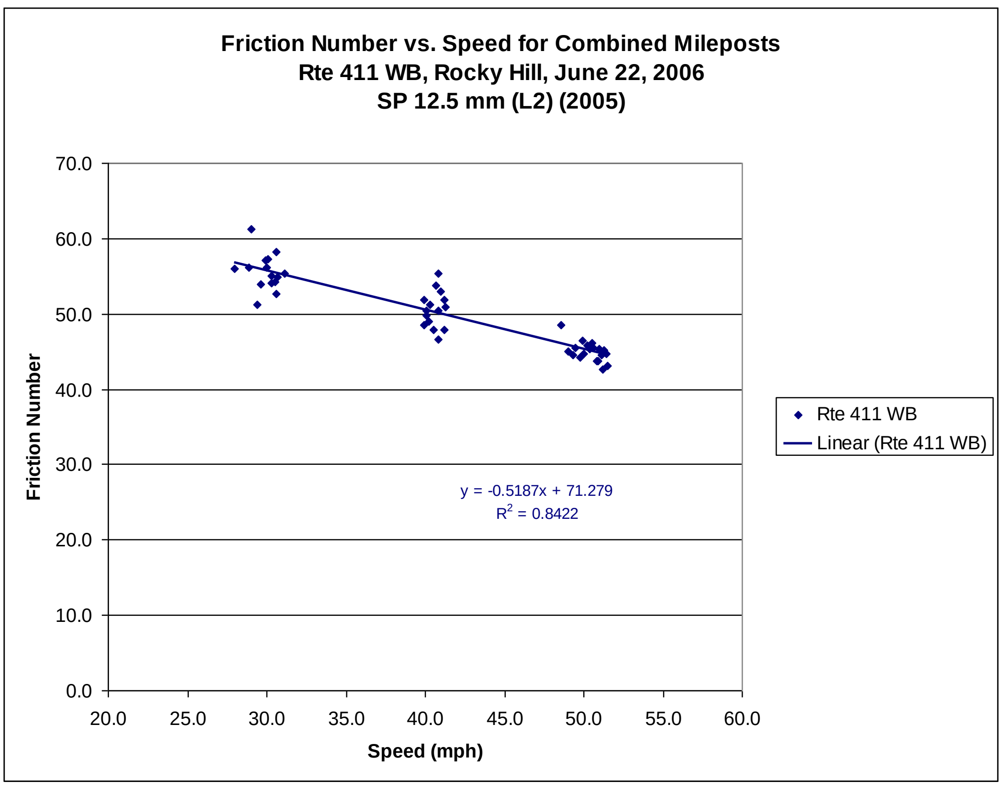

FIGURE 23 Speed gradients combined for Route 411 WB SP 12.5-mm pavement in Rocky Hill.

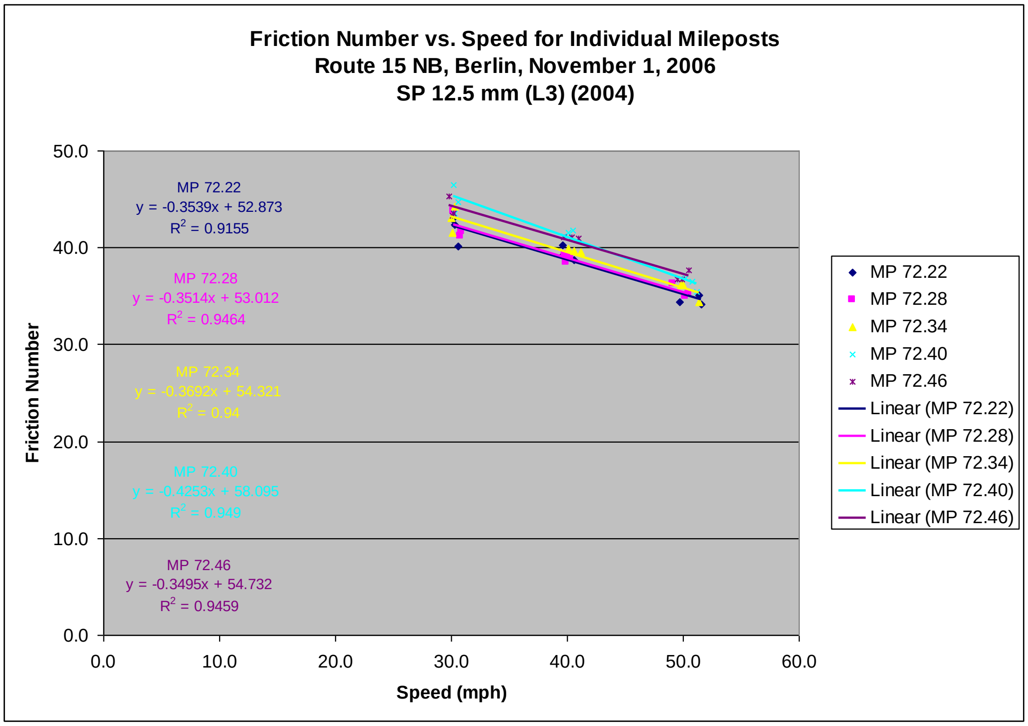

FIGURE 24 Speed gradients at individual mileposts for Route 15 NB SP 12.5-mm pavement in Berlin.

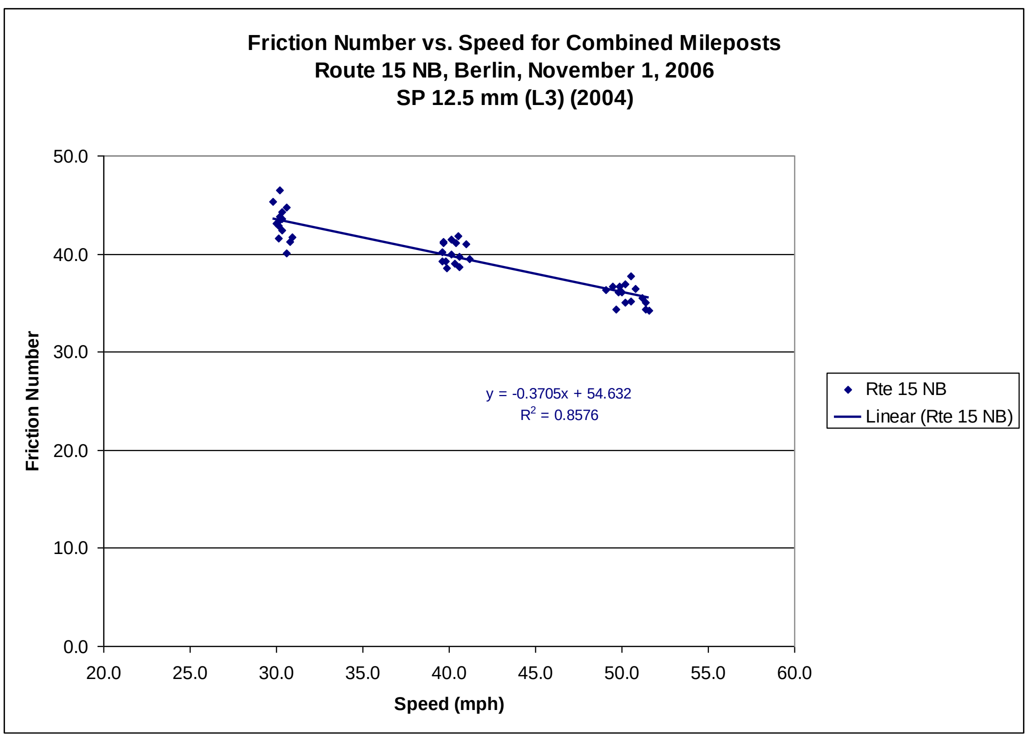

FIGURE 25 Speed gradients combined for Route 15 NB SP 12.5-mm pavement in Berlin.

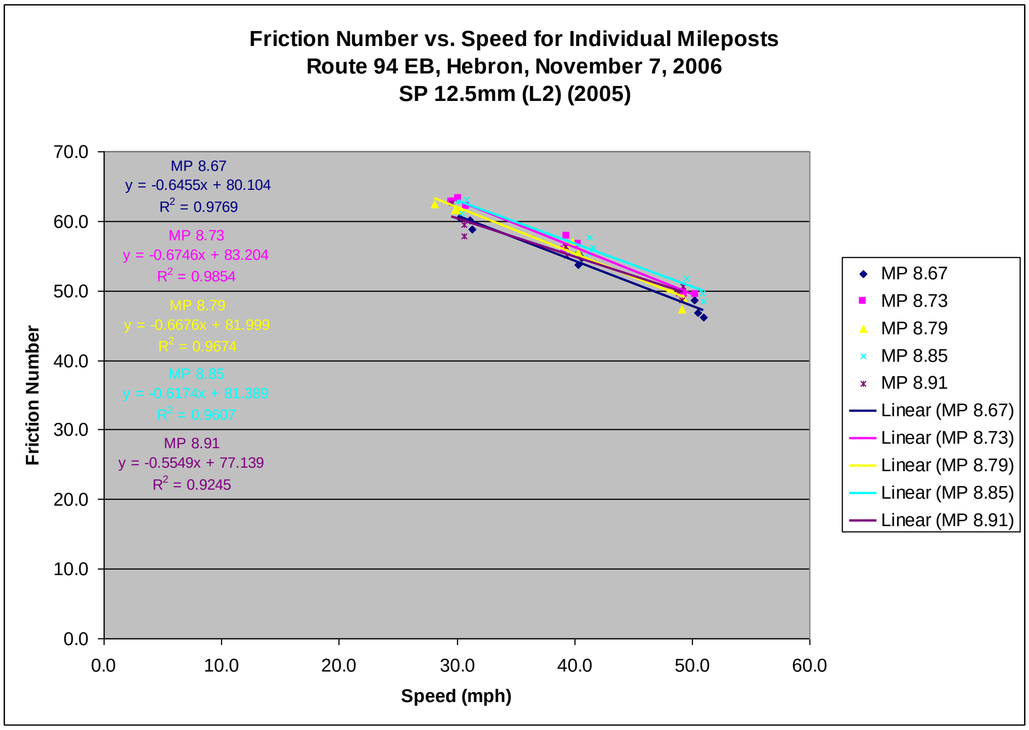

FIGURE 26 Speed gradients at individual mileposts for Route 94 EB SP 12.5-mm pavement in Hebron.

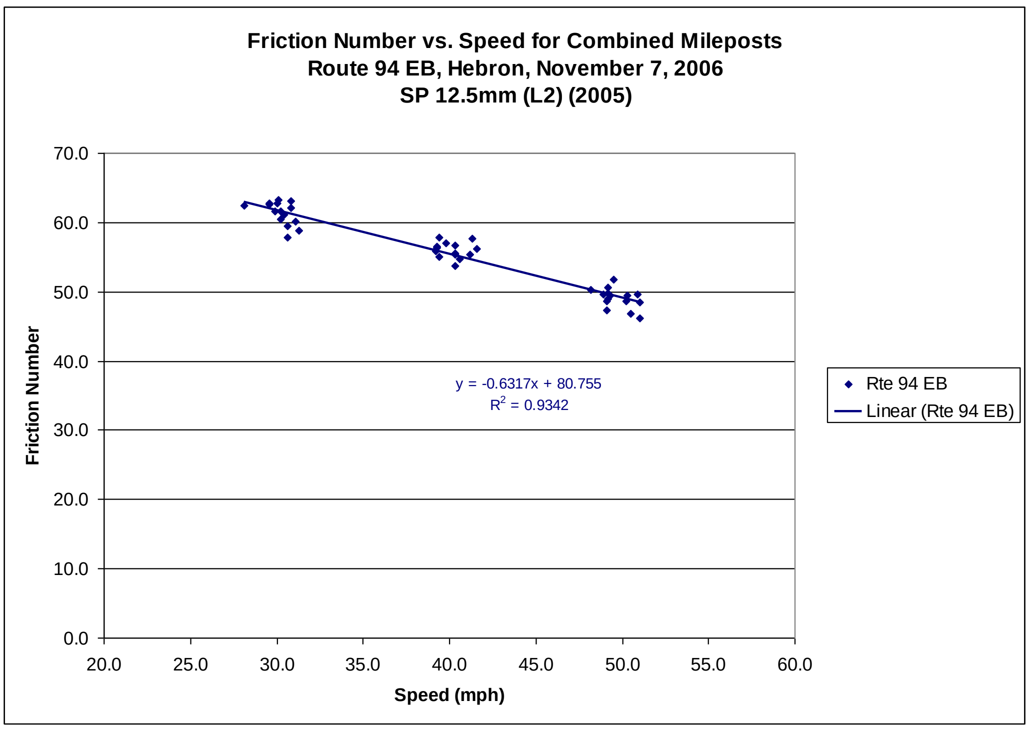

FIGURE 27 Speed gradients combined for Route 94 EB SP 12.5-mm pavement in Hebron.

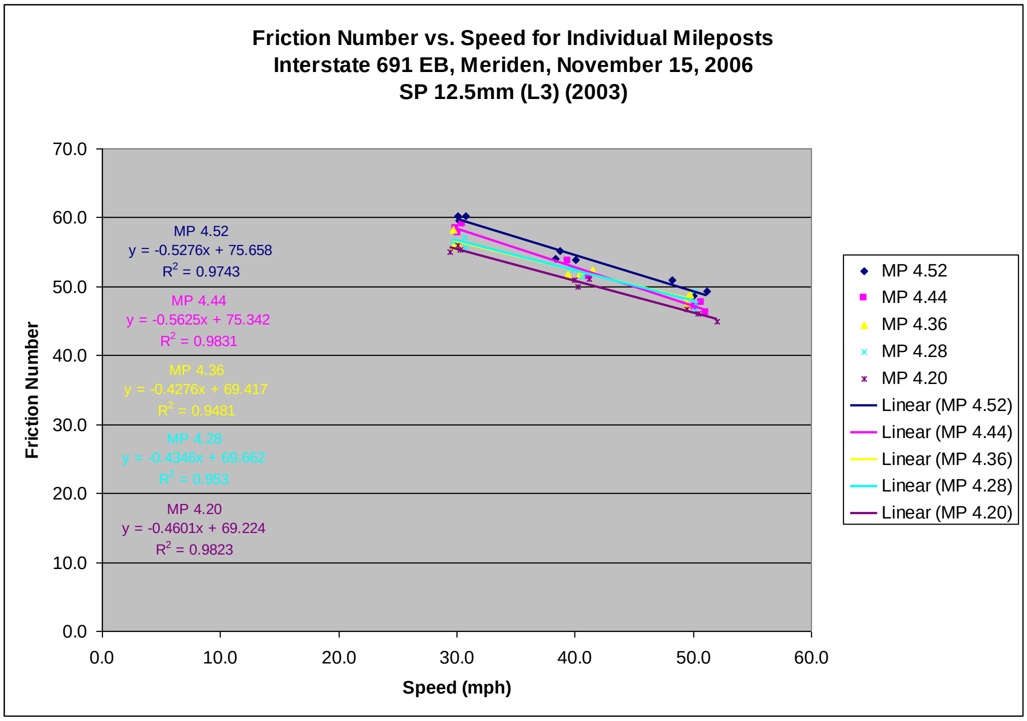

FIGURE 28 Speed gradients at individual mileposts for Route 691 EB SP 12.5-mm pavement in Meriden.

