Minnesota Department of Transportation

RESEARCH SERVICES

Office of Policy Analysis, Research & Innovation

Rolling Resistance Measurements at the MnROAD Facility

W. James Wilde, Principal Investigator
Center for Transportation Research and Implementation
Minnesota State University, Mankato

MnROAD
Office of Materials

March 2012

Research Project
Interim Report 2012-07

Your Destination...Our Priority

To request this document in an alternative format, call Bruce Lattu at 651-366-4718 or 1-800-657-3774 (Greater Minnesota); 711 or 1-800-627-3529 (Minnesota Relay). You may also send an e-mail to bruce.lattu@state.mn.us. (Please request at least one week in advance).

Technical Report Documentation Page

1. Report No.	2.	3. Recipients Accession No.
MN/RC 2012-07		

4. Title and Subtitle	5. Report Date
Rolling Resistance Measurements at the MnROAD Facility	March 2012
	6.
7. Author(s) Jerzy A. Ejsmont, Grzegorz Ronowski and W. James Wilde	8. Performing Organization Report No.
9. Performing Organization Name and Address Center for Transportation Research and Implementation Minnesota State University, Mankato 342 Trafton Science Center N. Mankato, MN 56001	10. Project/Task/Work Unit No. 11. Contract (C) or Grant (G) No. (c) 93028
12. Sponsoring Organization Name and Address Minnesota Department of Transportation Research Services Section 395 John Ireland Blvd., MS 330 St. Paul, MN 55155	13. Type of Report and Period Covered Interim Report 14. Sponsoring Agency Code

15. Supplementary Notes
http://www.lrrb.org/pdf/201207.pdf

16. Abstract (Limit: 250 words)

The Minnesota Department of Transportation and Minnesota State University, Mankato, contracted with the Technical University of Gdańsk, in Poland, to conduct rolling resistance at the MnROAD facility near Albertville, Minnesota. While the rolling resistance testing was conducted on all cells of the MnROAD mainline, the primary objective relative to this project was to obtain the rolling resistance data for Cells 7, 8, and 9 – the Portland cement concrete pavement cells with conventional and two innovative diamond grinding applications.

The research team from Poland conducted the testing for a week in the middle of September, 2011. All cells on the MnROAD mainline were tested, as well as one off-site location (US 212 near Shakopee, Minnesota). The collected rolling resistance data were analyzed and are presented in this report. Additional analyses that were conducted include a comparison of the rolling resistance data to surface texture, friction, and noise. Some of the comparisons are not consistent with those measured on other pavement surfaces (in Europe), but the authors present some possible reasons for the differences.

17. Document Analysis/Descriptors	18. Availability Statement
Materials by surface characteristics, Diamond grinding, Rolling resistance, Tire/pavement noise, Texture, Pavement friction, Friction, Ride quality, Pavements	No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312

19. Security Class (this report)	20. Security Class (this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	60	

Rolling Resistance Measurements at the MnROAD Facility

Interim Report

Prepared by:

Jerzy A. Ejsmont
Grzegorz Ronowski

Technical University of Gdańsk, Poland

W. James Wilde

Center for Transportation Research and Implementation
Minnesota State University, Mankato

March 2012

Published by:

Minnesota Department of Transportation
Research Services Section
395 John Ireland Boulevard, MS 330
St. Paul, Minnesota 55155-1899

ACKNOWLEDGEMENTS

This report is the result of a joint effort between researchers at the Technical University of Gdańsk, Poland, Minnesota State University – Mankato, the Minnesota Department of Transportation and a pooled fund study consisting of the states of Minnesota and Texas, and the Federal Highway Administration. The authors wish to express gratitude to Dr. Bernard Izevbekhai of MnDOT for initiating and arranging the testing in Minnesota, and to Mr. Steve Olson of MnDOT's MnROAD facility for driving the rolling resistance equipment and making all necessary arrangements.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

The Minnesota Department of Transportation and Minnesota State University, Mankato, contracted with the Technical University of Gdańsk, in Poland, to conduct rolling resistance at the MnROAD facility near Albertville, Minnesota. While the rolling resistance testing was conducted on all cells of the MnROAD mainline, the primary objective relative to this project was to obtain the rolling resistance data for Cells 7, 8, and 9 – the Portland cement concrete pavement cells with conventional and two innovative diamond grinding applications.

The research team from Poland conducted the testing for a week in the middle of September, 2011. All cells on the MnROAD mainline were tested, as well as one off-site location (US 212 near Shakopee, Minnesota). The collected rolling resistance data were analyzed and are presented in this report. Additional analyses that were conducted include a comparison of the rolling resistance data to surface texture, friction, and noise. Some of the comparisons are not consistent with those measured on other pavement surfaces (in Europe), but the authors present some possible reasons for the differences.

CHAPTER 1. INTRODUCTION

The Minnesota Department of Transportation (MnDOT) constructed the Minnesota Road Research Project (MnROAD) between 1990 and 1994. MnROAD is located along Interstate 94, 40 miles northwest of the Minneapolis / St. Paul metropolitan area, and is an extensive pavement research facility consisting of two separate roadway segments containing 51 distinct test cells. Each MnROAD test cell is approximately 500 feet long. Subgrade, aggregate base, and surface materials, as well as roadbed structure and drainage methods vary from cell to cell.

The objective of this report is to present the results of rolling resistance testing conducted by researchers at the Technical University of Gdańsk, Poland (TUG) in September 2011. While the rolling resistance (RR) testing was conducted on all of the cells on the MnROAD mainline, the primary focus of the current research project is the innovative diamond grinding on Cells 7, 8, and 9. This report, however, presents the results of RR testing on all of the mainline cells.

The TUG research team developed and tested the rolling resistance device, shown in Figure 1-1, to isolate the resistance to forward motion of a vehicle due to the rolling resistance, or the interaction between the tire and the pavement surface. The TUG research team was retained by the Minnesota Department of Transportation, through Minnesota State University, Mankato, to ship the RR trailer to the United States and to conduct the testing at the MnROAD facility.

Figure 1-1. Rolling resistance test trailer.

The test cells that are the primary focus of this research project are Cells 7, 8, and 9, where diamond grinding was conducted as a surface treatment in 2007 (Cells 7 and 8) and 2008 (Cell 9). Cell 8 received the standard, conventional grinding treatment, while Cells 7 and 9 received two different innovative grinding patterns (termed *Innovative Grind* and *Ultimate Grind*, respectively). The diamond grinding was used as a corrective action for defective pavement surface texture and poor ride quality. The underlying study and the grinding of these cells was described in detail in MnDOT Interim Report 2011-05 [1].

CHAPTER 2. TESTING CONDITIONS

The rolling resistance measurements consisted of various passes on the same roadway segment at different speeds and using three different passenger car tires. The different tires are presented in Figure 2-1. From left to right, these tires are labeled SRTT, AV4, and ME16. A description of each tire is given in Table 2-1.

Figure 2-1. Test tires used in the rolling resistance testing at MnROAD.

Table 2-1. Description and Characteristics of Test Tires.

	SRTT	AV4	ME16
Manufacturer	Uniroyal	Avon	Michelin
Tread	Tiger Paw	AV4	Energy Sever
Size	P225/60R16	195R14C	225/60R16
Load index	97	106/104	98
Speed index	S	N	V
Hardness [Sh]	65	62	63

During the measurements the tire load was 900 lb (4000 N) and regulated tire inflation was 30.5 psi (210 kPa). Prior to taking measurements with a different tire, each one was warmed by driving for at least 20 minutes. The measurements were taken at two different speeds: 31 mph (50 km/h) and 50 mph (80 km/h). Measurements were also conducted at selected combinations of pavement surface and tire type at two other speeds: 68 mph (110 km/h) and 81 mph (130 km/h). At speeds of 31 and 50 mph (50 and 80 km/h), at least three runs in each direction were made, while at 68 and 81 mph (110 and 130 km/h) only two runs in each direction were performed.

Road Surfaces

This section presents the characteristics of the individual road surfaces on which the rolling resistance testing was conducted. For purposes of continuity and the comprehensive nature of the testing, all pavement surfaces that were tested are included in this report. Specific data and conclusions for Cells 7, 8, and 9 (the innovative, conventional, and ultimate grind cells, respectively) will be presented in a later chapter. Table 2-2 provides the cell and subcell numbers, and the associated experiment and surface type of each cell on which the rolling resistance testing measurements were conducted. A photograph of the surface of each cell is provided in Appendix A.

Table 2-2. Summary of Road Surfaces Tested for Rolling Resistance.