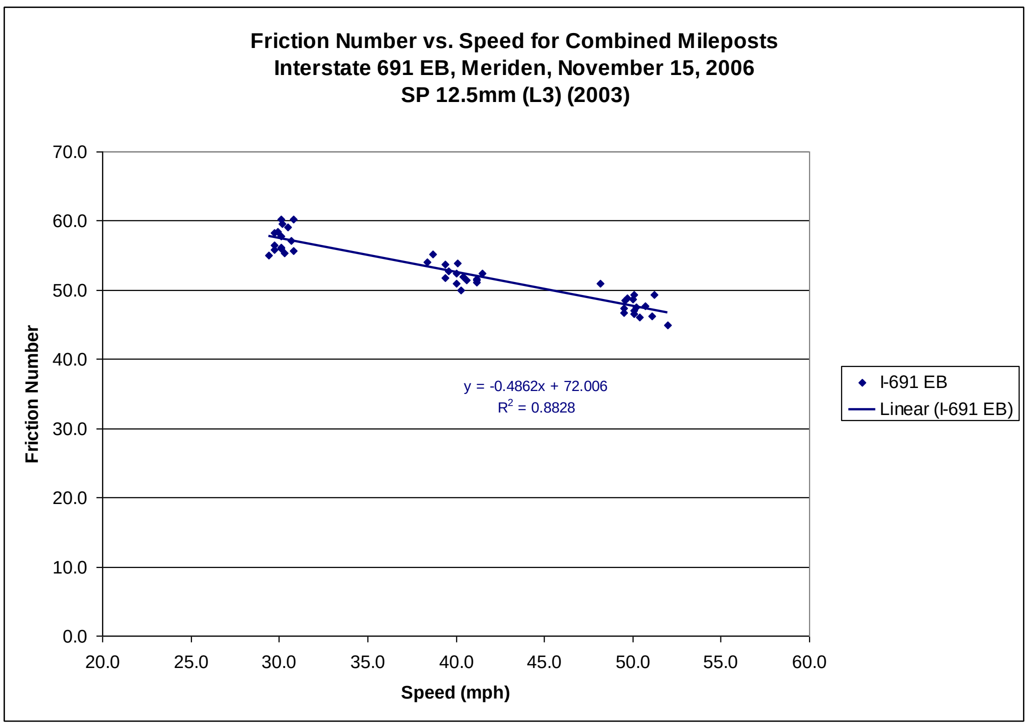

FIGURE 29 Speed gradients combined for Route 691 EB SP 12.5-mm pavement in Meriden.

A simple error bar chart for the 12.5-mm SuperPave mix is presented below in Figure 30. For this mix, three of the five CI's encompass the speed gradient of -0.50. The CI for Route 94 EB is less than -0.50, and the CI for Route 15 NB is greater than -0.50.

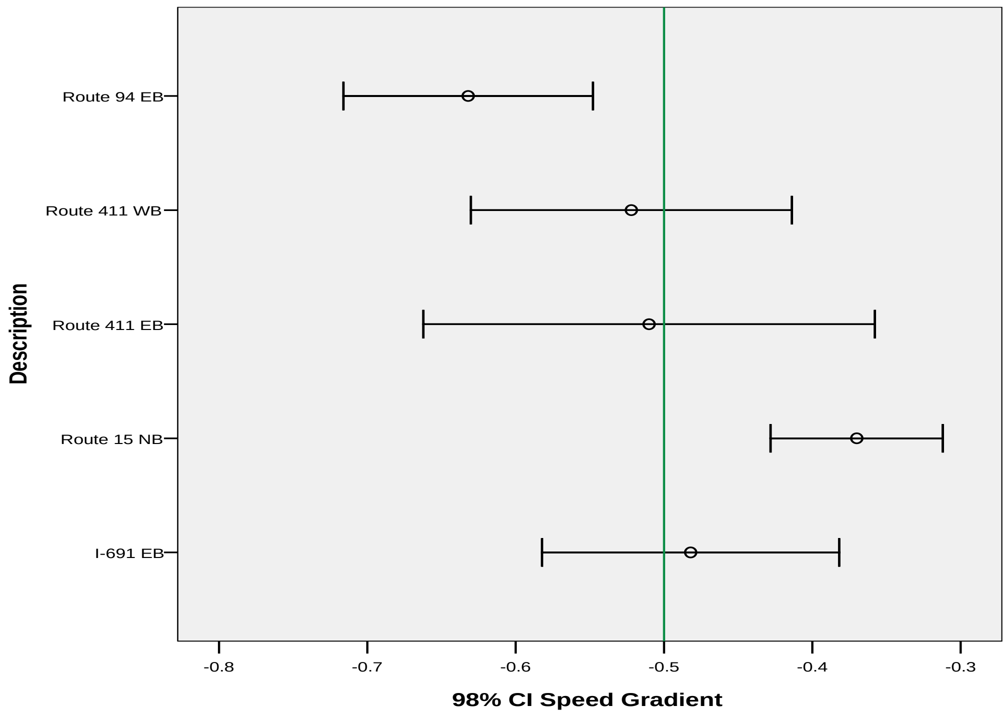

FIGURE 30 98% Confidence intervals for speed gradients for 12.5-mm Superpave pavements.

No. 4 Mix

This mix is called a No. 4 mix because the aggregates pass through the No. 4 sieve, which has a 4.75-mm (0.187-inch) opening. Therefore, the No. 4 mix is essentially a 4.75-mm Superpave mix. Speed gradients and R^2 values are presented in Tables 15 and 16. Figures 31 through 38 provide scatter plots and linear trend lines for each site, for both individual mileposts and for entire sites (mileposts combined). The average speed-gradient slope for the individual No. 4 mix mileposts was considerably steeper (-0.68) than for the other mixes, and the R^2 value was indicative of a strong linear association at 0.96. It is not surprising that the speed-gradient was steeper for this finer mix, because just as smooth tires are more sensitive to speed than ribbed tires, smoother (finer) pavements should be expected to be more sensitive to speed, especially for a pavement as fine as the No. 4 mix.

The standard deviation of the speed-gradient slopes between mileposts was +/-0.12. Therefore, the range within one standard deviation of the mean was -0.56 to -0.80, and the range within two standard deviations of the mean was -0.44 to -0.92.

TABLE 14 No. 4 Mix Speed Gradient Slopes and R^2 Values by Milepost

Route	Dir.	Year	Milepost	Speed Gradient Slope	R^2
9	NB	2004	17.68	-0.91	0.98
9	NB	2004	17.83	-0.67	0.96
9	NB	2004	17.98	-0.43	0.79
9	NB	2004	18.13	-0.79	0.97
9	NB	2004	18.28	-0.78	0.99
9	NB	2004	18.43	-0.48	0.91
9	NB	2004	18.58	-0.77	0.94
9	SB	2006	7.81	-0.80	0.96
9	SB	2006	7.91	-0.85	0.97
9	SB	2006	8.01	-0.77	0.98
9	SB	2006	8.11	-0.72	0.98
9	SB	2006	8.21	-0.96	0.88
9	SB	2006	8.31	-0.70	0.94
9	SB	2006	8.41	-0.59	0.94
9	SB	2006	8.51	-0.73	0.98
2	EB	2004	20.61	-0.62	0.98
2	EB	2004	20.86	-0.63	0.97
2	EB	2004	21.11	-0.61	1.00
2	EB	2004	21.61	-0.61	0.99
2	EB	2004	21.86	-0.63	0.99
2	EB	2004	22.11	-0.61	0.98
2	WB	2004	21.75	-0.61	0.98
2	WB	2004	22.00	-0.54	0.97
2	WB	2004	22.25	-0.70	0.96
2	WB	2004	22.50	-0.68	0.98
2	WB	2004	22.75	-0.62	0.98
2	WB	2004	23.00	-0.60	0.99
2	WB	2004	23.25	-0.54	0.99
Average				**-0.68**	**0.96**

TABLE 15 No. 4 Mix HMA Speed Gradient Slopes and R^2 Values by Site

Route	Dir.	Year Paved	Speed Gradient Slope, Average of Mileposts for Site	Speed Gradient Slope, Combined Data for Site	R^2, Average of Mileposts for Site	R^2, Combined Data for Site
9	NB		-0.69	-0.70	0.93	0.84
9	SB		-0.77	-0.77	0.95	0.82
2	EB		-0.62	-0.62	0.99	0.98
2	WB		-0.61	-0.61	0.98	0.96

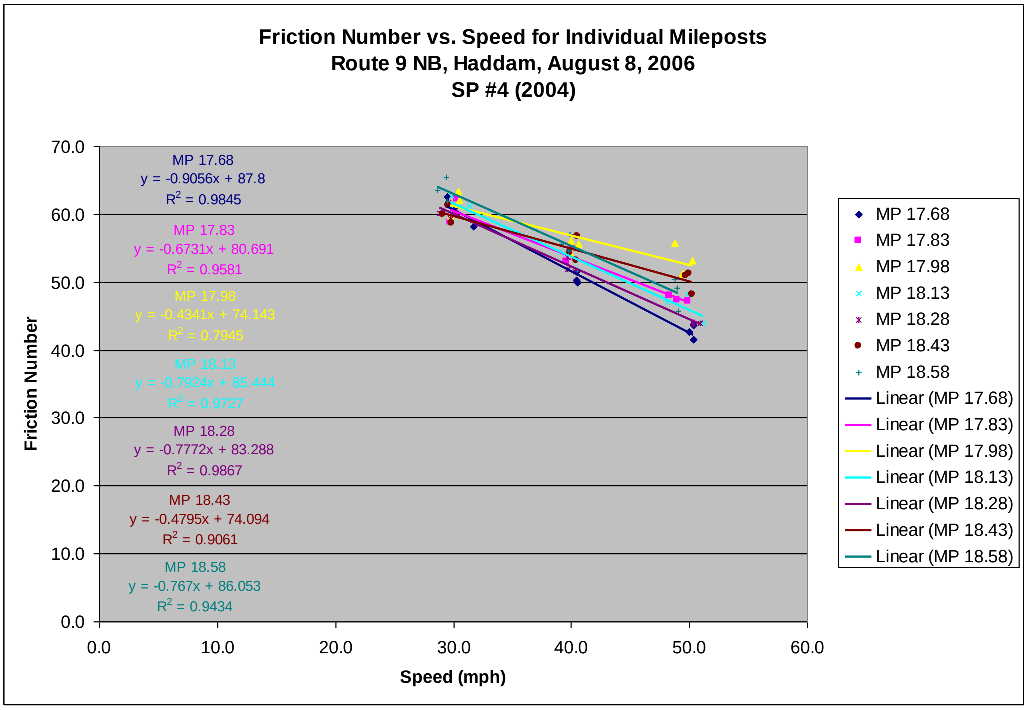

FIGURE 31 Speed gradients at individual mileposts for Route 9 NB SP #4 pavement in Haddam.

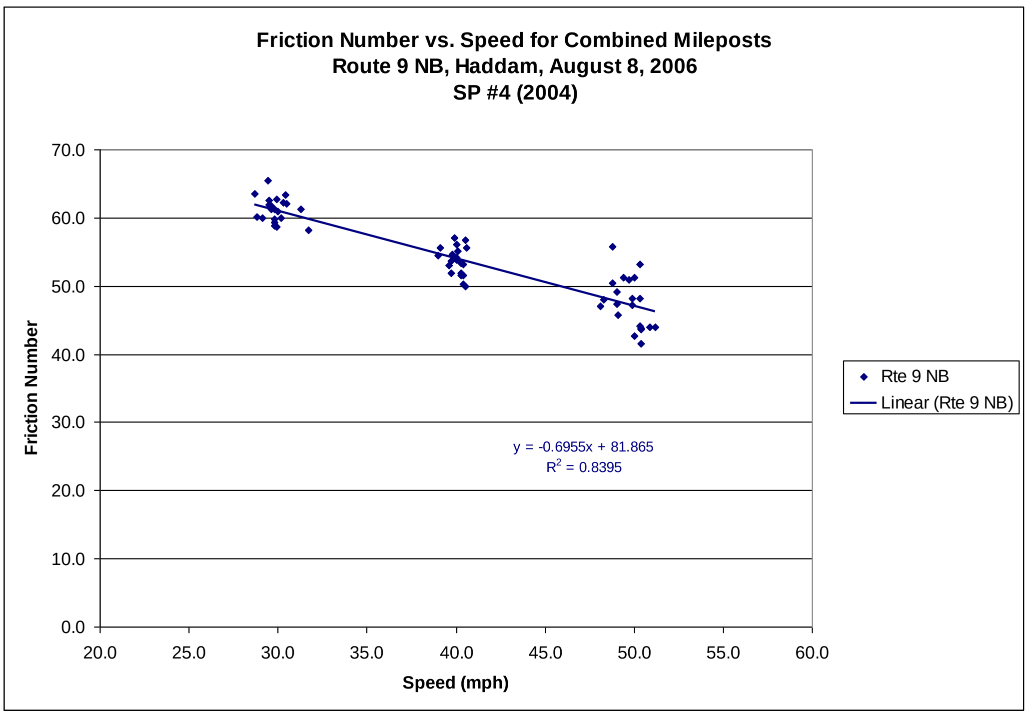

FIGURE 32 Speed gradients combined for Route 9 NB SP #4 pavement in Haddam.

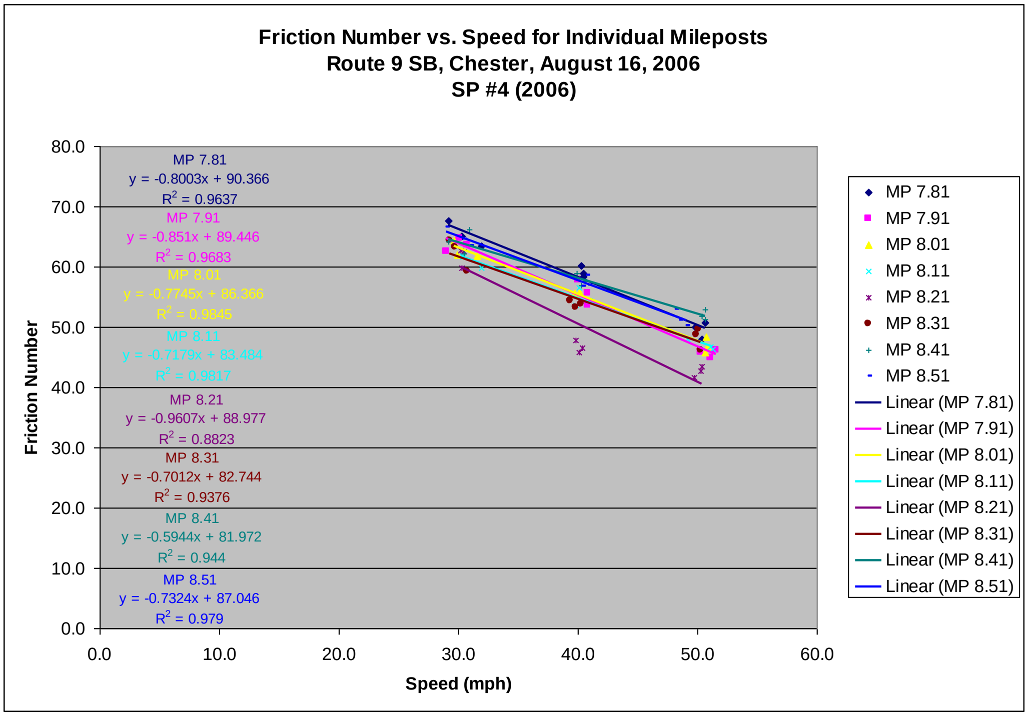

Figure 33 Speed gradients at individual mileposts for Route 9 SB SP #4 pavement in Chester.

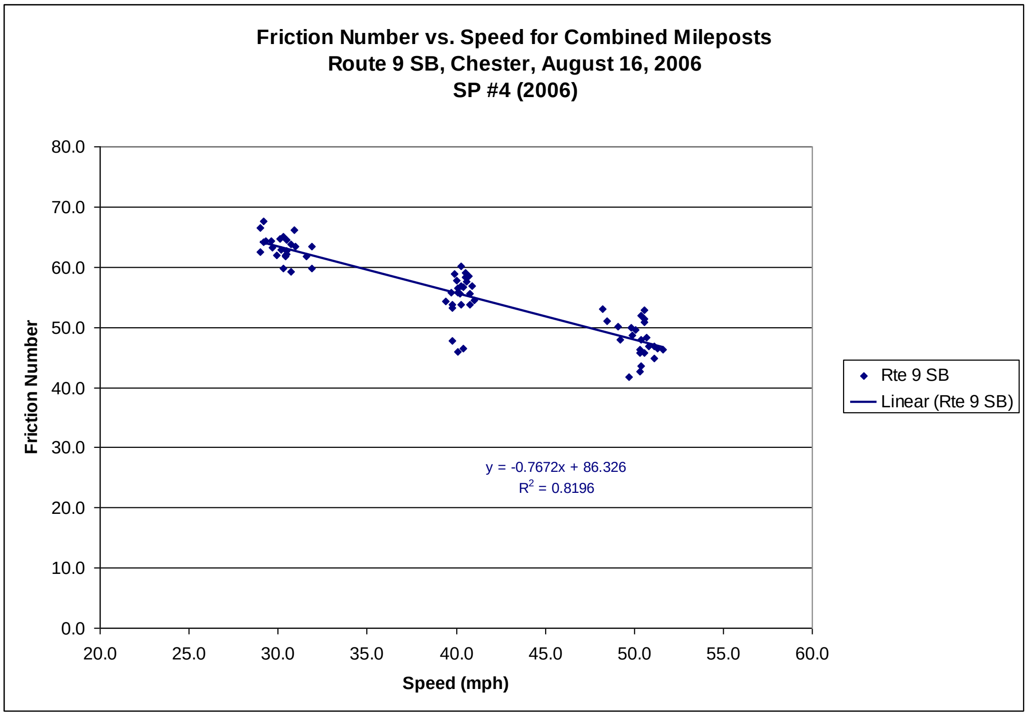

FIGURE 34 Speed gradients combined for Route 9 SB SP #4 pavement in Chester.

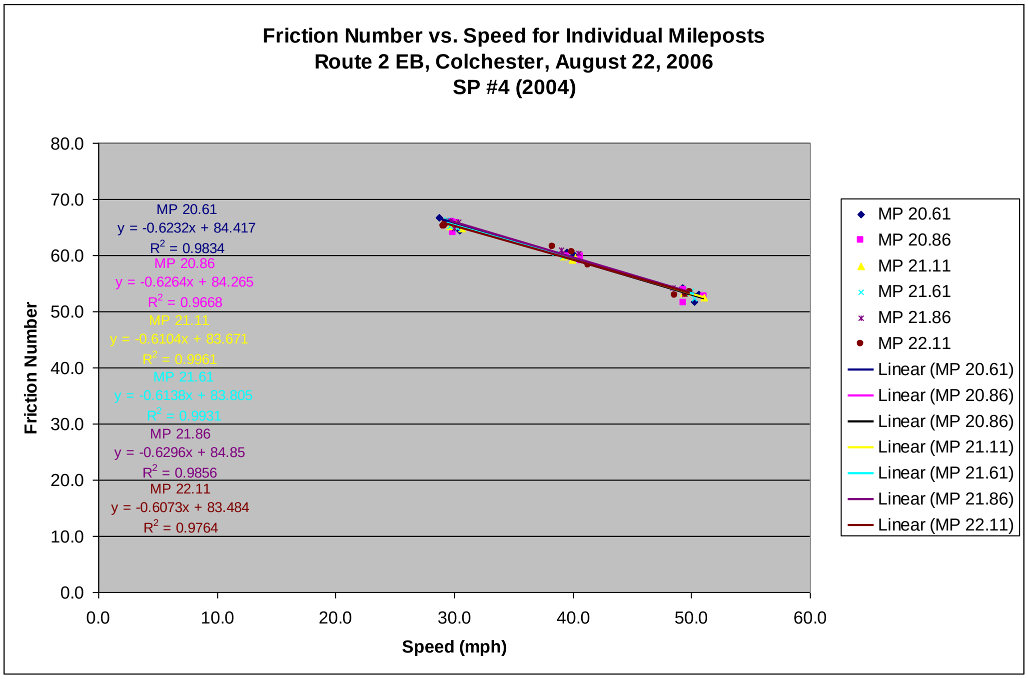

FIGURE 35 Speed gradients at individual mileposts for Route 2 EB SP #4 pavement in Colchester.

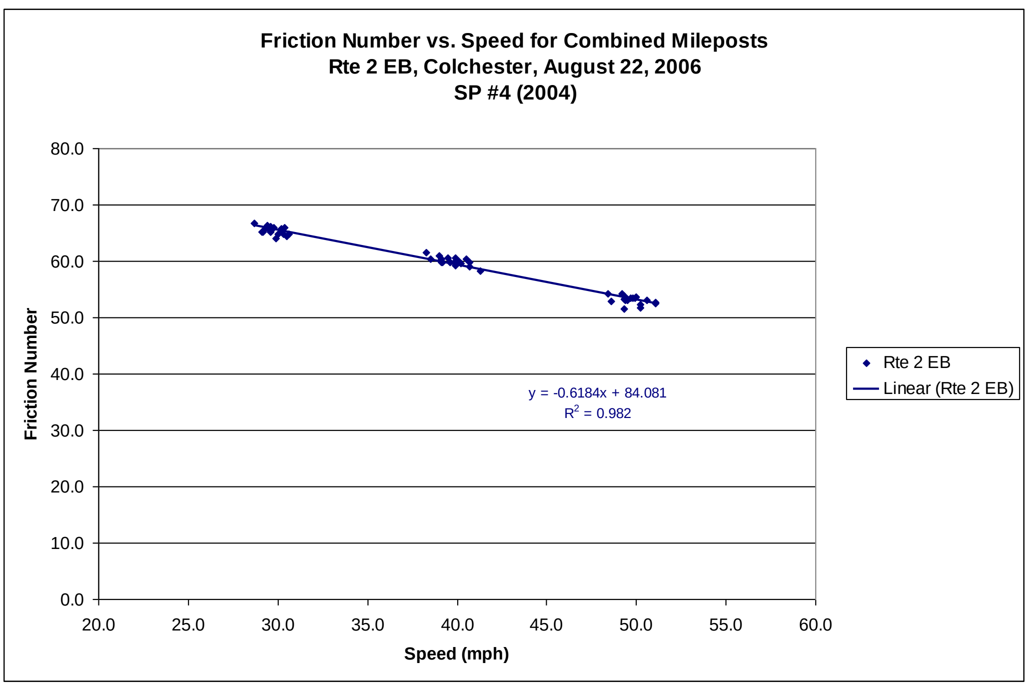

FIGURE 36 Speed gradients combined for Route 2 EB SP #4 pavement in Colchester.

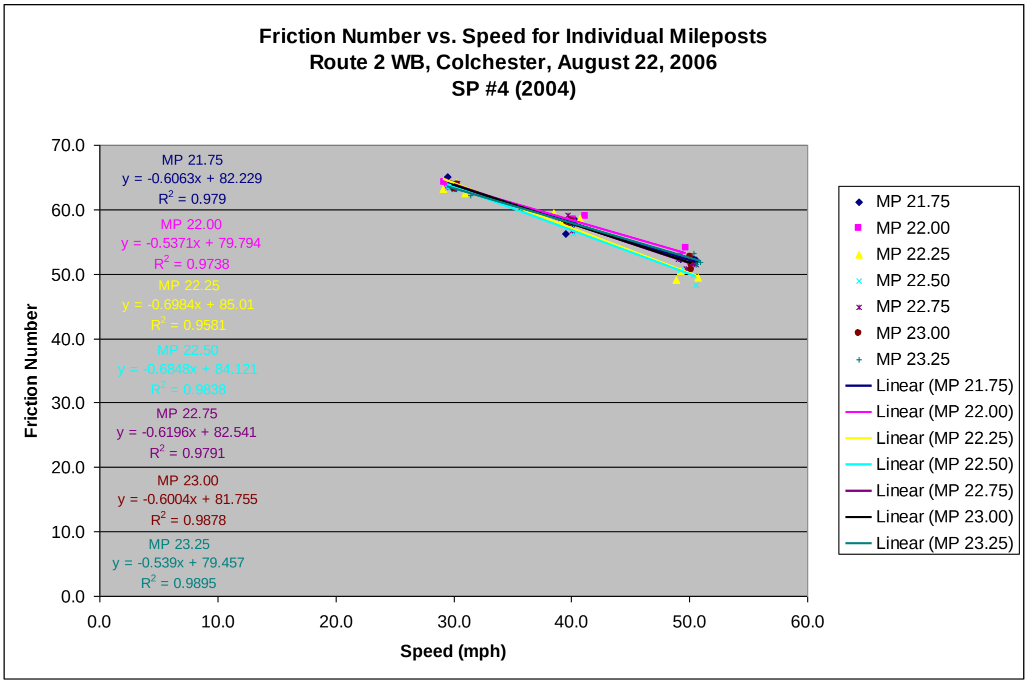

FIGURE 37 Speed gradients at individual mileposts for Route 2 WB SP #4 pavement in Colchester.

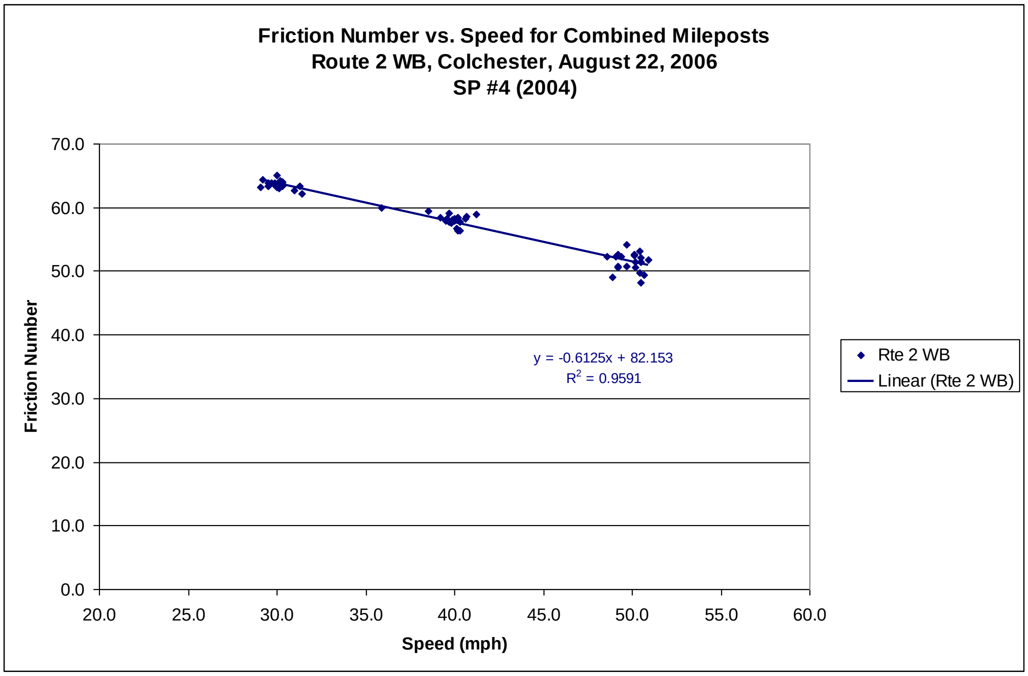

FIGURE 38 Speed gradients combined for Route 2 WB SP #4 pavement in Colchester.

A simple error bar chart for the No. 4 mix is presented in Figure 39. The Route 9 NB interval was the only one to encompass the speed gradient of negative 0.50 used in FN_{40R} calculations. Each of the remaining locations had lower speed gradient intervals. Considering the magnitude of how much lower these intervals are than negative 0.50, perhaps this value should not be used in future FN_{40R} calculations.

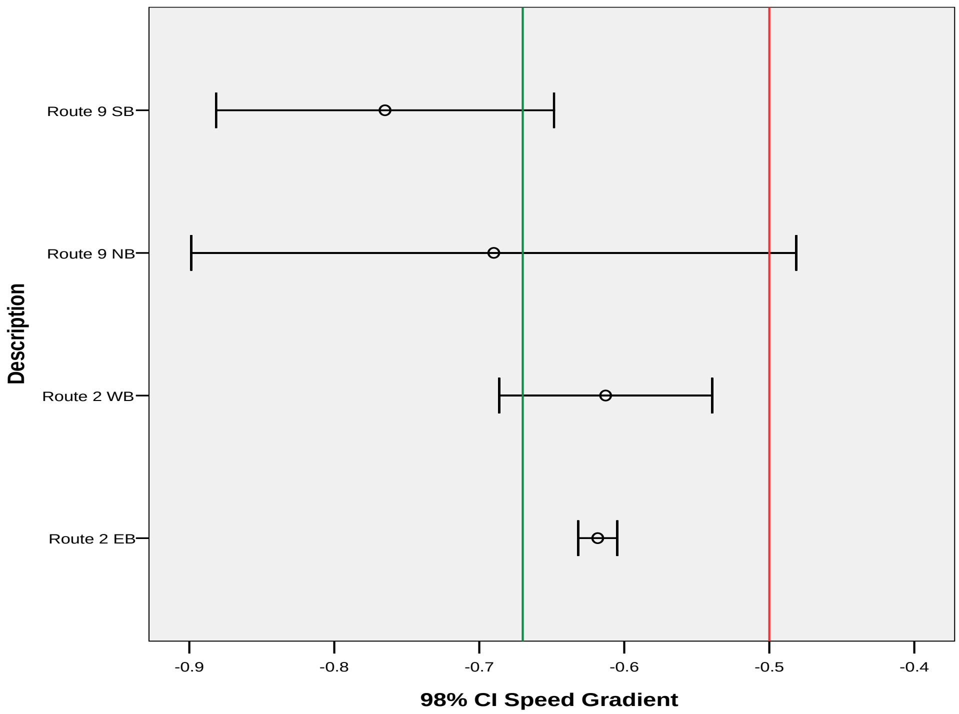

FIGURE 39 98% Confidence intervals for speed gradients for SuperPave No. 4 pavements.

9.5-mm Superpave

The average speed-gradient slope for the 9.5-mm Superpave mix was -0.43, with a standard deviation of +/- 0.04. Therefore, the range within one standard deviation was -0.39 to -0.47, and the range within two standard deviations was -0.35 to -0.51. The R^2 values were high for each milepost, which demonstrates a strong linear association between friction numbers and speed.

Considering that the 9.5-mm mix was finer than the 12.5-mm mix, it was initially surprising that the speed gradient was flatter for the 9.5-mm mix. Contrarily, the #4 mix (4.75-mm Superpave) which is considerably finer had a steeper speed gradient. So, it is likely that the grain-size distribution played a more significant role for the #4 mix versus the other mixes, whereas it was less predominant for the 9.5-mm mix, since the 9.5-mm Superpave is not that much finer than the 12.5-mm mix.