Cell	SubCell	Experiment	Surface Type
2		SemMaterials FDR Study	Ultra Thin Bonded Wearing Course
3		SemMaterials FDR Study	Ultra Thin Bonded Wearing Course
4		SemMaterials FDR Study	12.5 mm Dense Graded Superpave
5	505, 605		Transverse Broom
	305, 405		Longitudinal Tine
6	306, 406		Longitudinal Tine
7		5 year design PCC - Widened lane - PASB - longer panel	Innovative Diamond Grind
8		5 year design PCC - Widened lane - PASB - Supplemental Steel	Conventional Diamond Grind
9		5 year design PCC - Widened lane - PASB	Ultimate Diamond Grind (2008)
60		Thin Bonded Concrete Overlay of HMA - 5 inch - sealed	Turf
61		Thin Bonded Concrete Overlay of HMA - 5 inch - unsealed	Turf
62		Thin Bonded Concrete Overlay of HMA - 4 inch - sealed	Turf
63		Thin Bonded Concrete Overlay of HMA - 4 inch - unsealed	Conventional Diamond Grind
96		Thin Bonded Concrete Overlay of HMA - 5 by 6 panels	Conventional Diamond Grind
70		SHRP II Composite Pavement Study - DL Doweled, PL Not Doweled	12.5 mm Dense Graded Superpave
71		SHRP II Composite Pavement Study - Diamond Grind Surface	2010 Ultimate Diamond Grind (Driving)
			Conventional Diamond Grind (Passing)
72		SHRP II Composite Pavement Study - EAC Surface	Exposed Aggregate
12		10 year design PCC - Drained base	Transverse Tine
13	513, 413, 313, 213, 113	PCC Thickness Optimization - 5 inch - Flat Plate Dowels - 12 and 15 foot panel lengths	Longitudinal Turf Drag
14	914, 814, 714, 614, 514, 414, 314, 214, 114		Longitudinal Broom Drag
15		Warm Mix Asphalt Overlay	12.5 mm Dense Graded Superpave

Table 2-2, continued. Summary of Road Surfaces Tested for Rolling Resistance.

Cell	SubCell	Experiment	Surface Type
16		Recycled Unbound Base Study, Warm Mix Asphalt Surface	12.5 mm Dense Graded Superpave
17		Recycled Unbound Base Study, Warm Mix Asphalt Surface	12.5 mm Dense Graded Superpave
18		Recycled Unbound Base Study, Warm Mix Asphalt Surface	12.5 mm Dense Graded Superpave
19		Recycled Unbound Base Study, Warm Mix Asphalt Surface	12.5 mm Dense Graded Superpave
20		Low Temperature Cracking, RAP Study	12.5 mm Dense Graded Superpave
21		Low Temperature Cracking, RAP Study	12.5 mm Dense Graded Superpave
22		Low Temperature Cracking, RAP Study	12.5 mm Dense Graded Superpave
33		Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave
34		Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave
35		Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave
36		LVR design PCC - SUBGRADE R70 subgrade - doweled	Transverse Tine
37		LVR design PCC - SUBGRADE R70 subgrade -undoweled	Conventional Diamond Grind (TS3) Innovative Diamond Grind (TS 1 and 2) 2010 Diamond Grind (TS 5) Transverse Tine (TS 4 and Inside)
38		LVR design PCC - Standard base - doweled	Transverse Tine
39		Porous Concrete Overlay Experiment	Pervious Overlay
40		LVR design PCC - 7-5.5-7 inch Trapezoidal - undoweled	Transverse Tine
24		Aging Study, WMA Control	12.5 mm Dense Graded Superpave, Fog seals each year in 100-ft sections
85		Pervious Concrete Experiment - Low Volume Road - Sand subgrade	Pervious Concrete
86		Porous HMA Study	Porous Hot Mixed Asphalt
87		Porous Pavement Study - Control Section	12.5 mm Dense Graded Superpave
88		Porous HMA Study	Porous Hot Mixed Asphalt
89		Pervious Concrete Experiment - Low Volume Road - Clay subgrade	Pervious Concrete
27		Geocomposite Capillary Barrier Drain	Chip Seals (FA-2 and FA-3)
28		Stabilized Full Depth Reclamation	Double Chip Seal
77		Fly Ash Study, Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave
78		Fly Ash Study, Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave
79		Fly Ash Study, Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave
31		2004 LVR Taconite Superpave	12.5 mm Dense Graded Superpave
32		LVR design PCC - Thin Slab	Longitudinal Turf Drag
52		5 year design PCC - Load testing - FRP dowels	Longitudinal Turf Drag
53		60- year PCC	Transverse Broom
54		PCC mix experiment - Mesabi Select aggregates	Longitudinal Turf Drag
US 212		Stone Matrix Asphalt	Stone Matrix Asphalt

CHAPTER 3. ROLLING RESISTANCE RESULTS

As previously mentioned, all rolling resistance testing was conducted during the middle of September 2011. The data were analyzed at the Technical University of Gdańsk during the months of October and November 2011. The results discussed in this report refer to the Coefficient of Rolling Resistance (CRR), which is defined as:

$$CRR = \frac{F_R}{L} \qquad \text{Equation 1}$$

where:

F_R = Rolling resistance force, and
L = Tire load.

The final CRR values for each run, in both directions, were averaged and corrected for temperature to 77°F (25 C). These data are shown in Tables B.1, B.2, and B.3 in Appendix B, for tires SRTT, AV4 and ME16, respectively.

One of the analyses conducted to assess the variability in the data included the run-to-run variations in rolling resistance measurements. These are shown in Figures 4 and 5. Figure 3-1 presents typical run-to-run variations of the CRR, measured in one direction for Cells 22 through 60. The labeled rectangle enclosures show data windows that were used for the rolling resistance evaluations for each cell, as defined by MnROAD personnel. The vertical lines extending from the bottom of the graph about halfway up simply indicate the locations of the markers triggering the data collection apparatus so that data were collected at exactly the same location on each run. It is important to note that the data windows are somewhat shorter than the cells, in order to eliminate transient data as the rolling resistance apparatus travels from one cell to the next. The heavier line in this figure is the average of the variations indicated by the thin lines. The thin lines represent the rolling resistance coefficient for each of the three runs with the ME16 tire at 50 mph (80 km/h).

Figure 3-2 presents similar information as in the previous figure – variations in the data measurements, although in this figure the differences between measurements are averaged for each direction (driving from Cell 22 towards Cell 60, and in the opposite direction). Both Figures 4 and 5 indicate that run-to-run variations are not large, but many of the cells show different rolling resistance coefficients at different locations along the travel patch.

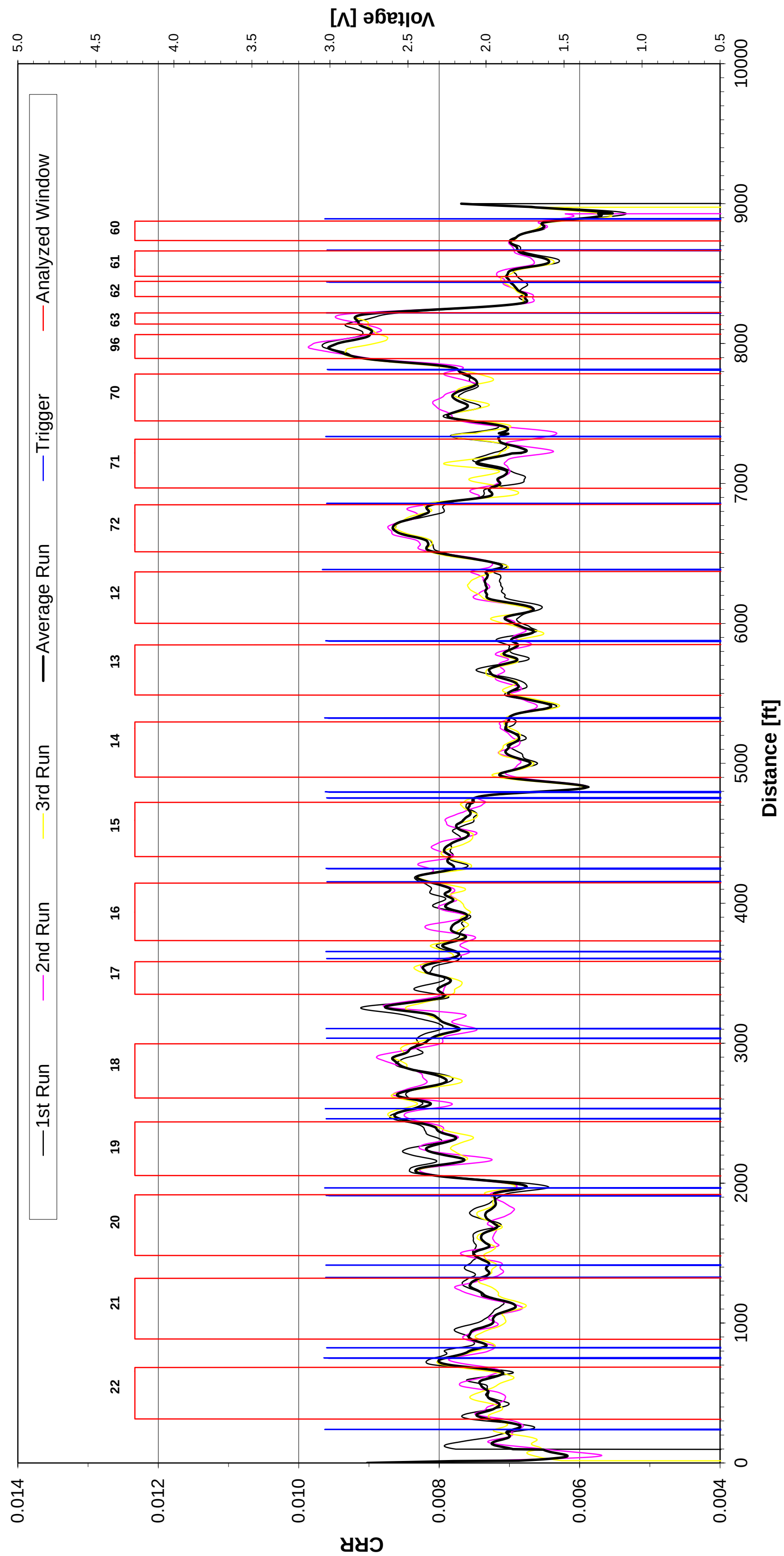


Figure 3-1. Typical run-to-run variation of CRR for tire ME16, 50 mph (80 km/h).

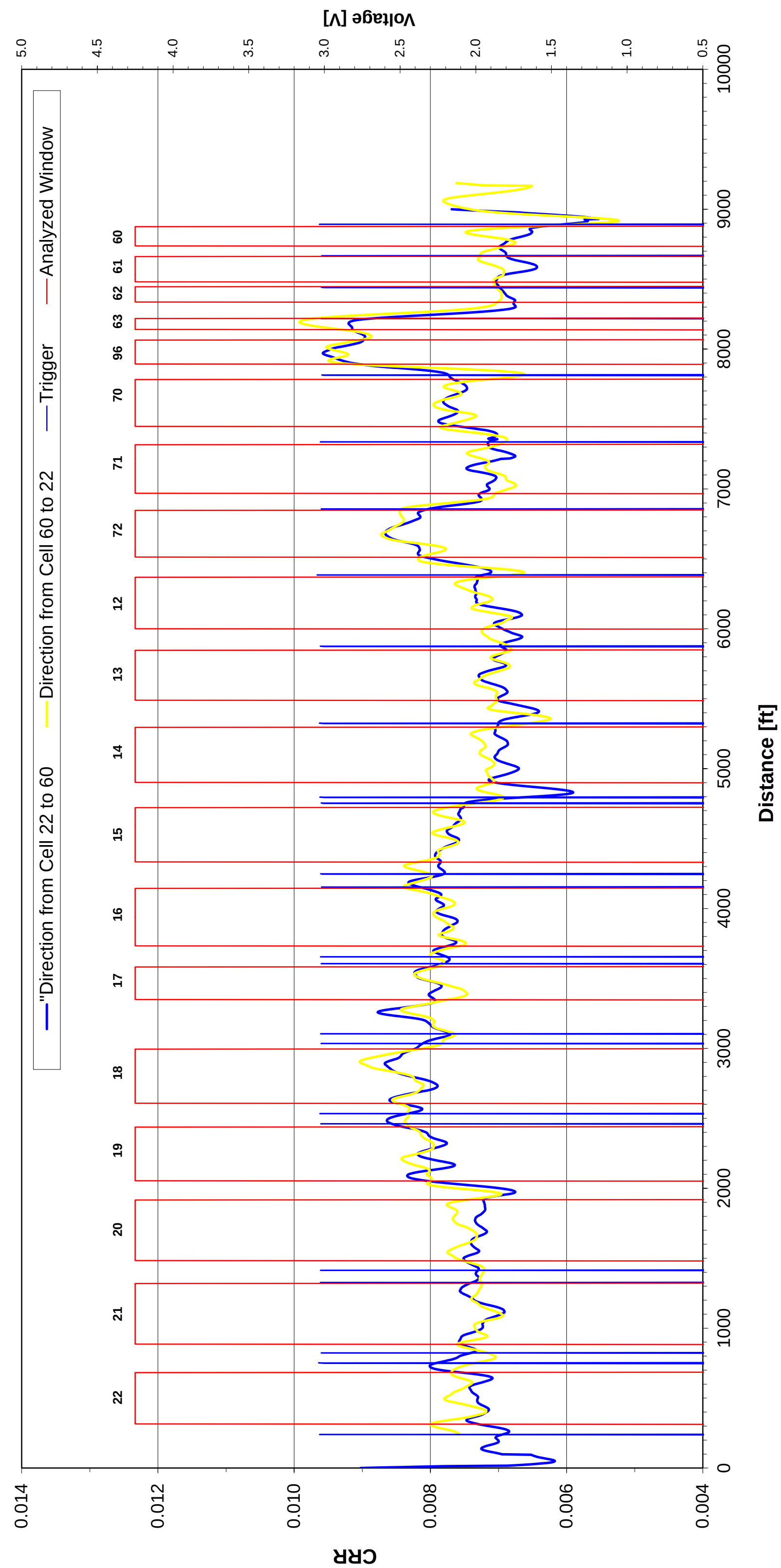


Figure 3-2. Typical run-to-run variation of CRR for tire ME16, opposing directions, 50 mph (80 km/h).

Figures 3-3, 3-4, and 3-5 show the influence of speed on the measured CRR value for the various different cells and different tires (tires SRTT, AV4, and ME16, respectively). It must be stressed, however, that the length of test cells was too short for making reliable measurements at speeds over 50 mph (80 km/h), because of transients and discontinuities at the transitions between cells. This implies that results for 68 mph (110 km/h) and especially for 81 mph (130 km/h) are not very reliable. Measurements at these speeds were not originally expected as part of the project contract and were done only for informative purposes.

The data consistently show that one cell (Cell 28) exhibits very high levels of rolling resistance coefficients. According to the information obtained from MnROAD, Cell 28 was recently constructed. It has an emulsion-stabilized full-depth reclamation layer covered by only a chip seal, and the surface texture is rather rough. More importantly, the pavement structure was very soft, exhibited by extremely high deflections measured by the falling weight deflectometer (FWD).

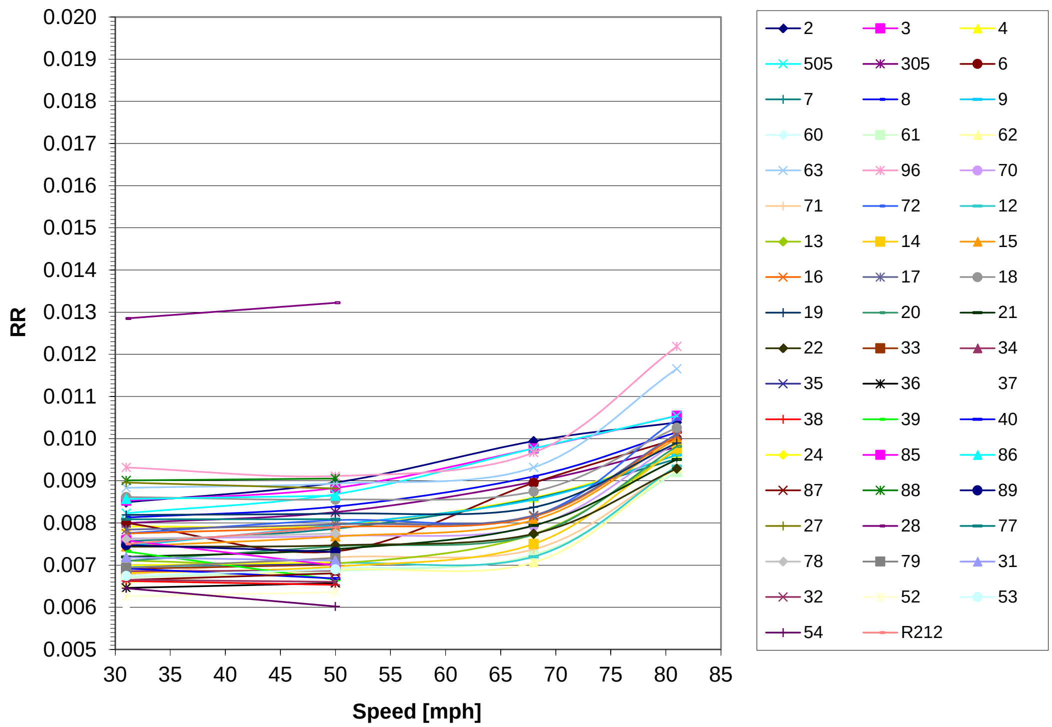


Figure 3-3. Influence of speed on rolling resistance measurements with tire SRTT.