TABLE 16 9.5-mm Superpave HMA Speed Gradient Slopes and R^2 Values by Site

Route	Dir.	Year Paved	Milepost	Speed Gradient Slope	R^2
91	NB	2004	5.20	-0.45	0.74
91	NB	2004	5.40	-0.37	0.95
91	NB	2004	5.60	-0.45	0.96
91	NB	2004	5.80	-0.41	0.92
91	NB	2004	6.00	-0.46	0.77
Average				**-0.43**	**0.87**

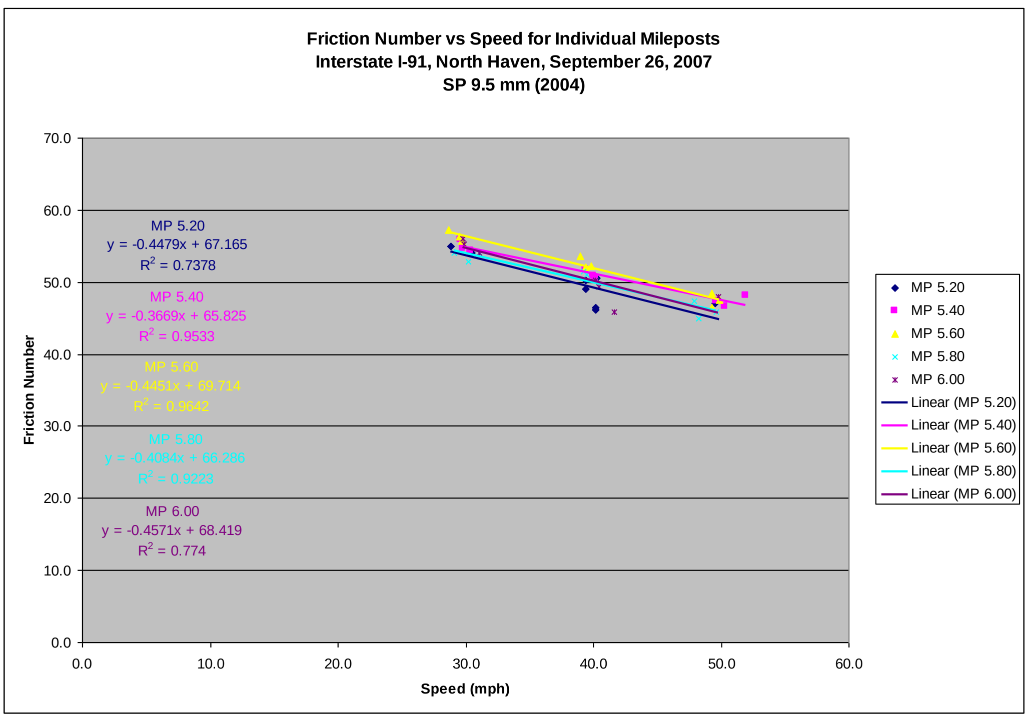

FIGURE 40 Speed gradients at individual mileposts for I-91 NB SP 9.5-mm pavement in North Haven.

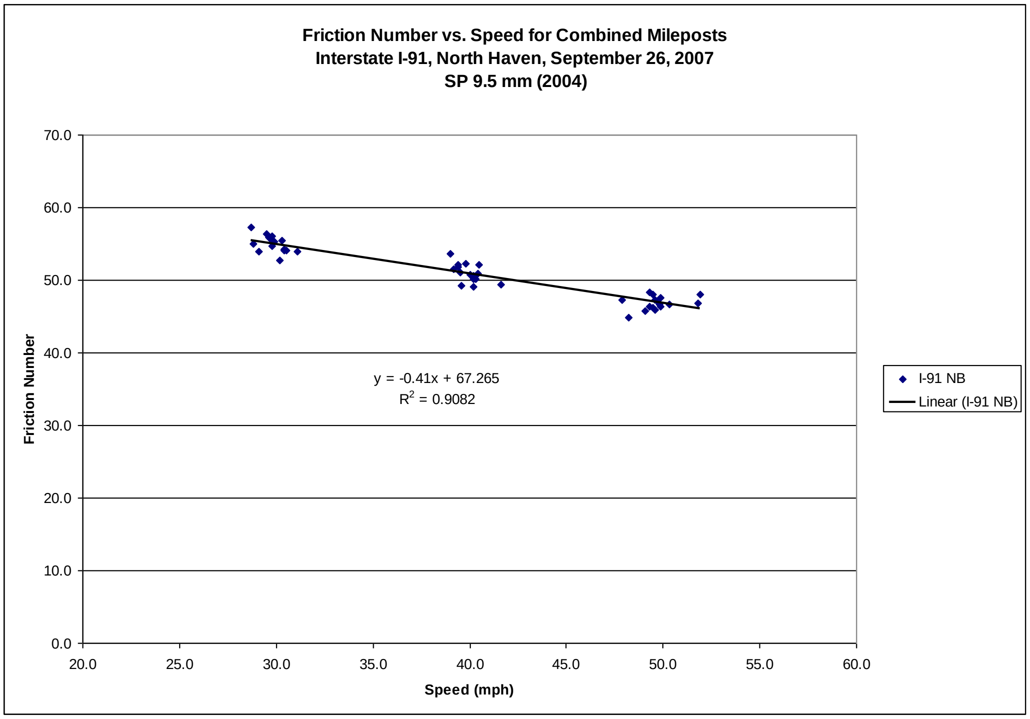

FIGURE 41 Speed gradients combined for I-91 NB 9.5-mm SP pavement in North Haven.

The 98% CI for the 9.5-mm Superpave speed gradients is shown in Figure 42. This range is greater than the -0.50 used in FN_{40R} calculations. Therefore, calculated FN_{40R} values would be slightly different from those calculated with a gradient of -0.50.

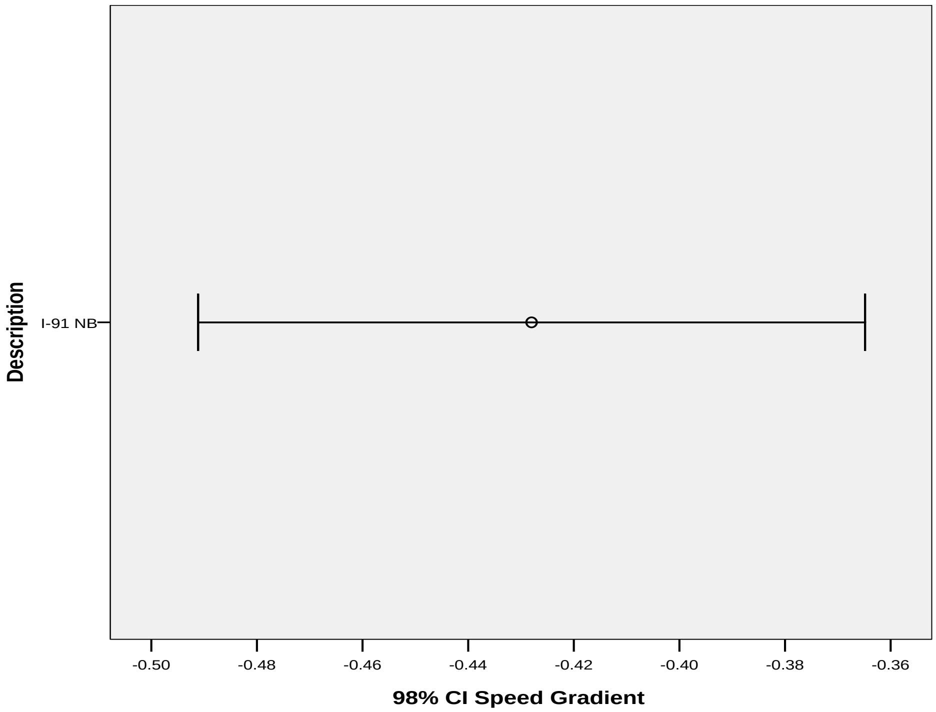

FIGURE 42 98% Confidence interval for speed gradient for 9.5-mm SuperPave pavement on I-91 NB in North Haven.

Portland Cement Concrete Diamond Ground Pavements

For the PCC diamond ground pavements, the average speed-gradient slope was -0.52, and the average R^2 value was 0.85. The speed gradients varied considerably more for the different diamond ground pavements than for the HMA pavements, as the standard deviation was +/-0.12. The range within one standard deviation of the mean was -0.40 to -0.65, and the range within two standard deviations of the mean was -0.28 to -0.77.

TABLE 17 PCC Diamond Ground Pavement Speed Gradient Slopes and R2 Values by Milepost

Route	Dir.	Milepost	Speed Gradient Slope	R^2
I-691	EB	7.03	-0.56	0.96
I-691	EB	6.83	-0.25	0.52
I-691	EB	6.63	-0.36	0.95
I-691	EB	6.43	-0.37	0.78
I-691	EB	6.23	-0.62	0.8
I-691	WB	6.04	-0.55	0.84
I-69 1	WB	6.24	-0.47	0.66
I-691	WB	6.44	-0.44	0.74
I-691	WB	6.64	-0.44	0.67
I-691	WB	6.84	-0.51	0.94
9	SB	34.7	-0.43	0.94
9	SB	34.75	-0.66	0.91
9	SB	34.8	-0.58	0.93
9	SB	34.85	-0.62	0.97
9	SB	34.9	-0.56	0.8
9	NB	36.59	-0.67	0.91
9	NB	36.64	-0.58	0.95
9	NB	36.69	-0.74	0.95
9	NB	36.74	-0.64	0.98
9	NB	36.79	-0.42	0.87
AVERAGE			**-0.52**	**0.85**

TABLE 18 PCC Diamond Ground Pavement Speed Gradient Slopes and R2 Values by Site

Route	Dir.	Speed Gradient Slope, Average of Mileposts	Speed Gradient Slope, Combined Data	R^2, Average of Mileposts	R^2, Combined Data
I-691	EB	-0.43	-0.44	0.80	0.55
I-691	WB	-0.48	-0.49	0.77	0.53
9	SB	-0.57	-0.57	0.91	0.76
9	NB	-0.61	-0.61	0.93	0.79
Average		**-0.52**	**-0.52**	**0.85**	**0.66**

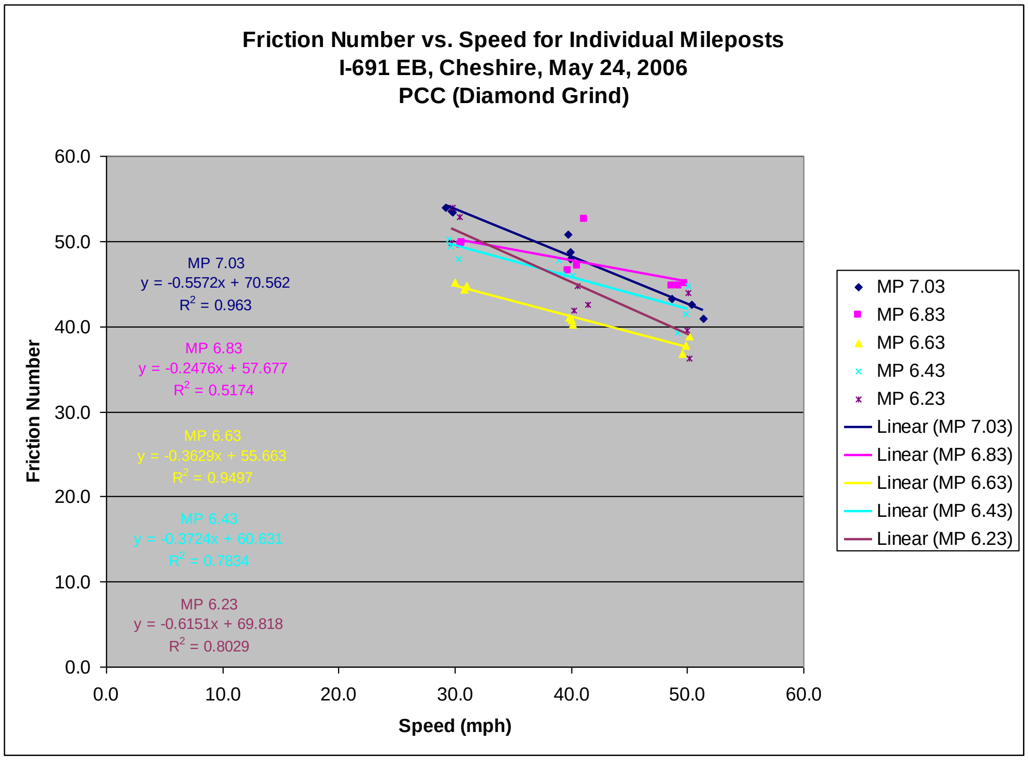

FIGURE 43 Speed gradients at individual mileposts for I-691 EB Diamond Ground PCC pavement in Cheshire.

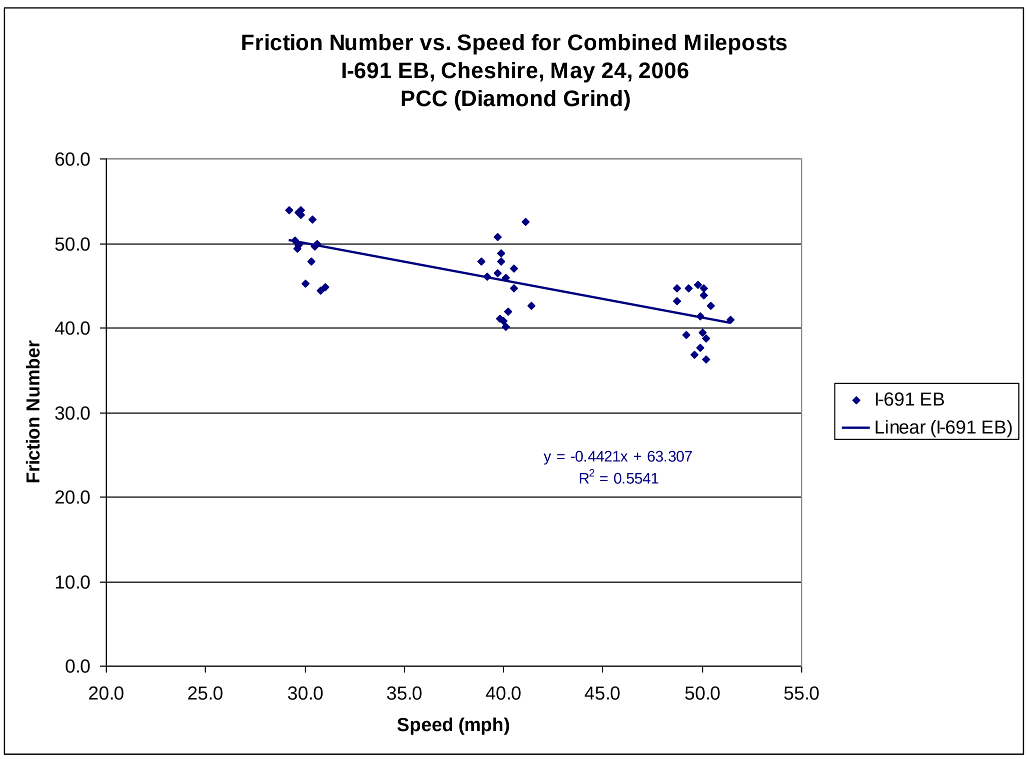

FIGURE 44 Speed gradients combined for I-691 NB Diamond Ground PCC pavement in Cheshire.

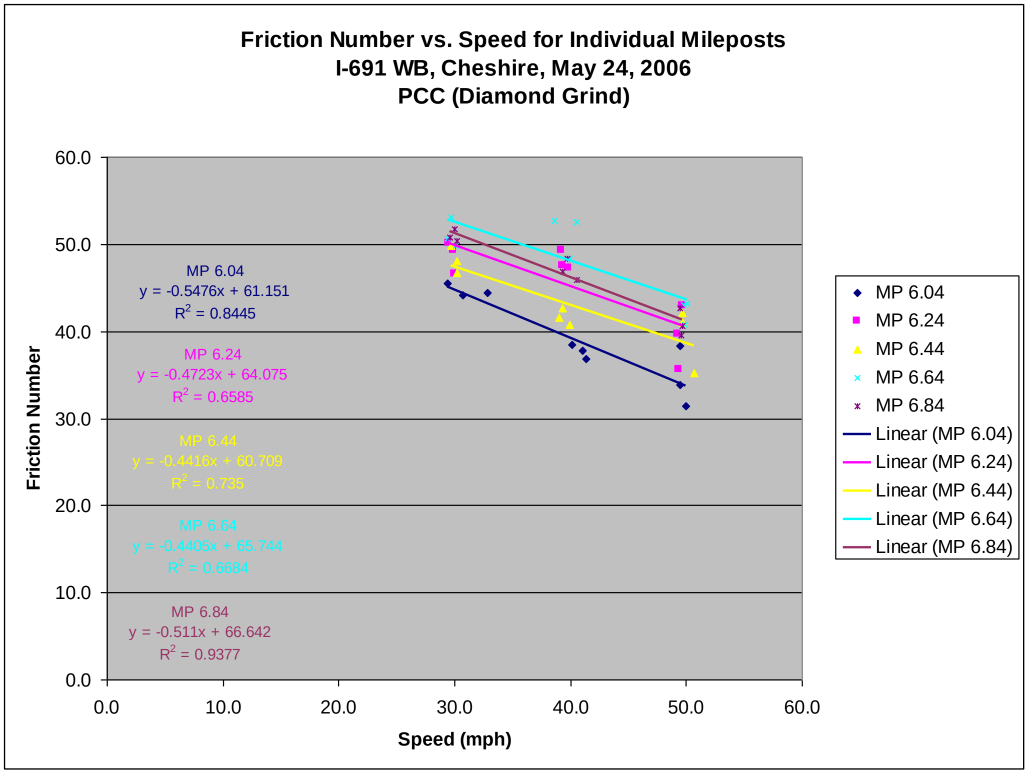

FIGURE 45 Speed gradients at individual mileposts for I-691 WB Diamond Ground PCC pavement in Cheshire.

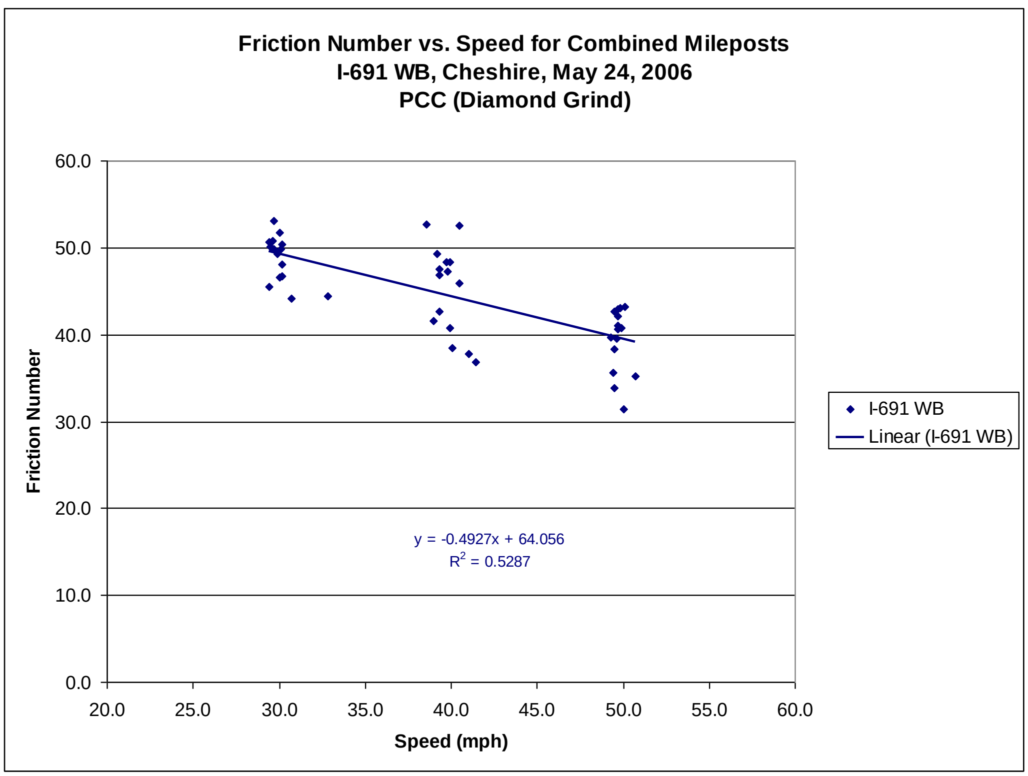

FIGURE 46 Speed gradients combined for I-691 WB Diamond Ground PCC pavement in Cheshire.

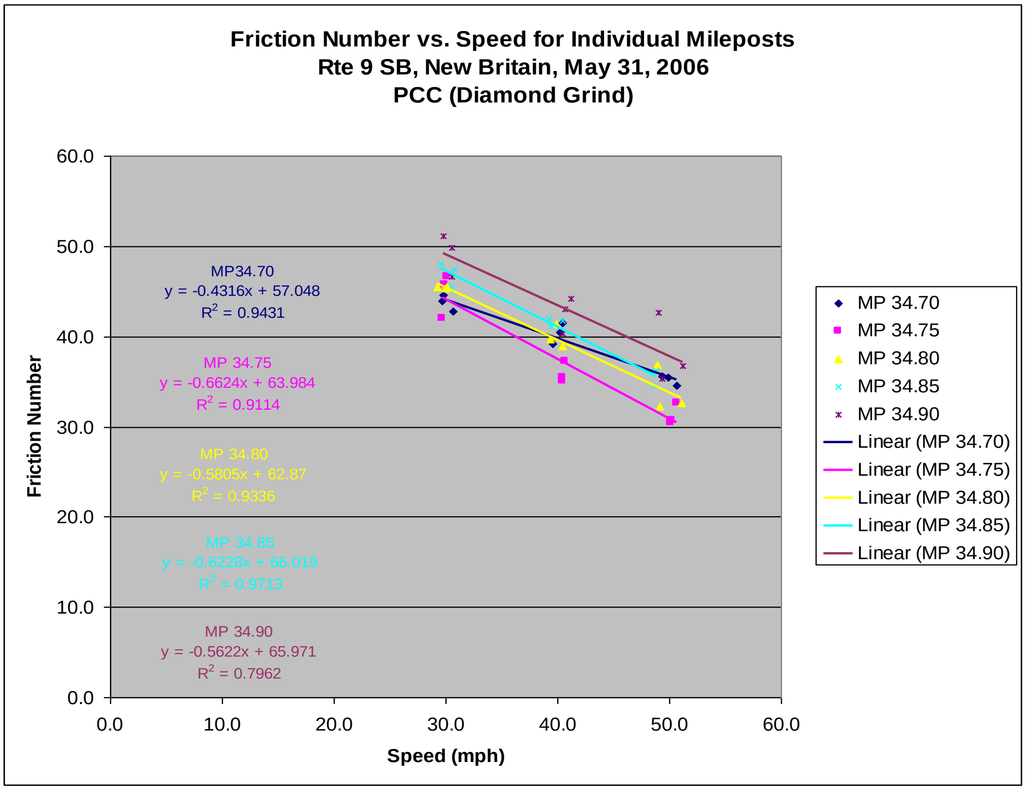

FIGURE 47 Speed gradients at individual mileposts for Route 9 SB Diamond Ground PCC pavement in New Britain.

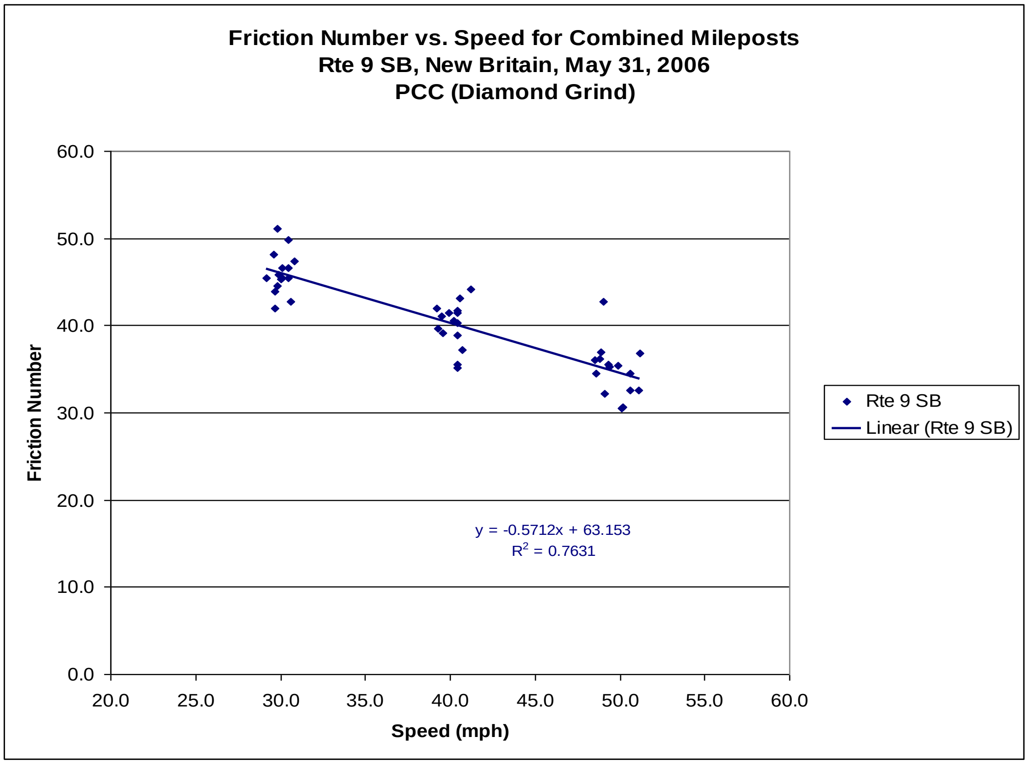

FIGURE 48 Speed gradients combined for Route 9 SB Diamond Ground PCC pavement in New Britain.

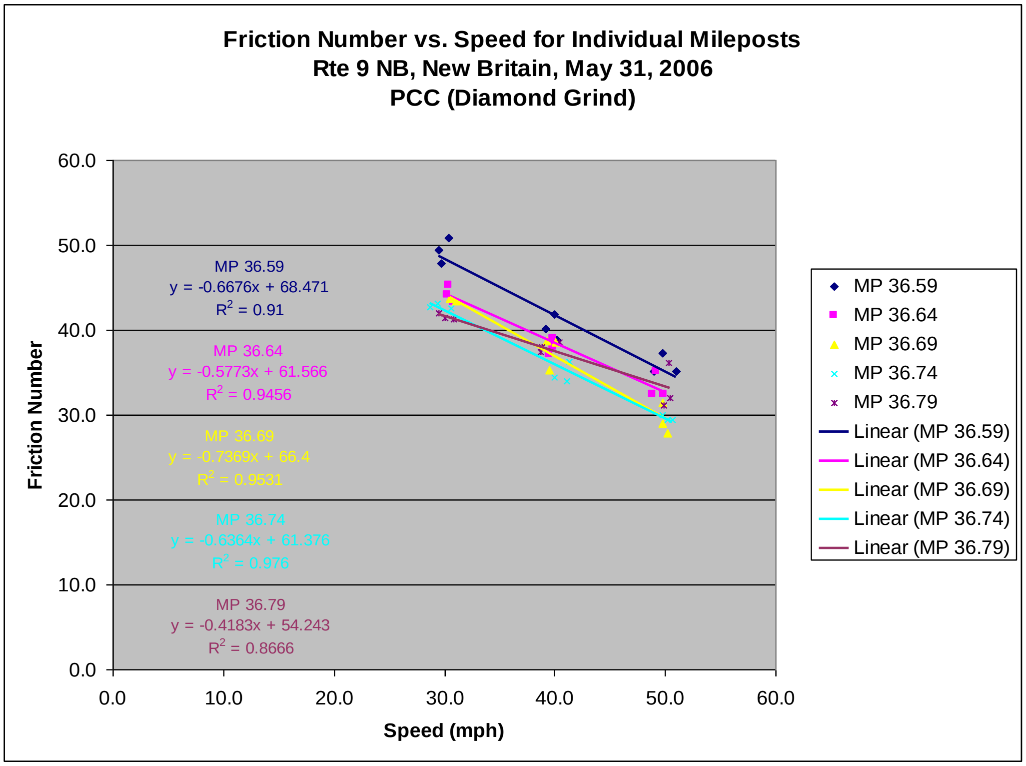

FIGURE 49 Speed gradients at individual mileposts for Route 9 NB Diamond Ground PCC pavement in New Britain.

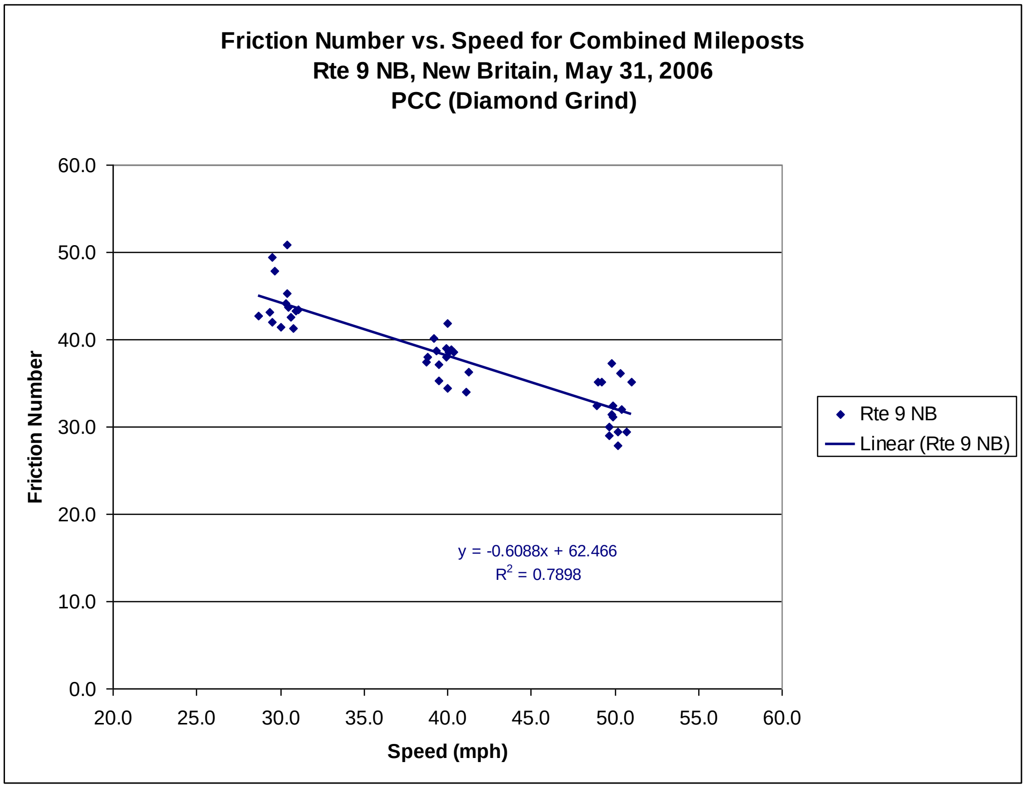

FIGURE 50 Speed gradients combined for Route 9 NB Diamond Ground PCC pavement in New Britain.

Simple error bars for the PCC diamond ground pavement are presented below in Figure 51. The red line represents a gradient of -0.50 and is encompassed by all of the 98% CI's for the mix. The green line, which represents the average gradient, is also encompassed by each of the 98% CI's. In this instance, a gradient of -0.50 falls within the range of values that the population mean would fall at a designated likelihood of 98%.