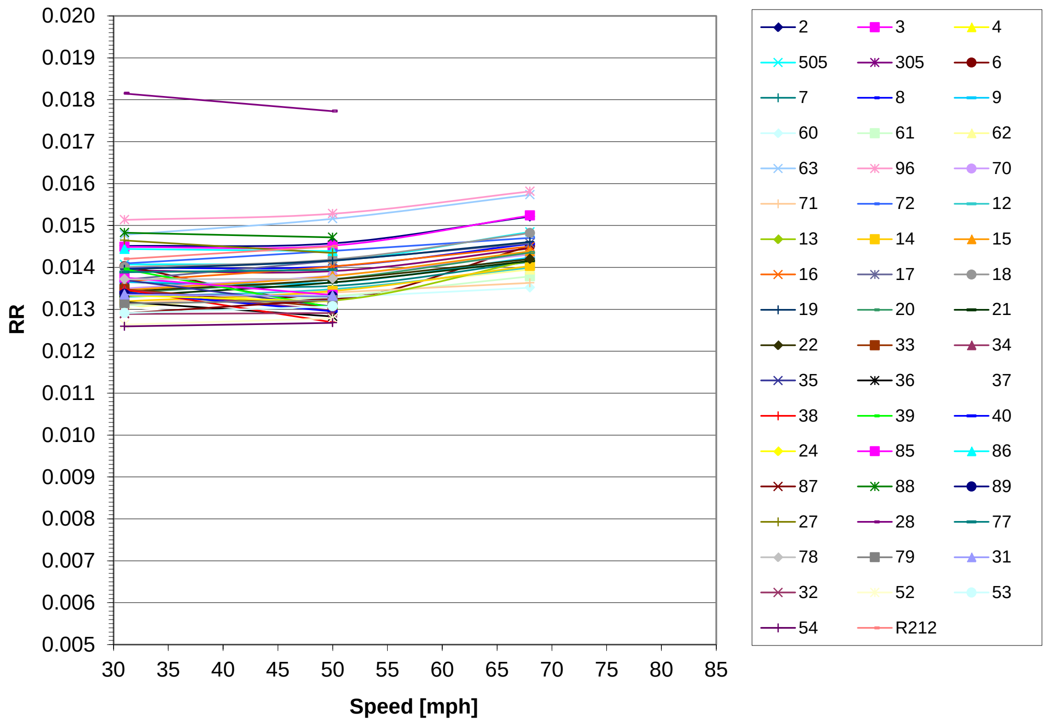


Figure 3-4. Influence of speed on rolling resistance measurements with tire AV4.

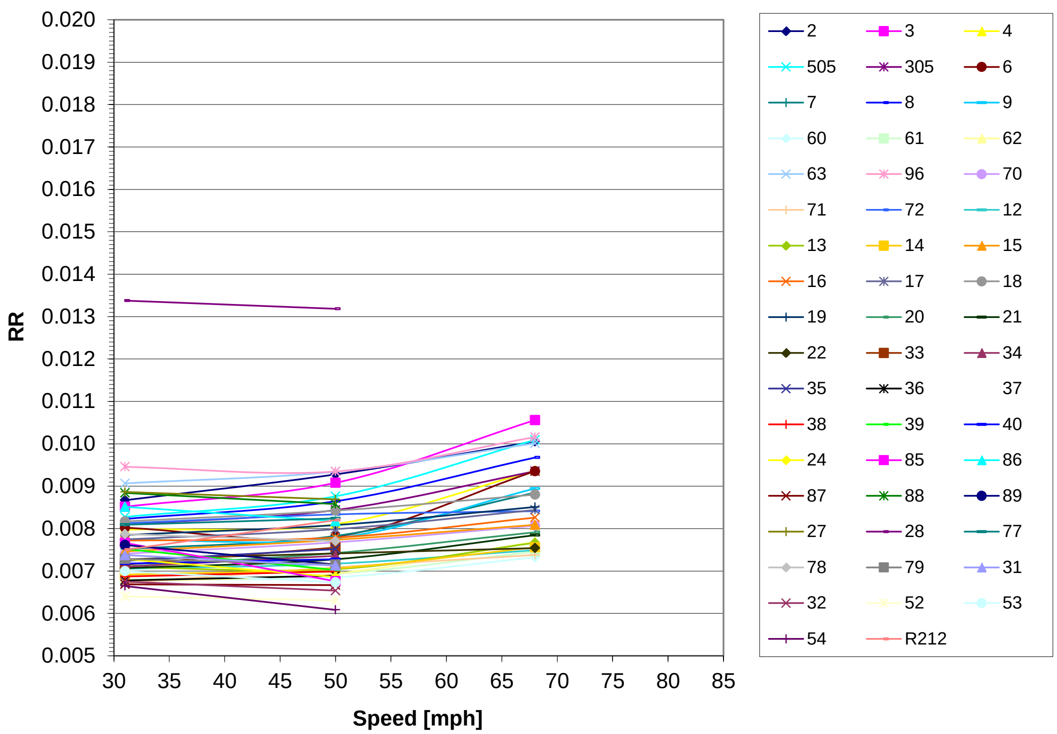


Figure 3-5. Influence of speed on rolling resistance measurements with tire ME16.

In order to reduce the size of the data, the results for all three test tires and test speeds 31 and 50 mph (50 and 80 km/h) were averaged. Due to this averaging, a method of ranking the surfaces was established. The ranking is presented in Figures 9 and -3. Excluding the rolling resistance measurement on Cell 28, the spread between Rolling Resistance Coefficients ranges from a low value of CRR = 0.0085 on Cell 54 (PCC, Longitudinal Turf Drag) and a high value of CRR = 0.0113 on Cell 96 (Thin Bonded Concrete Overlay of HMA, Conventional Diamond Grind). Cell 28 (Double Chip Seal), as mentioned before had a rolling resistance measurement much greater than the others, with a CRR = 0.0148.

The relative difference between surfaces with the lowest and the highest CRR is 33% (or 74%, accounting for Cell 28). A rough estimate indicates that there could be a difference in fuel consumption (comparing the surfaces with the highest and lowest CRR values, driving at a moderate speed, not including Cell 28) of 10%. Comparing Cell 28 to the lowest CRR would indicate a 25% difference.

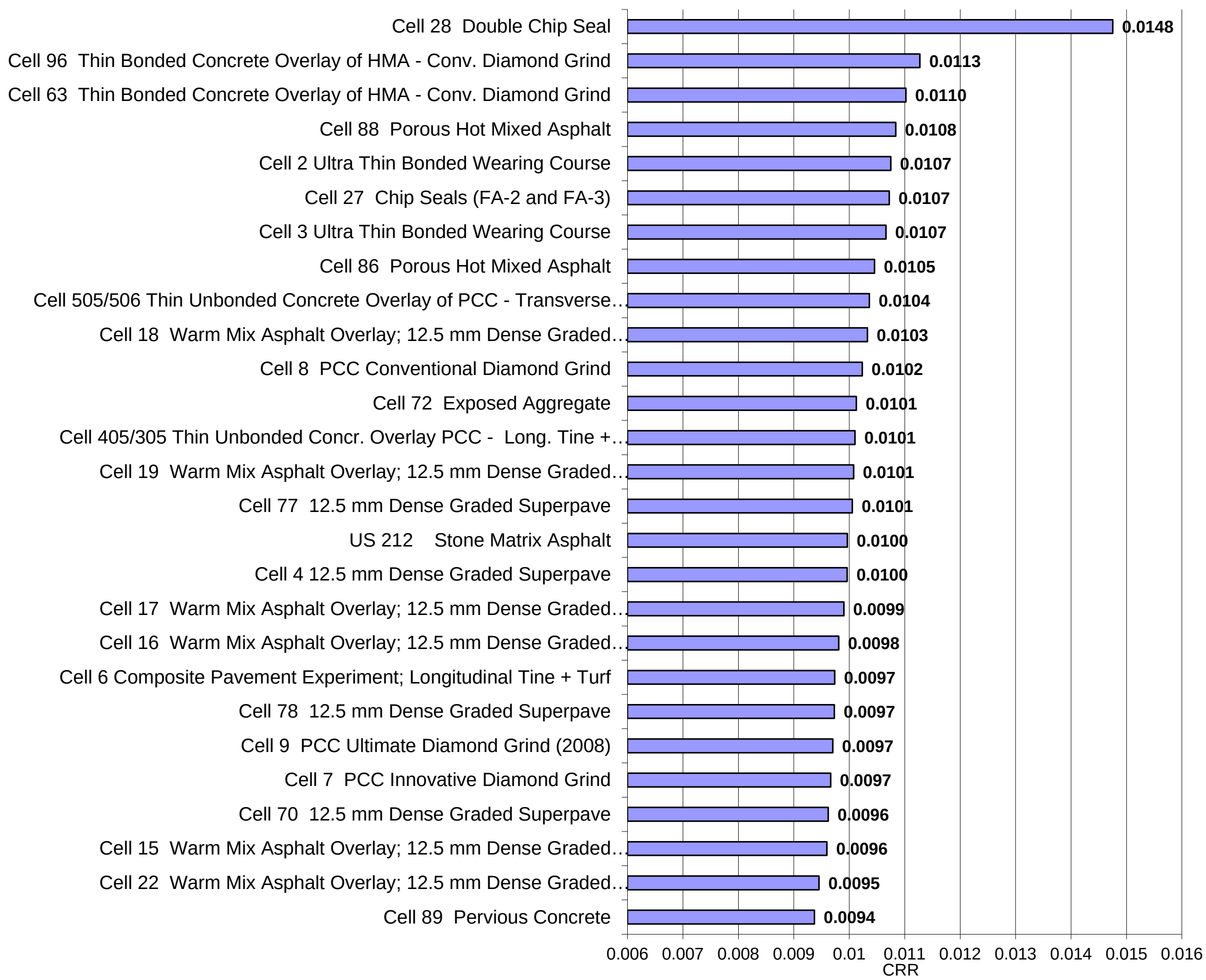


Figure 3-6. Surface ranking based on average CRR.

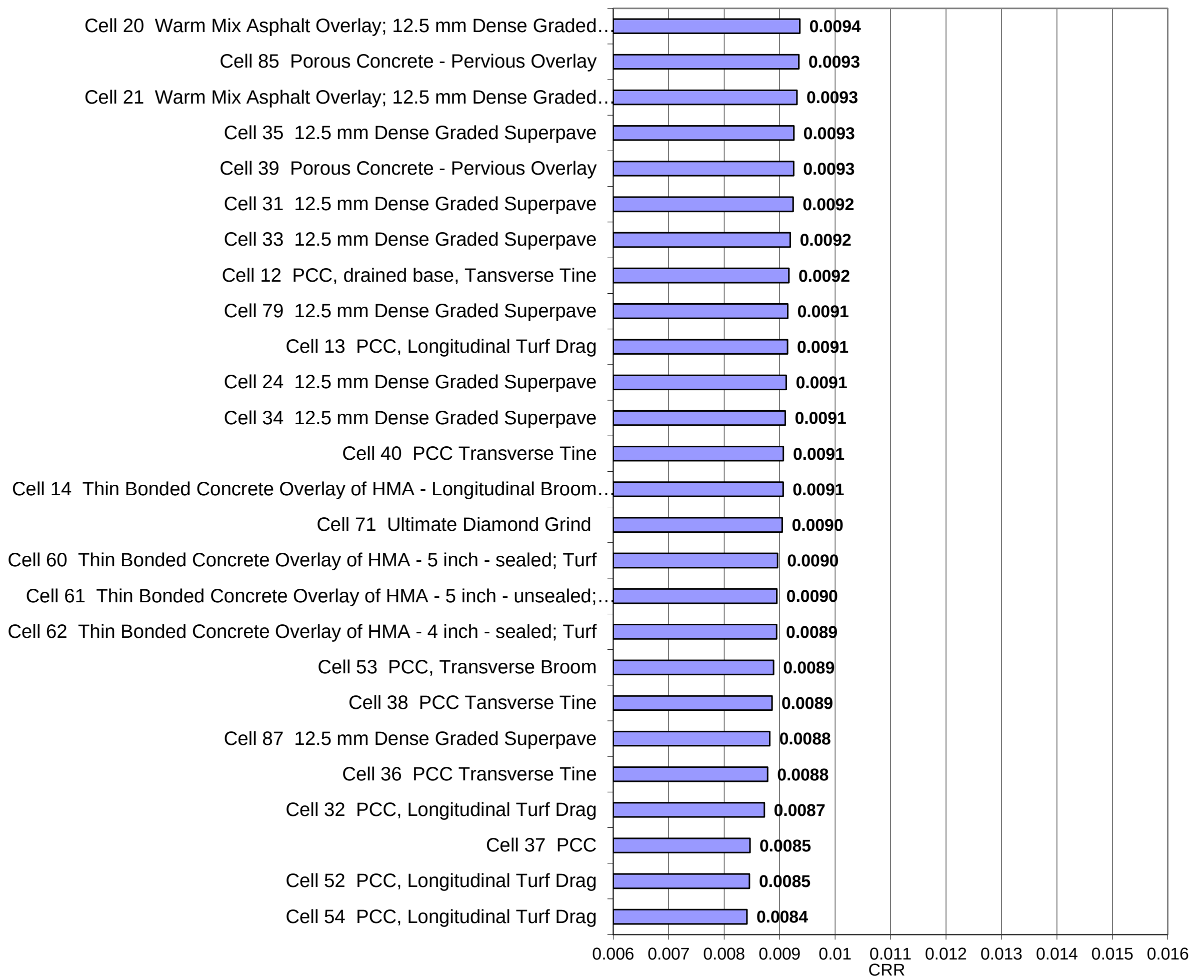


Figure 3-6, continued. Surface ranking based on average CRR.

Figure 3-7 shows the relationships between rolling resistance values measured with different tires. Each of the tires used for the measurements ranked the surfaces in a similar order, but tire AV4 exhibits much higher Rolling Resistance Coefficient values than tires SRTT and ME16. In this figure, data points lying on a 45° line would indicate the same CRR values for both tires. As can be seen in the figure, the CRR data measured with tires SRTT and ME16 are very similar. The comparison of data between SRTT and AV4 shows that the relative differences are similar (the relationship is at a 45° angle), but that there is a vertical shift of about 0.008 CRR indicating that more rolling resistance is measured on the same surface texture when using the AV4 tire compared to the SRTT and ME16 tires.

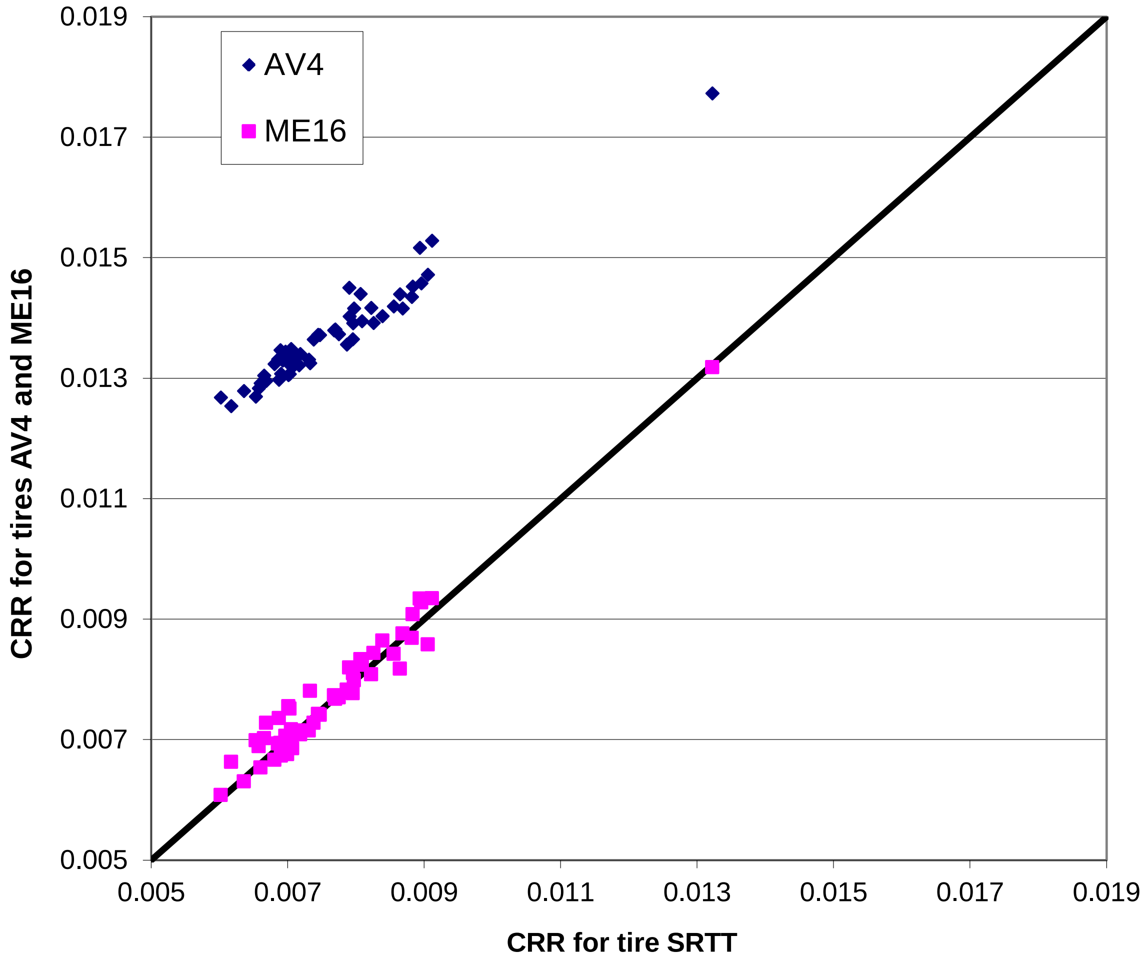


Figure 3-7. Relationship between CRR measured with different tires.

CHAPTER 4. RELATIONSHIPS WITH OTHER TIRE/ROAD CHARACTERISTICS

The Minnesota Department of Transportation supplied the rolling resistance team from the Technical University of Gdańsk with selected data about surface texture, friction and noise measured on the test cells previous to (but at about the same time) the rolling resistance testing. An evaluation of relationships between the rolling resistance coefficient and the noise in decibels (dB) measured by On-Board Sound Intensity (OBSI) shows no correlation, as indicated in Figure 4-1. The additional data are summarized in Table 4-1. Cell 28 was not included as there were no noise data for this surface. Surface texture, in terms of mean profile depth (MPD) was measured by MnDOT using the Circular Texture Meter (CTM). Ride quality is presented in terms of the International Roughness Index (IRI), also measured by MnDOT.

Surface friction was tested by MnDOT with smooth and ribbed tires. The correlation between rolling resistance measured with the SRTT tire and friction measured with a smooth tire is shown in Figure 4-2. Figure 4-3 shows the correlation between rolling resistance measured with the SRTT tire and friction measured with a ribbed tire, while in Figure 4-4 friction results for smooth and ribbed tires are averaged.