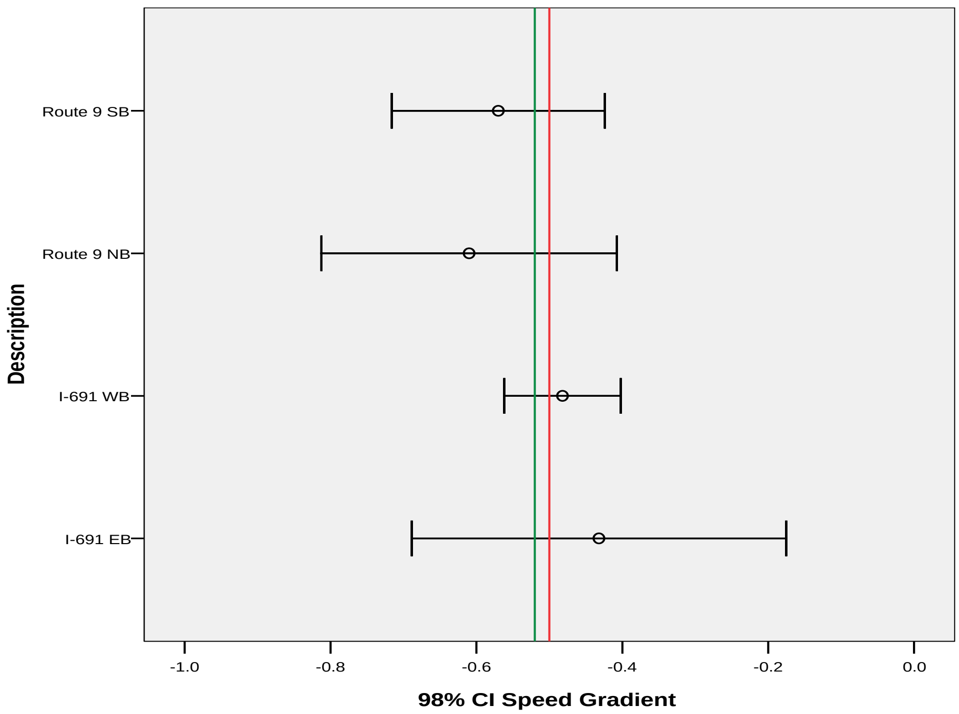

FIGURE 51 98% Confidence interval for speed gradients for PCC Diamond Ground pavement.

One Sample T-Tests for Speed Gradients

One Sample T-Tests were conducted in order to compare mean speed gradients for each pavement to the hypothesized value that has been used (-0.5).

Hypotheses:

- Null: There is no significant difference between the sample mean and the hypothesized value of -0.5.
- Alternate: There is a significant difference between the sample mean and hypothesized value of -0.5.

TABLE 19 One-Sample Statistics for Speed Gradients

	N	Mean	Std. Deviation	Std. Error Mean
Class 1 Pavement	27	-.4041	.09221	.01775
SP 12 mm Pavement	25	-.5032	.10303	.02061
No. 4 Mix Pavement	28	-.6768	.12257	.02316
PCC Pavement	20	.5235	.12364	.02765
SP 9.5 mm Pavement	5	-.4280	.03768	.01685

TABLE 20 One-Sample Tests for Speed Gradients

	Test Value = -0.5					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Class 1 Pavement	5.406	26	1.155E-005	.09593	.0595	.1324
SP 12.5 mm Pavement	-.155	24	.8779	-.00320	-.0457	.0393
No. 4 Mix Pavement	-7.632	27	3.290E-008	-.17679	-.2243	-.1293
PCC Pavement	37.02	19	3.553E-019	1.02350	.9656	1.0814
SP 9.5 mm Pavement	4.272	4	.0129	.07200	.0252	.1188

For the Class 1 HMA, the mean value was -0.40, which differed by 0.1 from the hypothesized value of -0.5. The results of the One Sample T-Test calculated a t value of 5.406 and 26 degrees of freedom. The significance value was only 1.155E-005, which is considerably less than the chosen significance level of 0.05. Note: the significance level is the probability of rejecting the null hypothesis when it is true. Therefore, the sample mean of -0.40 is significantly different than -0.50. The null hypothesis is rejected for the Class 1 HMA samples.

The null hypothesis was also rejected for the No. 4 and 9.5-mm Superpave HMA mixes, and for the PCC pavement.

For the 12.5-mm Superpave HMA, the value is -0.50. This is very close to the hypothesized value. The results of the One Sample T-test show a t value of -0.155 and 24 degrees of freedom. The significance value is 0.88, which is greater than 0.05. Therefore, the test failed to reject the null hypothesis for the 12.5-mm Superpave HMA.

Discussion

A research objective was to update friction number speed correction factors for FN_{40R} calculations based upon the various pavement mix designs used in Connecticut. Currently, ConnDOT uses a speed correction factor of -0.5

for all pavements. This factor is used in the following equation:

$$FN_{40R} = FN - 0.5 * (40 - speed)$$

where,

FN_{40R} = friction number with a standard Ribbed Tire based upon a corrected speed o 40 mph,

FN = measured friction number, and

speed = measured speed in mph.

One Sample T-tests demonstrated significant differences between sample speed gradient means and the hypothesized value of -0.5 for the ConnDOT Class 1, 9.5-mm Superpave, and No. 4 HMAs. Conversely, the T-Test failed to reject the null hypothesis for the 12.5-mm Superpave HMA. This implies that the data were not sufficiently persuasive to indicate a significant difference exists between the sample mean 12.5-mm speed gradient and the hypothesized value of -0.5.

Finer mixes, such as the #4 mix (4.75-mm Superpave), appear to be most problematic. The average #4 mix speed gradient was significantly less than -0.5 (-0.68). This is because finer mixes result in less open-graded surfaces. The author's theory is that these dense-surfaced mixes behave similarly to smooth tires insofar as the tire-pavement interface is concerned, and just as smooth tires have steeper speed gradients, so do smooth pavements. In fact, a smooth-tire speed gradient of nearly -1.0 was measured from the ConnDOT friction tester at the Virginia Smart Road at an equipment rodeo and reported in a paper by de Leon et al *(15)*. A smooth-surfaced pavement likely results in a steep gradient.

CONNDOT'S PRELIMINARY EVALUATION OF THE INTERNATIONAL FRICTION INDEX COEFFICIENTS

Since ConnDOT personnel can now measure pavement texture with either the CTMeter or with the high-speed laser device mounted to the friction tester, they have the ability to calculate the IFI of pavement surfaces on Connecticut roadways.

The practice of calculating the IFI of a pavement is performed in accordance with ASTM 1960. The specification states "The IFI was developed in the PIARC [Permanent International Association of Road Congresses] International experiment to Compare and Harmonize Texture and Skid Resistance Measurements." It also states the IFI provides a way of harmonizing pavement friction measured with different equipment to a common calibrated index, and for harmonizing friction measured with a smooth test tire.

Two parameters are calculated in the practice: the calibrated wet friction at 60 km/h (*F60*) and the speed constant of wet pavement friction (S_p). S_p is sometimes referred to as the speed gradient. The equation for calculating the speed gradient is:

$$S_p = 14.2 + 89.7\ MPD. \qquad (1)$$

Before *F60* can be calculated, the measured friction (*FRS*) at some slip speed (*S*) is used with S_p to calculate the friction at 60 km/h (*FR60*). The equation for calculating *FR60* is:

$$FR60 = FRS \times \mathrm{EXP}[(S-60)/\ S_p]. \qquad (2)$$

Finally, two calibration constants (*A,B*) are used with *FR60* to calculate *F60* as follows:

$$F60 = A + B \times FR60. \qquad (3)$$

The problem that was encountered in using equation (3) above was that A and B are determined from a linear regression of the values of *FR60* calculated with yet another equation which requires a Dynamic Friction Tester (DFTester) number measured with a device called the Dynamic Friction Tester, which ConnDOT does not own:

$$FR60 = 0.081 + 0.732(DFT_{20})(\mathrm{EXP}(-40/\ S_p)) \qquad (4)$$

where

DFT_{20} is the Dynamic Friction Tester number at 20 km/h measured in accordance with ASTM E 1911 for a "set of at least 10 different pavements having a range of macrotexture and microtexture."

The previous ASTM E 1960 standard from 1998 (E 1960-98), provided the calibration constants (*A,B,C*) in an appendix. Since ConnDOT does not currently own a Dynamic Friction Tester (DFTester), the constants from the 1998 version of ASTM E 1960-98 had to be used for this research in order to calculate the IFI coefficient *F60.* The 1998 equation was:

$$F60 = A + B \times FR60 + C \times MPD \qquad (5)$$

Equations (1), (2), and (5) were used to calculate the IFI parameters S_p and *F60*, presented as IFI(*F60*,S_p), for the 24 pavement sections at the Smart Roads facility in Virginia. Table 20 below presents the results calculated with both the CTMeter and the high-speed laser. S_p values calculated with the CTMeter MPDs ranged from 61 to 186 km/h, and *F60* values ranged from 0.399 to 0.589. S_p values calculated with the high-speed laser MPDs ranged from 55 to 169 km/h, and *F60* values ranged from .405 to .481. The two sets of *F60* values described above did not correlate well to one another, as the R^2 value was only 0.28. When the Cargill sections were excluded from the dataset, as they were for comparing MPD values in Report 2 of this study *(16)*, the R^2 value improved only slightly to 0.36. Since S_p values were calculated with a linear equation (equation (1)), they corresponded to one another exactly as the MPD values that were used to calculate them. The coefficient of determination comparing all of the S_p values was only 0.20, but when the Cargill sections were excluded, the R^2 value increased to 0.61. Since the Cargill section does not compare to anything used in Connecticut at this time, excluding the Cargill section is reasonable.

TABLE 21 International Friction Index Parameters (Sp and F60) Calculated with ConnDOT Measurements for Smart Road Sections

	MPD ConnDOT CTM (mils)	MPD ConnDOT CTM (mm)	MPD ConnDOT Laser (mils)	MPD ConnDOT Laser (mm)	Sp Calc. w/ CTM MPD (km/h)	Sp Calc. w/ Laser MPD (km/h)	FRS	S (km/h)	FR60 Calc. w/ CTM MPD	FR60 Calc. w/ Laser MPD	F60 Calc. w/ CTM MPD	F60 Calc. w/ Laser MPD
Eastbound												
Loop	36	0.92	43	1.09	97	112	0.596	65.2	0.629	0.624	0.449	0.463
A	20	0.52	19	0.48	61	57	0.651	64.6	0.702	0.705	0.454	0.452
B	26	0.67	19	0.48	74	57	0.649	64.7	0.691	0.704	0.462	0.452
C	27	0.69	29	0.74	76	80	0.610	65.1	0.653	0.651	0.441	0.444
D	21	0.53	18	0.46	62	55	0.598	65.4	0.653	0.660	0.425	0.422
I	37	0.93	25	0.64	98	71	0.635	64.1	0.662	0.672	0.470	0.447
J	41	1.03	31	0.79	107	85	0.609	64.4	0.634	0.641	0.463	0.443
K	63	1.60	68	1.73	158	169	0.456	64.6	0.470	0.469	0.419	0.431
L	36	0.92	43	1.09	97	112	0.516	65.7	0.547	0.543	0.399	0.413
Cargill	67	1.71	30	0.76	168	83	0.608	66.5	0.632	0.658	0.528	0.451
EP5	46	1.17	31	0.79	119	85	0.543	65.4	0.568	0.579	0.437	0.405
CRCP	28	0.71	18	0.46	78	55	0.645	65.0	0.687	0.706	0.464	0.450
Westbound												
CRCP	30	0.77	27	0.69	83	76	0.646	63.4	0.674	0.676	0.461	0.455
Cargill	76	1.92	25	0.64	186	71	0.684	63.9	0.699	0.723	0.589	0.478
EP5	47	1.19	54	1.37	121	137	0.594	63.6	0.612	0.610	0.465	0.481
L	41	1.03	44	1.12	107	114	0.570	64.4	0.595	0.593	0.439	0.446
K	65	1.64	63	1.60	161	158	0.467	65.3	0.482	0.483	0.430	0.427
J	33	0.83	56	1.42	89	142	0.591	64.6	0.623	0.611	0.436	0.487
I	28	0.70	29	0.74	77	80	0.609	65.0	0.650	0.648	0.440	0.442
D	27	0.69	27	0.69	76	76	0.563	64.1	0.595	0.595	0.405	0.405
C	31	0.79	31	0.79	85	85	0.591	64.8	0.625	0.625	0.434	0.434
B	42	1.07	37	0.94	110	99	0.619	64.3	0.644	0.647	0.473	0.462
A	35	0.90	28	0.71	95	78	0.619	65.0	0.653	0.660	0.461	0.447
Loop	31	0.78	49	1.24	84	126	0.617	62.5	0.636	0.630	0.440	0.481

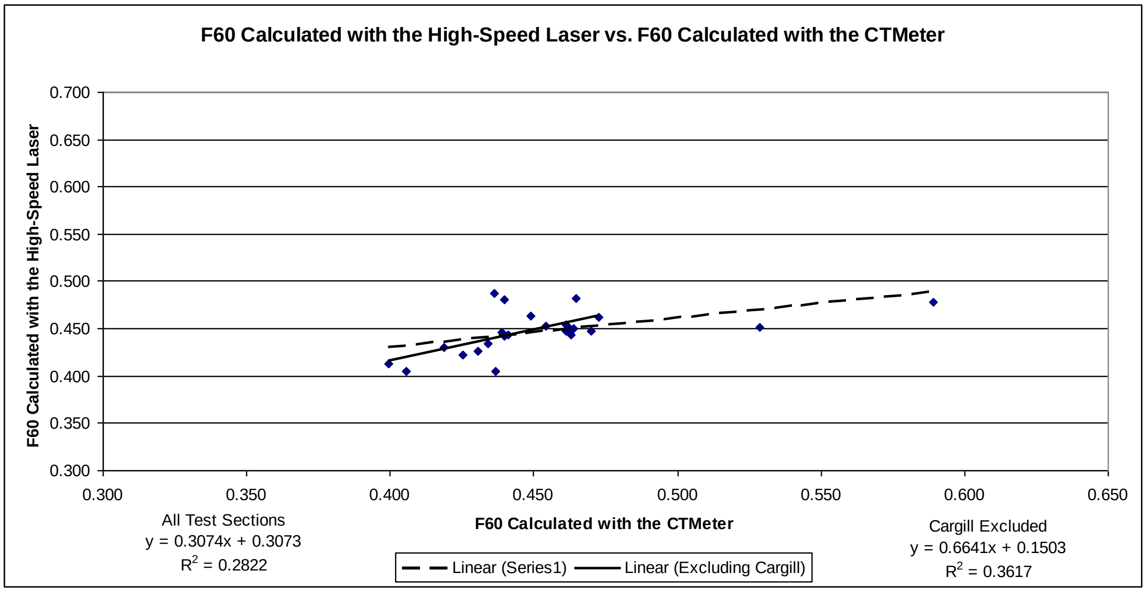

FIGURE 52 ***F60*** **Values Calculated from High-Speed Laser MPDs versus** ***F60*** **Values Calculated with CTMeter MPDs**