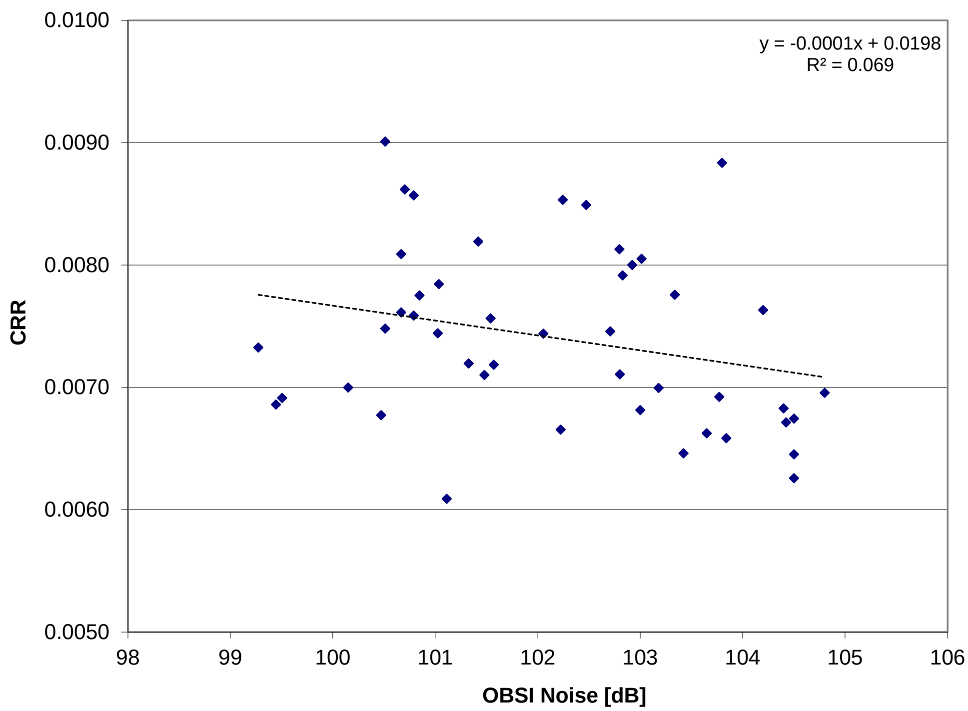


Figure 4-1. Correlation of OBSI noise to rolling resistance coefficient – SRTT tire, 31 mph (50 km/h).

Table 4-1. Additional Tire / Road Characteristics at MnROAD.

Cell	Noise [dB]	Friction			MPD (CTM)	Skew (CTM)	Robotex			IRI m/km
		Av.	Ribbed	Smooth			MPD	RMS	Skew	
1	102.4	35.9	48.5	23.2						
2	102.5	54.9	54.1	55.6	1.03	-0.956	1.189	0.765	-0.952	0.860
3	102.2	57.9	56.3	59.5	1.00	-1.000	1.190	0.769	-0.945	0.994
4	102.8	44.9	53.2	36.5	0.64	-0.086	0.657	0.303	-0.126	1.541
505/605	103.0	52.3	61.6	43.0	0.50	-0.520	0.495	0.234	-0.302	1.449
405/305	103.0	45.8	50.3	41.3	0.50	0.330	0.281	0.131	-0.404	1.045
6	102.9	55.8	55.9	55.6	0.27		0.572	0.283	-0.185	1.676
7	101.5	46.9	44.1	49.6	0.70		0.318	0.147	-0.608	1.150
8	102.8	46.4	46.3	46.4	0.64	-0.730	0.411	0.186	-0.406	1.200
9	102.7	49.8	48.9	50.6	1.49	-1.160	1.074	0.491	0.047	3.460
60	104.4	28.5	45.2	11.8	0.51		0.265	0.106	-0.096	2.026
61	104.4	34.1	47.7	20.5	0.76		0.294	0.123	-0.163	1.580
62	103.8	31.7	45.0	18.4	0.33	-0.720	0.280	0.118	-0.201	1.426
63	103.8	60.9	62.3	59.4	0.86		0.456	0.196	0.092	1.446
96		63.5	62.9	64.0	0.86		0.485	0.202	0.313	1.698
70	104.2	38.6	52.2	24.9	0.33	-0.760	0.482	0.213	-0.415	1.205
71	100.5	43.7	41.0	46.4	1.06	0.120	0.416	0.193	-0.569	1.493
72	103.3	44.1	49.0	39.2	0.75	-0.060	0.610	0.264	0.014	1.718
12	104.8	37.5	46.7	28.3	0.97		0.536	0.428	-2.076	1.416
13	102.8	43.7	49.3	38.1	0.42	-0.930	0.376	0.159	-0.081	1.511
14	103.0	35.1	44.9	25.3	0.38	-0.700	0.326	0.135	-0.068	1.150
15	101.0	41.1	50.8	31.3	0.33		0.591	0.252	-0.208	1.265
16	100.8	43.3	52.6	34.0	0.30		0.603	0.260	-0.264	1.096
17	101.0	45.6	53.4	37.8	1.00		0.622	0.274	-0.277	1.248
18	100.7	45.8	51.5	40.1	0.28		0.654	0.289	-0.271	1.009
19	101.4	46.8	53.3	40.2	0.62	-0.949	0.678	0.303	-0.278	1.066
20	101.5	41.1	53.1	29.1	0.20	0.395	0.589	0.240	-0.054	0.864
21	101.3	40.6	52.7	28.5	0.23		0.562	0.221	-0.022	0.736
22	102.1	39.1	50.8	27.4	0.43	-0.516	0.541	0.209	0.044	0.945
33	99.5	49.9	57.5	42.3	0.33		0.692	0.320	-0.305	1.245
34	99.4	51.6	58.5	44.7	0.36		0.695	0.323	-0.329	1.369
35	100.2	52.2	57.0	47.4	0.41		0.734	0.348	-0.336	1.388
36	103.4	53.4	57.8	48.9	0.71		0.564	0.412	-1.973	1.378
37	101.1	59.3	58.2	60.3	0.53	-0.710				
38	103.6	55.1	61.9	48.3	0.74	0.600	0.523	0.374	-1.938	1.823
39	99.3	59.6	58.3	60.9	2.09	-0.170	2.271	1.545	-0.883	4.171
40	103.8	58.4	62.2	54.9	0.73	-0.730	0.638	0.497	-1.967	2.050
24	103.2	17.0	24.8	9.2	0.31	-0.170	0.447	0.191	-0.317	1.150
85	100.8	57.8	54.1	61.4	1.91	-1.214	2.218	1.580	-1.005	4.351
86	100.8	58.5	59.0	58.0	2.19	-1.009	2.324	1.492	-0.725	3.010
87		51.0	63.2	38.8	0.38	-1.117	0.525	0.220	-0.138	2.750
88	100.5	59.1	60.4	57.7	2.12	-1.123	2.221	1.451	-0.777	3.395
89	100.5	55.5	54.4	56.5	1.80	-0.820	2.185	1.556	-0.991	5.074
27		64.3	63.6	64.9	2.31	-0.270	1.616	0.781	0.046	1.834
28		62.0	61.7	62.2	0.56	-0.690	1.372	0.589	0.152	2.331
77	100.7	57.8	59.6	55.9	0.51	-1.121	0.820	0.419	-0.446	2.075
78	100.7	57.5	62.4	59.0	0.41	0.327	0.762	0.386	-0.511	1.924
79		51.1	61.4	40.7	0.51		0.709	0.334	-0.331	1.909
31	101.6	49.9	57.3	41.5	0.58		0.721	0.378	-0.621	1.771
32	102.2	40.2	55.0	25.4	0.41		0.368	0.159	-0.201	3.145
52	104.5	39.4	55.0	23.7	0.79		0.312	0.128	-0.025	2.025
53	104.5	52.9	61.2	44.5	0.86		0.527	0.239	-0.202	2.128
54	104.5	43.5	54.0	33.0	0.71	-0.318	0.402	0.164	0.023	1.733

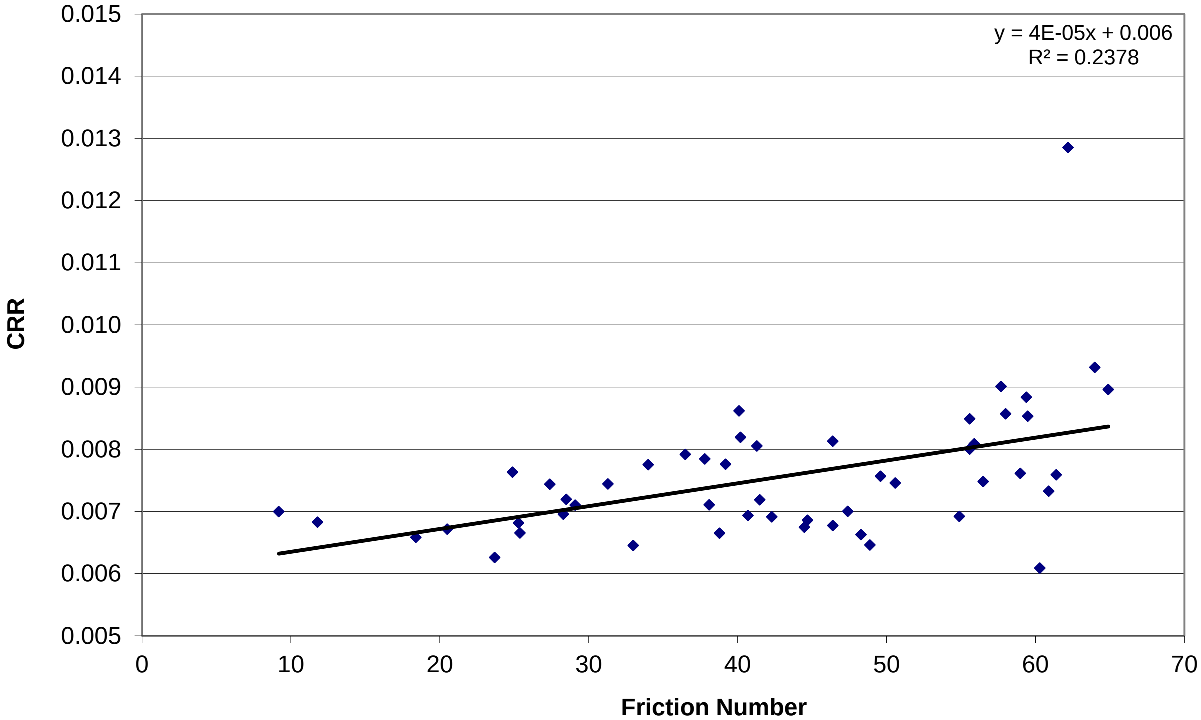


Figure 4-2. Correlation between friction (smooth tire) and RR with SRTT tire, 31 mph (50 km/h).

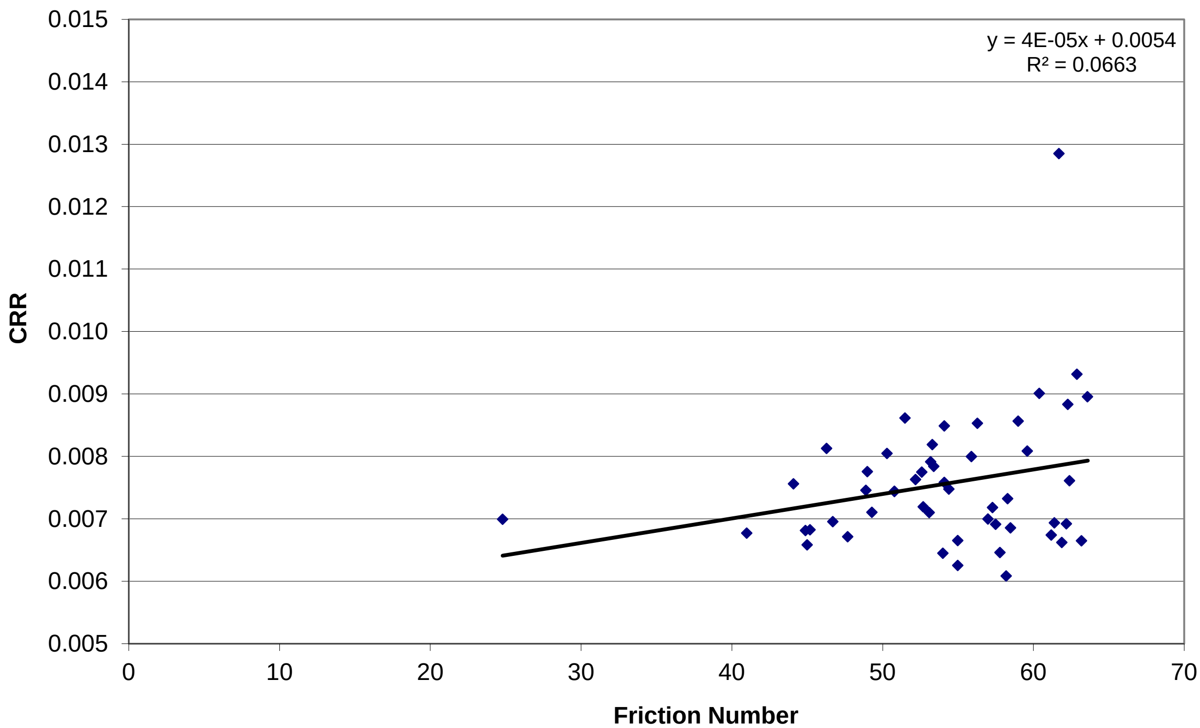


Figure 4-3. Correlation between friction (ribbed tire) and RR with SRTT tire, 31 mph (50 km/h).

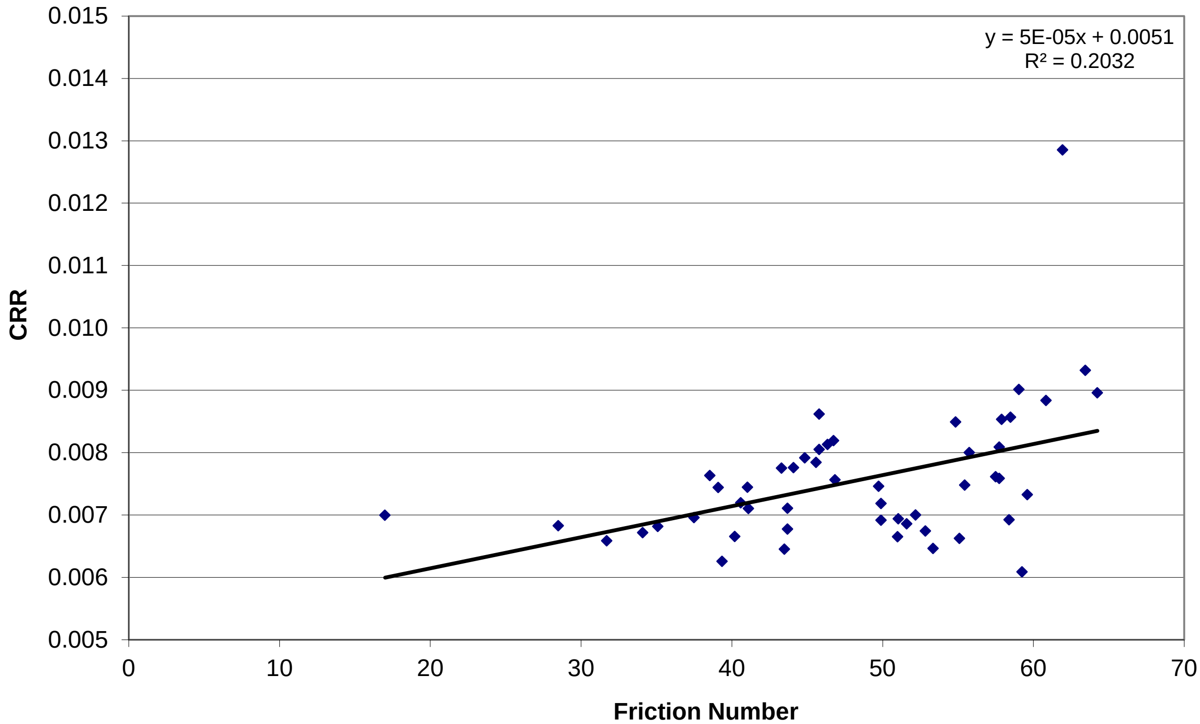


Figure 4-4. Correlation between friction (smooth and ribbed average) and RR with SRTT tire, 31 mph (50 km/h).

The results indicate some correlation between friction and noise, most probably related to the texture. One of the objectives of the study was to evaluate the influence of texture on tire rolling resistance. This part of the report was co-authored with professor Ulf Sandberg from the Swedish National Road and Transport Research Institute (VTI), in Sweden. The MnROAD staff supplied TUG with texture data obtained by the CTM meter. The texture was characterized in terms of MPD values, shown in Figures 9 through 11. Figure 4-8 shows the relationship between MPD and rolling resistance averaged for all tires at both 31 and 50 mph (50 and 80 km/h).

The results indicate that correlation between MPD measured by the CTM unit and rolling resistance during the tests on the MnROAD facility was less than expected. A more typical level of influence for different tires obtained in Europe is presented in Figure 4-9. This figure is taken from a report produced by the authors in Poland, which explains the polish language in the graph and on the axes. Some of the difference may be related to the fact that in Europe the MPD is measured by the linear method while at MnROAD the MPD was evaluated using the CTM.