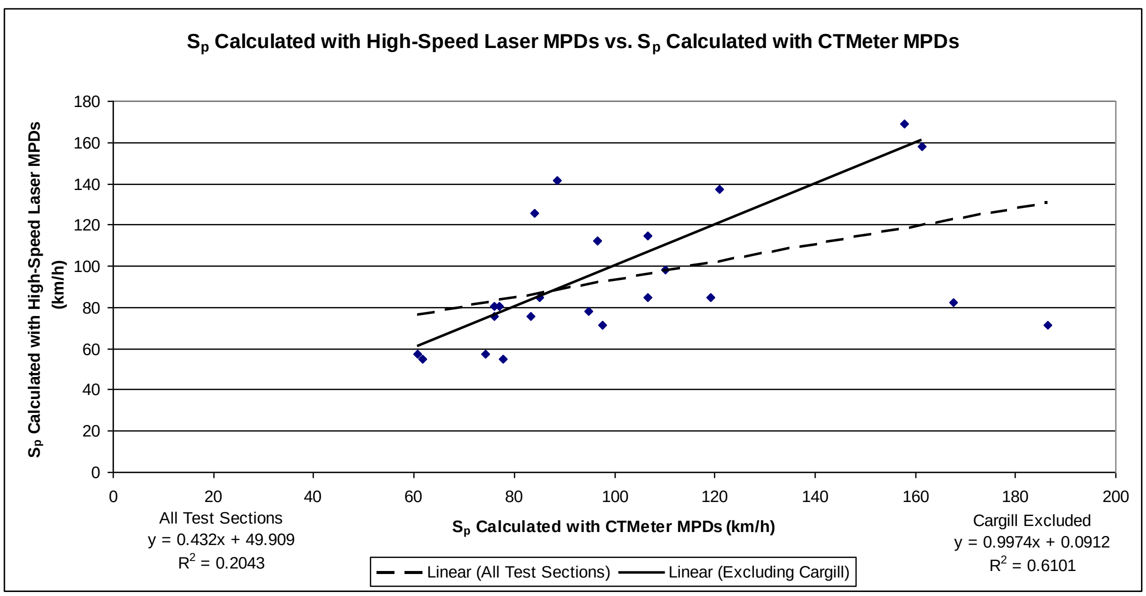

FIGURE 53 S_p **Values Calculated from High-Speed Laser MPDs versus** ***F60*** **Values Calculated with CTMeter MPDs.**

Before going to a site to perform friction testing, friction tests are performed in front of the ConnDOT Central Lab, where the friction tester is garaged, in order to verify that the equipment is working properly. The pavement was placed in 2005 and is a Superpave 12.5 mm HMA mix. The tables below present results of these tests performed on four different dates: September 17, 2007, June 4, 2008, July 2, 2008, and October 14, 2008. Results presented include the mileage, average MPD, friction number, and speed. Using these values and the constants *A*, *B*, and *C*, the IFI parameters S_p and *F60* were determined and tabulated. These were determined at 0.050 mile increments starting at 0.000 at the intersection between West Street and the driveway to the Central Lab and ending at 0.300 miles for at total of seven tests for each date. A summary table is also provided showing the IFI(*Sp,F60*) parameters for each date and mileage. It is interesting to note that the calibrated friction value at 60 km/h (*F60*) was repeatable from mileage 0.100 to 0.250 during the three tests performed during 2008. The pavement texture is more homogeneous starting at about 0.100 miles from the intersection because less turning traction wear exists as traffic completes the turn onto West Street.

During the 2008 tests, *F60* ranged between 0.325 and 0.337 at mileage 0.100, between 0.336 and 0.343 at mileage 0.150, between 0.334 and 0.337 at mileage 0.200, and between 0.348 and 0.360 at mileage 0.250. This demonstrates that *F60* measured with ConnDOT's Dynatest 1295 Pavement Friction Tester is repeatable.

TABLE 22 IFI Parameters Measured in Front of ConnDOT Central Lab, Starting at Lab Driveway Heading WB, SuperPave 12.5 mm September 17, 2007

Mileage	Ave MPD	Ave MPD	Ave FN	Ave Speed	Ave Speed	S_p	FRS	A	B	C	FR60	F60
	(in)	(mm)		(mph)	(km/h)	(km/h)						
0.000	0.021	0.53	35.7	39.5	63.6	62.0	0.357	-0.023	0.607	0.098	0.378	0.259
0.050	0.019	0.49	36.6	40.2	64.7	57.9	0.366	-0.023	0.607	0.098	0.397	0.266
0.100	0.021	0.53	40.1	40.5	65.2	62.0	0.401	-0.023	0.607	0.098	0.436	0.294
0.150	0.021	0.54	41.2	41.1	66.1	62.5	0.412	-0.023	0.607	0.098	0.455	0.306
0.200	0.018	0.46	40.5	40.6	65.3	55.6	0.405	-0.023	0.607	0.098	0.446	0.293
0.250	0.020	0.50	43.9	40.0	64.4	59.3	0.439	-0.023	0.607	0.098	0.473	0.313
0.300	0.025	0.64	45.7	39.5	63.6	71.2	0.457	-0.023	0.607	0.098	0.481	0.331

TABLE 23 IFI Parameters Measured in Front of ConnDOT Central Lab, Starting at Lab Driveway Heading WB, SuperPave 12.5 mm June 4, 2008

Mileage	Ave MPD	Ave MPD	Ave FN	Ave Speed	Ave Speed	S_p	FRS	A	B	C	FR60	F60
	(in)	(mm)		(mph)	(km/h)	(km/h)						
0.000	0.025	0.63	42.7	33.3	53.6	70.7	0.427	-0.023	0.607	0.098	0.390	0.275
0.050	0.025	0.64	44.6	36.2	58.3	71.2	0.446	-0.023	0.607	0.098	0.435	0.303
0.100	0.025	0.63	46.1	38.3	61.6	70.7	0.461	-0.023	0.607	0.098	0.472	0.325
0.150	0.024	0.62	46.9	39.3	63.2	69.8	0.469	-0.023	0.607	0.098	0.491	0.336
0.200	0.023	0.58	46.1	40.3	64.9	66.1	0.461	-0.023	0.607	0.098	0.496	0.335
0.250	0.028	0.71	47.9	41.0	66.0	77.5	0.479	-0.023	0.607	0.098	0.517	0.360
0.300	0.035	0.88	47.6	40.6	65.3	93.0	0.476	-0.023	0.607	0.098	0.504	0.369
0.350	0.030	0.75	49.7	39.4	63.4	81.6	0.497	-0.023	0.607	0.098	0.518	0.365

TABLE 24 IFI Parameters Measured in Front of ConnDOT Central Lab, Starting at Lab Driveway Heading WB, SuperPave 12.5 mm July 2, 2008

Mileage	Ave MPD	Ave MPD	Ave FN	Ave Speed	Ave Speed	S_p	FRS	A	B	C	FR60	F60
	(in)	(mm)		(mph)	(km/h)	(km/h)						
0.000	0.025	0.63	50.1	38.2	61.5	70.6	0.501	-0.023	0.607	0.098	0.512	0.349
0.050	0.025	0.64	47.6	40.1	64.5	71.6	0.476	-0.023	0.607	0.098	0.507	0.348
0.100	0.024	0.61	44.8	41.5	66.8	68.9	0.448	-0.023	0.607	0.098	0.494	0.337
0.150	0.024	0.61	46.3	41.0	66.0	68.9	0.463	-0.023	0.607	0.098	0.505	0.343
0.200	0.023	0.58	45.3	41.3	66.5	66.6	0.453	-0.023	0.607	0.098	0.499	0.337
0.250	0.024	0.60	46.5	41.6	66.9	68.0	0.465	-0.023	0.607	0.098	0.515	0.348
0.300	0.029	0.74	48.1	41.3	66.5	80.3	0.481	-0.023	0.607	0.098	0.521	0.366

TABLE 25 IFI Parameters Measured in Front of ConnDOT Central Lab, Starting at Lab Driveway Heading WB, SuperPave 12.5 mm October 14, 2008

Mileage	Ave MPD	Ave MPD	Ave FN	Ave Speed	Ave Speed	S_p	FRS	A	B	C	FR60	F60
	(in)	(mm)		(mph)	(km/h)	(km/h)						
0.000	0.023		43.4	37.2	59.9	66.0	0.434	-0.023	0.607	0.098	0.433	0.297
0.050	0.022		44.7	36.7	59.1	64.3	0.447	-0.023	0.607	0.098	0.441	0.299
0.100	0.021		46.2	39.5	63.6	60.9	0.462	-0.023	0.607	0.098	0.490	0.325
0.150	0.022		48.8	38.5	62.0	63.9	0.488	-0.023	0.607	0.098	0.503	0.337
0.200	0.021		46.0	40.6	65.3	62.0	0.460	-0.023	0.607	0.098	0.501	0.334
0.250	0.025		48.1	40.3	64.9	70.7	0.481	-0.023	0.607	0.098	0.515	0.351
0.300	0.034		46.9	40.3	64.9	92.0	0.469	-0.023	0.607	0.098	0.494	0.362

TABLE 26 International Friction Index Summary in Front of ConnDOT Central Lab, Starting at Lab Driveway Heading WB Superpave 12.5 mm

	S_p					F60				
Mileage	9/17/2007	6/4/2008	7/2/2008	10/14/2008	Average	9/17/2007	6/4/2008	7/2/2008	10/14/2008	Average
0.000	62.0	70.7	70.6	66.0	67.3	0.259	0.275	0.349	0.297	0.295
0.050	57.9	71.2	71.6	66.0	66.7	0.266	0.303	0.348	0.299	0.304
0.100	62.0	70.7	68.9	60.9	65.6	0.294	0.325	0.337	0.325	0.320
0.150	62.5	69.8	68.9	63.9	66.3	0.306	0.336	0.343	0.337	0.330
0.200	55.6	66.1	66.6	62.0	62.6	0.293	0.335	0.337	0.334	0.325
0.250	59.3	77.5	68.0	70.7	68.9	0.313	0.360	0.348	0.351	0.343
0.300	71.2	93.0	80.3	92.0	84.1	0.331	0.369	0.366	0.362	0.357

Next, the repeatability of the IFI parameters were examined for tests performed on the same day and pavement, but at different speeds (30 and 50 mph) and with different tires (ribbed and smooth). This was done on I-84 WB in Vernon from 75.743 to 75.092 miles on November 28, 2007. Descriptive statistics are provided below in Tables 26 and 27.

Recall that the intent of the IFI is to harmonize tests performed at different speeds, tires, and equipment. In this scenario, different speeds and tires were used. Based upon the descriptive statistics shown below in Tables 26 and 27, it appears the IFI failed to accomplish this harmonization, as the mean S_p and *F60* values were different for each speed and test tire. Note again that these were calculated using the calibration constants (*A,B, and C*) from ASTM E 1960-98, as opposed to determining them from a linear regression of the values of *F60* calculated with DFTester measurements.

TABLE 27 Descriptive Statistics for IFI Parameters Calculated for Tests Performed at or near 50 mph

Wheel		N	Minimum	Maximum	Mean	Std. Deviation
Smooth Tire	FN	18	54.9	63.4	58.7	2.3
	MPD	18	.012	.019	.015	.002
	Speed	18	48.2	50.5	49.5	.6
	S_p	18	41.5	57.5	49.0	4.9
	F60	18	.770	.968	.861	.050
Ribbed Tire	FN	18	51.0	57.4	54.4	1.8
	MPD	18	.013	.024	.018	.003
	Speed	18	48.5	51.9	50.1	.8
	S_p	18	43.8	68.9	54.7	6.7
	F60	18	.469	.552	.505	.020

TABLE 28 Descriptive Statistics for IFI Parameters Calculated for Tests Performed at or near 30 mph

Wheel		N	Minimum	Maximum	Mean	Std. Deviation
Smooth Tire	FN	18	59.7	71.1	65.9	2.8
	MPD	18	.009	.016	.013	.002
	Speed	18	29.0	31.5	30.2	.7
	S_p	18	34.7	50.7	43.1	5.0
	F60	18	.468	.563	.511	.022
Ribbed Tire	FN	18	63.4	69.1	66.4	1.8
	MPD	18	.011	.016	.013	.001
	Speed	18	29.7	31.6	30.4	.5
	S_p	18	39.3	50.7	44.3	2.8
	F60	18	.308	.356	.323	.012

In a 2008 TRB Paper that included a preliminary evaluation of the IFI, Trifirò et al *(16)* indicated that the calibration constants from equation (5) above from the 1998 specification may need to be adjusted for particular devices considered (such as ConnDOT's pavement friction tester) before implementing the IFI by an agency (such as ConnDOT). Perhaps this is why the 1998 specification was revised in 2007 to require that a linear regression be performed to determine the calibration constants in equation (3) above, and to replace equation (5) with equation (3). Note that the calibration constant *C* from equation (5) was dropped in the 2007 specification, likely owing to the fact that *C* was so small that it was determined to be negligible. Nevertheless, because ConnDOT does not own a DFTester at this time, equation (5) was used in lieu of equation (3) as an exercise in calculating the IFI of pavement surfaces. Future research should be conducted in Connecticut to include the use of either a borrowed or purchased DFTester to determine DFT_{20} and use equation (3) above contained in ASTM E 1960-07.

CONCLUSIONS

Speed Gradients for Pavement Friction Testing

The results of this study, as well as the literature reviewed *(15)*, suggest that blindly using a ribbed-tire correction factor of -0.5 for calculating a friction number based on a corrected speed of 40 mph may result in non-conservative FN_{40R} values. Densely-graded pavements with low MPDs (smooth texture) are of particular concern because they tend to have steeper speed gradients. Case in point, the average speed gradient calculated for the No. 4 mix in this study was -0.68.

Pavement Texture

Another objective was to research relationships between texture and friction; however, as a first step before developing a relationship between texture and friction, pavement texture was characterized for the different pavement surfaces in Connecticut. This was addressed in Report No. CT-2243-2-10-3 published as part of this study.

The most significant relationship between texture and friction found during this research was that densely-graded pavements having lower MPDs (smoother texture) tended to have steeper speed gradients. Therefore, measured friction numbers were more sensitive to speed. This behavior is analogous to how smooth tires are more sensitive to speed than ribbed tires, as documented by de León Izeppi et al

(15). This likely owes to water having an escape route for more open-textured (higher MPDs) pavements at higher speeds, whereas water does not have an escape route for densely-textured (lower MPDs) pavements. Higher speeds tend to compound this phenomenon.

The entire report will not be duplicated here, but the conclusions from CT-2243-2-10-3 are listed below once again in this, the final report published for this research.

- Scatter plots showing the relationship between mean profile depth (MPD) values measured with the high-speed laser instrument mounted to the friction tester versus values measured with the CTMeter were analyzed. The linear association between these variables was relatively strong, as coefficients of determination (R^2 coefficients) of 0.65 and 0.87 were calculated for the VA Smart Road and CT SPS 9A sites, respectively. As such, the high-speed laser instrument appears to provide viable relative macrotexture measurements.
- In response to a FHWA Technical Advisory titled *Surface Texture for Asphalt and Concrete Pavements*, ConnDOT has begun to establish targets for pavement texture depth on high-speed facilities by characterizing the macrotexture of a few different ConnDOT HMA pavement mixes. The mean profile depth or MPD appears to be the best measure for characterizing pavement macrotexture, since it can be measured using either the high-speed laser instrument or CTMeter.
- The characterizing MPDs measured for ConnDOT mixes ranged between .021 and .022 inches (0.53 to 0.56 mm) for the 12.5-mm Superpave design, .015 inches (0.38 mm) for 9.5-mm Superpave design, .012 to .015 inches (0.30 to 0.38 mm) for the 6.35-mm Superpave design, and 0 to .004 inches (0 to 10 mm) for the 4.75-mm design. These characterizing values are still preliminary and more research is needed to determine the best application(s) for each pavement design.
- There was a linear association between measured MPD values and the percents passing the #4 and #8 sieves for a respective pavement’s grain-size distribution. MPD values tended to increase as mixes became coarser.
- Laser profiler macrotexture measurements were repeatable from one day to the next. 399 macrotexture measurements were taken on the same 9.5-mm Superpave mix on I-91 NB in Connecticut, and the mean MPD for these measurements was .015 inches (0.38 mm) on both days. The standard

deviation was also identical on both days (+/- .0027 inches or 0.069 mm).

- The ConnDOT CTMeter compared almost identically to the Virginia Tech CTMeter at the Smart Road facility in Blacksburg, VA during an equipment Rodeo.

International Friction Index (IFI)

The intent of the IFI is to harmonize tests performed at different speeds, tires, and equipment. As part of this research, IFI parameters were calculated using the calibration constants (*A,B, and C*) from tables contained in ASTM E 1960-98. The results of his research suggest that the IFI calculated using the above calibration constants was not effective in harmonizing tests performed at different speeds and tires. The latest ASTM E 1960 (2007) specification requires that these constants be determined from a linear regression of the values of *F60* calculated with DFTester measurements, as opposed to using values from tables. Note: ConnDOT does not currently own a DFTester.

Effect of Roadway Geometry on Friction Measurements

A short study of the effects of horizontal and vertical alignment on friction measurements was performed. The testing along horizontal curves was performed at the Consumer Union Test Track in Colchester, CT. The testing along vertical curves was performed on Route 66 in Marlborough, CT.

Friction tests were performed along horizontal curves of 24 and 28 degrees, and were compared to tests performed along straight tangents of the same pavement. The average FN_{40R} values increased slightly for sharper degrees of curvature, but valid statistical conclusions can not be drawn without more data. In general, the ranges within which tangent and nontangent FN_{40R} values occurred were similar.

In order to obtain more data, more testing of this nature would need to be performed. The testing that was performed was carried out at the Consumer Union Test Track. Unfortunately, ConnDOT does not own a track, so special arrangements would be required for additional testing. Therefore, it is concluded that continued research of this nature would be better suited for organizations that own or have regular access to a test track.

This research was successful at demonstrated that comparable results are obtainable, even when the friction tester is pushed to its limits along sharp horizontal curves. Note that these tests were performed along these curves without any superelevation. The banking capabilities provided by superelevated pavement would further enhance the friction tester's ability to perform valid tests.

Literature related to tangent versus nontangent sections was reviewed *(14)*. Zimmer and Tonda indicated that friction test results were similar between tangent and nontangent sections, but they suggested limiting the horizontal g-force on the skid trailer to 0.3 g's. They also suggested performing tests along horizontal curves during dry pavement conditions, because virtually all of the traction forces are transferred to the non-test wheel during testing. Dry conditions along the non-test wheel will therefore provide greater side-force traction to maintain the skid trailer on the roadway without sliding.

The testing that was performed on positive versus negative grades also demonstrated that similar results between these vertical grades are obtainable.

RECOMMENDATIONS

Speed Gradients for Pavement Friction Testing

It is recommended that for instances where friction testing cannot be performed at 40 mph, FN_{40R} and FN_{40S} be calculated using the following formulas:

$$FN_{40R} = FN + (\text{speed gradient})*(40\text{-speed})$$
or
$$FN_{40S} = FN + (\text{speed gradient})*(40\text{-speed})$$

These speed gradients should be determined on a case-by-case basis in accordance with ASTM E 274 Section 7.6. For sharp horizontal curves, the speed gradient of adjacent pavement of the same mix and construction should be tested to determine the gradient.

For situations where individual speed gradients cannot be determined, it is recommended that a FN_{40R} envelope be determined using speed gradient values between -0.3 and -0.7. This would provide more conservative FN_{40R} values, and avoid the use of non-conservative values. Special attention should be given to dense-graded pavement surfaces, as these pavements are more sensitive to test speed.

Pavement Texture

The following recommendations from Report No CT-2243-2-10-3 are presented below *(3)*:

- Mean profile depths (MPDs) measured with the high-speed laser instrument are adequate for providing relative values for characterizing pavement macrotexture on typical HMA pavements used in Connecticut. These typical pavements include but are not limited to 12.5-mm, 9.5-mm, 6.35-mm, and 4.75-mm HMA mixes. Care should be taken in exercising these measurements for other pavements. To that end, it is recommended that further comparative testing be performed between the high-speed laser instrument and other proven instruments, such as the CTMeter, prior to exercising high-speed laser measurements for uncommon pavements. Uncommon pavements in Connecticut include but are not limited to portland cement concrete (PCC) pavements, open-graded friction courses, and other surface treatments.
- Until demonstrated otherwise, the #4 mix (4.75-mm) should not be used to pave high-speed (50-mph or greater) facilities because it does not appear to have adequate texture depth in comparison to the other mixes evaluated. This mix should be used only on low-speed facilities that require very thin pavement lifts, but an evaluation of the site geometrics, traffic levels, and vehicle speeds should be conducted before selecting this mix.
- Until demonstrated otherwise, ConnDOT should continue to use the 12.5-mm Superpave mix for high-speed facilities because it appears to provide the most texture depth of the pavements evaluated.
- The 6.35-mm and 9.5-mm Superpave mixes had grain-size distributions that were similar to one another, and each provided approximately the same level of surface texture. These mixes appear to provide marginal levels of surface texture for high-speed roadways in comparison to the 12.5-mm Superpave mix evaluated in this study. These mixes should provide an adequate level of surface texture for low-speed roadways, although an evaluation of the site geometrics, traffic levels, and vehicle speeds should be conducted before selecting these mixes. Continued use for high-speed roadways for special applications should be monitored by performing periodic friction (smooth and ribbed tire) and texture measurements.

International Friction Index (IFI)

At this time, the IFI is not recommended for implementation. Further research should be conducted to evaluate the IFI in conjunction with the latest update to ASTM E 1960-07 which includes DFTester measurements for calibration constant determinations. Accordingly, a DFTester should be purchased.

Roadway Geometry

An accelerometer should be purchased and mounted to the skid trailer to measure the horizontal g-forces that occur during testing along nontangent sections.

Smooth- and Ribbed-Tires for Friction Testing

Based upon the literature reviewed, it is recommended that both the ASTM E501 Standard Rib Tire and ASTM E524 Standard Smooth Tire be used for pavement friction testing performed in response to requests received for safety evaluation purposes. Tentative guidelines for evaluating friction at high wet accident sites are provided in Appendix A.

DELIVERABLES

Deliverables for this project include the following products:

- Upgraded pavement friction tester
- CTMeter
- Quarterly progress reports
- ConnDOT Report No. CT-2243-1-10-1 titled "Historical Overview of Friction Testing in Connecticut"
- ConnDOT Report No. CT-2243-2-10-3 titled "Characterizing the Macrotexture of Asphalt Pavement Designs in Connecticut"
- This Final Report No. CT-2243-F-10-4
- Meet the Author Poster Session presented at the 89th TRB Annual Meeting in Washington, D.C. in Session Number 580, "Traveled Surface Texture, Friction, Noise, and Profile."
- A trading card for the overall project, and for CT-2243-1-10-1, which was presented in Washington, D.C. in a poster session.
- ConnDOT Video on Demand: *About ConnDOT's Pavement Friction Testing and Safety Evaluation Program*, http://www.ct.gov/dot/cwp/view.asp?a=1617&q=273484#b10, presented on March 27, 2008.
- ConnDOT Video on Demand: *Pavement Surface Properties Consortium: A Collaborative Research Program*,

http://www.ct.gov/dot/cwp/view.asp?a=1617&q=448232, recorded on September 24, 2009.

IMPLEMENTATION

Another objective of this research was to implement the appropriate latest technology and procedures for pavement friction data request, collection, and processing.

As part of the effort to implement the latest technology for pavement friction data requests, a draft web page was developed by a Summer Worker during the summer of 2008. The web page included links to "fillable" pdf's and to historical friction testing memorandum. The "fillable" pdf's would be used by any ConnDOT unit to request pavement friction tests.

The Summer Worker has since moved on, but the web page draft still exists and is available. A copy of the web page is presented in Appendix B.

In this report, recommendations were made regarding speed gradients and their application, use of smooth and ribbed tires, pavement texture, and literature was reviewed regarding intervention levels. In the context of implementing findings, draft friction testing procedures and a draft policy statement are presented in Appendices C and D, respectively, which address the above recommendations.

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APPENDIX A

Below are tentative guidelines for evaluating friction at high wet weather accident sites. These are largely influenced by Hall et al. (11) guidelines, but are customized in consideration of other literature reviewed *(8,17)* and existing ConnDOT procedures.

TABLE A-1 Tentative Guidelines for Evaluating Friction at High Wet Accident Sites in Connecticut

	Friction Number Range	Tentative Guidelines
1.	FN40R < 30 or FN40S < 15	The results of friction testing indicate that a less than desirable level of skid resistance exists. Corrective action may be warranted. An evaluation of site geometrics, pavement condition, traffic levels, and vehicle speeds should be conducted.
2.	[FN40R ≥ 30 and 15 ≤ FN40S ≤ 25] or [30 ≤ FN40R ≤ 37 and FNS > 15]	The results of friction testing indicate that marginal skid resistance exists. An evaluation of the site geometrics, pavement condition, traffic levels, and vehicle speeds should be conducted to determine if corrective action is warranted.
3.	FN40R > 37 and FN40S > 25	The results of friction testing indicate that an acceptable level of skid resistance exists…

APPENDIX B

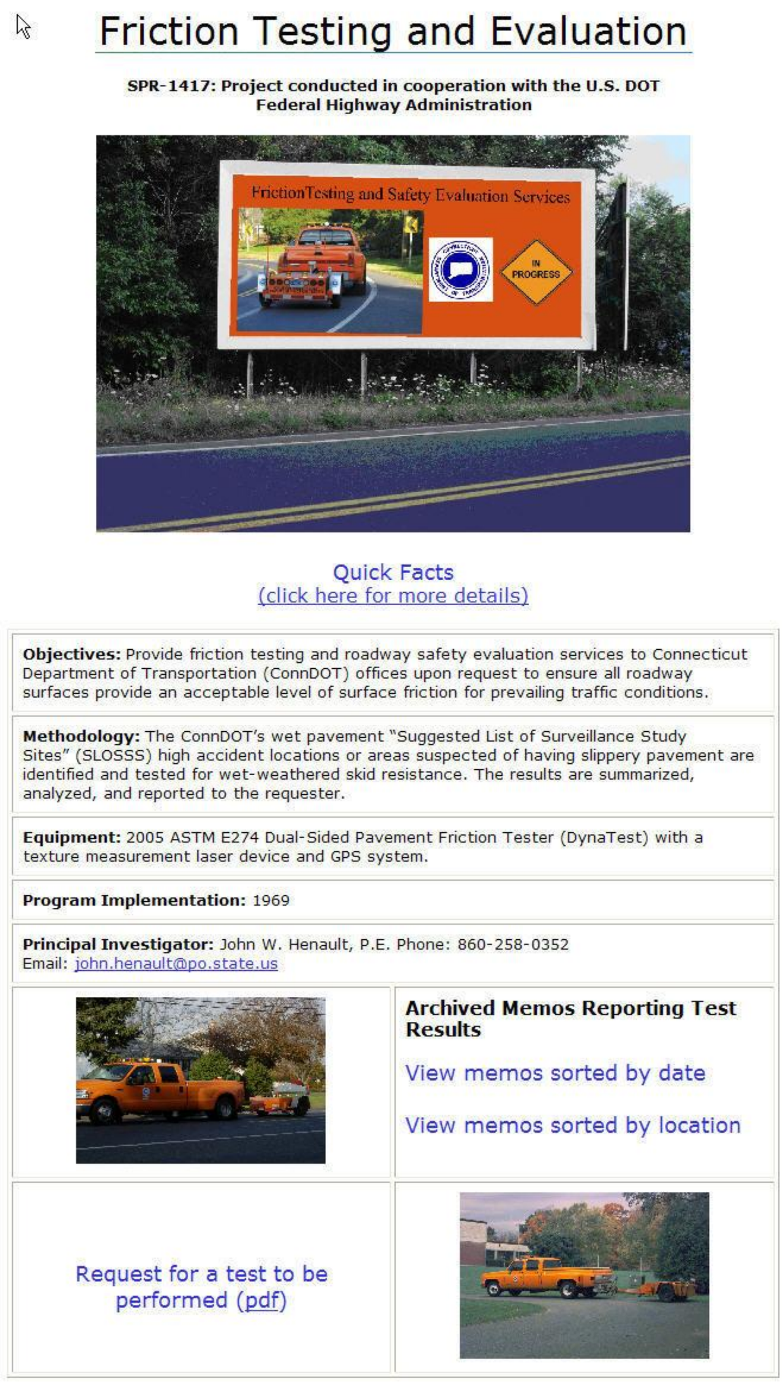

FIGURE B-1 Web page developed by Summer Worker.

APPENDIX C

Procedure for Handling Friction Test Requests

1. Receive request with map or sketch attached. Call requester if map is not attached, and have one sent.

2. Look up site on DigitalHiway (photolog), and check for the following:
   - Posted speed
   - Intersection control (stop sign, signal, or other)
   - Severity of curves
   - Other features that would prohibit testing at 30 mph

3. If location cannot be tested at 30 mph:
   - Arrange for local police protection, if this will allow test to be performed safely, OR
   - Notify requestor if location cannot be safely tested

4. Perform friction tests
   - Note posted advisory and legal speeds
   - Note unusual features not observed from photolog; particularly anything that could be contributing to a high accident rate.
   - Obtain minimum of five friction tests per direction in order to calculate a valid average

5. Analyze skid data in the office:
   - Transfer data from tester’s laptop PC to desktop PC
   - Select section of interest; obtainprintout containing speed corrected data;
   - Summarize appropriately in response to request; treat severe curves or intersection separately from overall section.
   - Note and consider physical features such as hills, curves, traffic conflicts, turning maneuvers, etc, in the analysis when determining need for remedial action.
   - In most cases the response should include one of the following statements:
     a. The results of friction testing indicate that an acceptable level of skid resistance exists…
     b. The results of friction testing indicate that marginal skid resistance exists. An evaluation of the site geometrics, pavement condition,

traffic levels, and vehicle speeds should be conducted to determine if corrective action is warranted.

c. The results of friction testing indicate that a less than desirable level of skid resistance exists. Corrective action may be warranted. An evaluation of site geometrics, pavement condition, traffic levels, and vehicle speeds should be conducted.

6. Prepare memo and send results to requesting party. Copies of the memo shall be forwarded to Transportation Maintenance, Maintenance Operations, Maintenance Planning, Traffic Engineering, and Pavement Management.

APPENDIX D

POLICY STATEMENT DRAFT

SUBJECT: Policy on Friction Testing and Safety Evaluation Services

The Office Research and Materials shall provide friction testing and safety evaluation services for the Department, upon request, to ensure roadway surfaces provide an acceptable level of surface friction for prevailing traffic conditions.

Any area detected either during routine maintenance surveys or through accident experience, shall be referred via a memorandum to the Office of Research and Materials for field friction tests. The termini of the area to be tested shall be defined and shown on a map of the area in question that shall be attached to the request memorandum.

Research personnel shall schedule, complete and forward the results of friction tests on the questioned area to the requesting party. Copies of all correspondence shall be forwarded to Bureau of Highway Operations, Traffic Engineering, and Pavement Management personnel for review.

It is imperative that, if an area is found to be potentially hazardous because of low skid resistance, corrective action be initiated at the earliest possible time. To insure proper follow-up, the requesting unit shall prepare a memorandum stating its action after receiving testing results. Highway Operations personnel shall make a field inspection of the area in question and report the corrective action, with copies to the Transportation Division Chief – Research and Materials, and the Manager of Traffic Engineering.