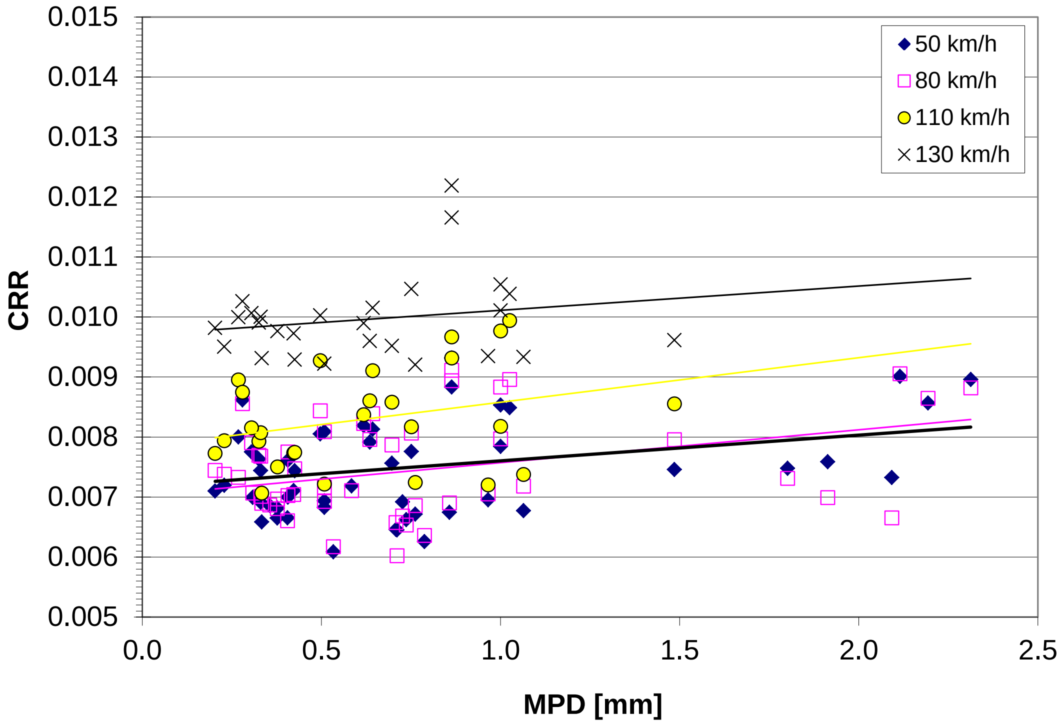


Figure 4-5. Relationship between MPD and rolling resistance measured with tire SRTT.

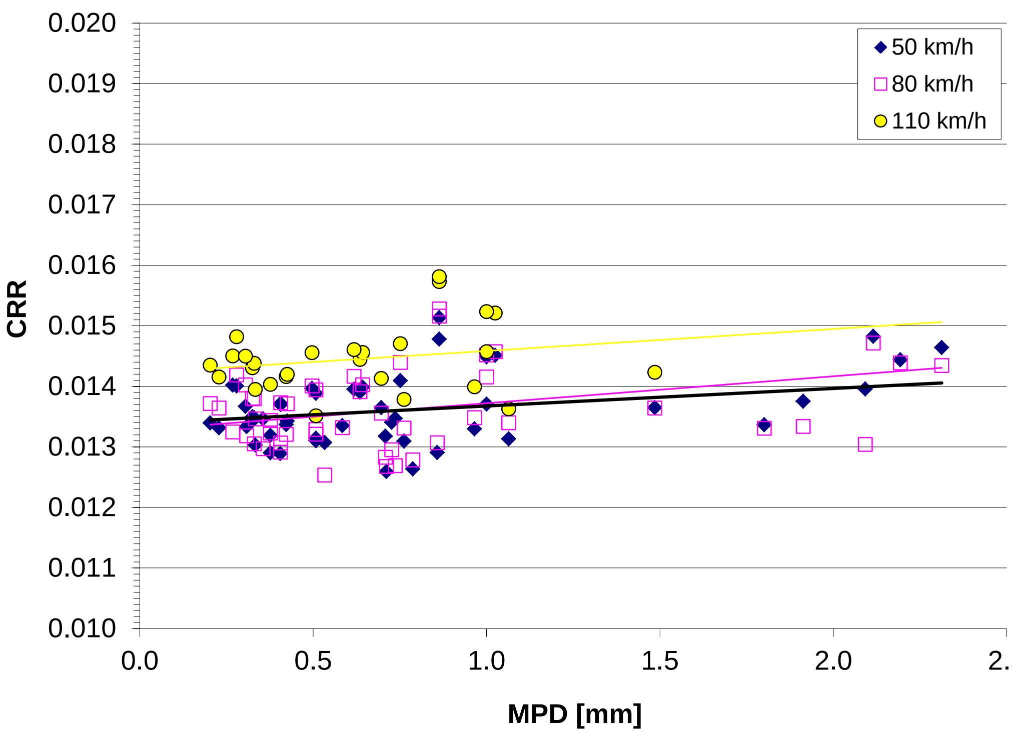


Figure 4-6. Relationship between MPD and rolling resistance measured with tire AV4.

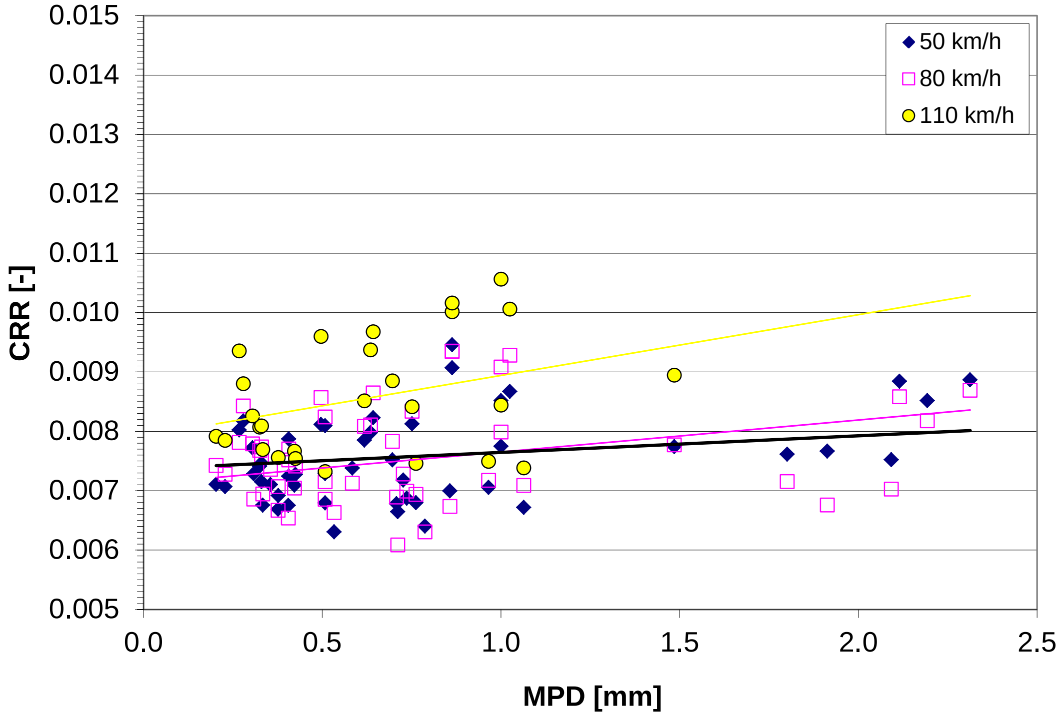


Figure 4-7. Relationship between MPD and rolling resistance measured with tire ME16.

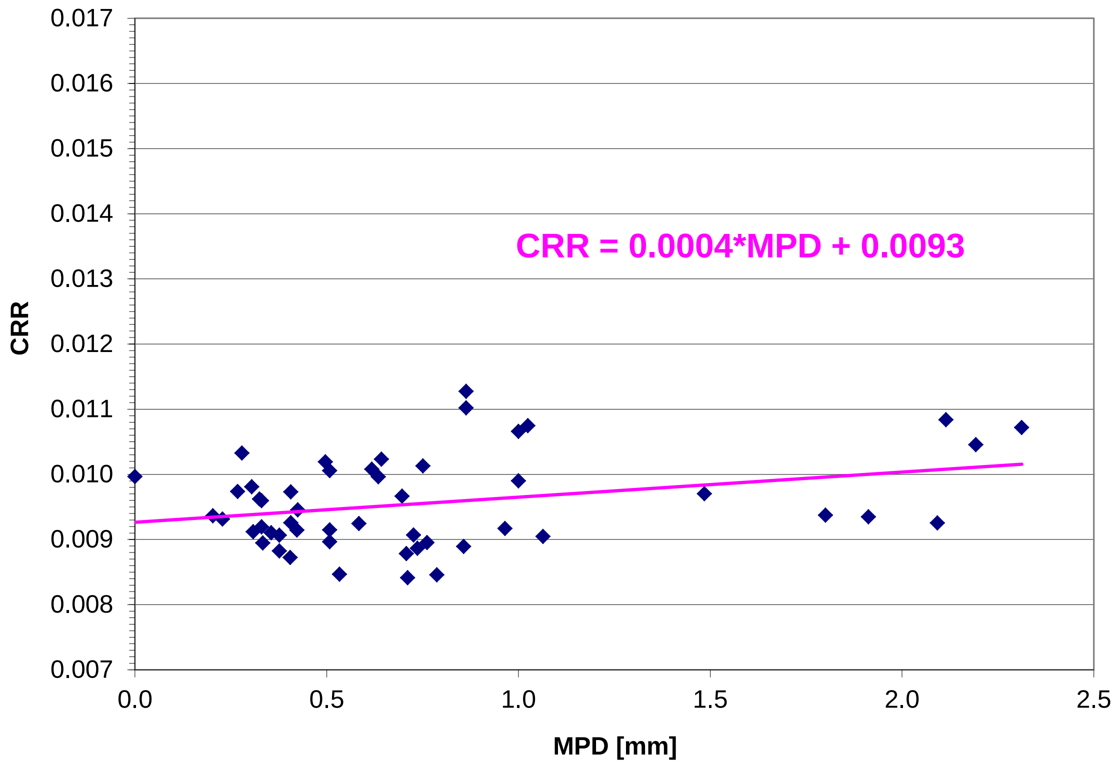


Figure 4-8. Relationship between MPD and rolling resistance, averaged for all tires.

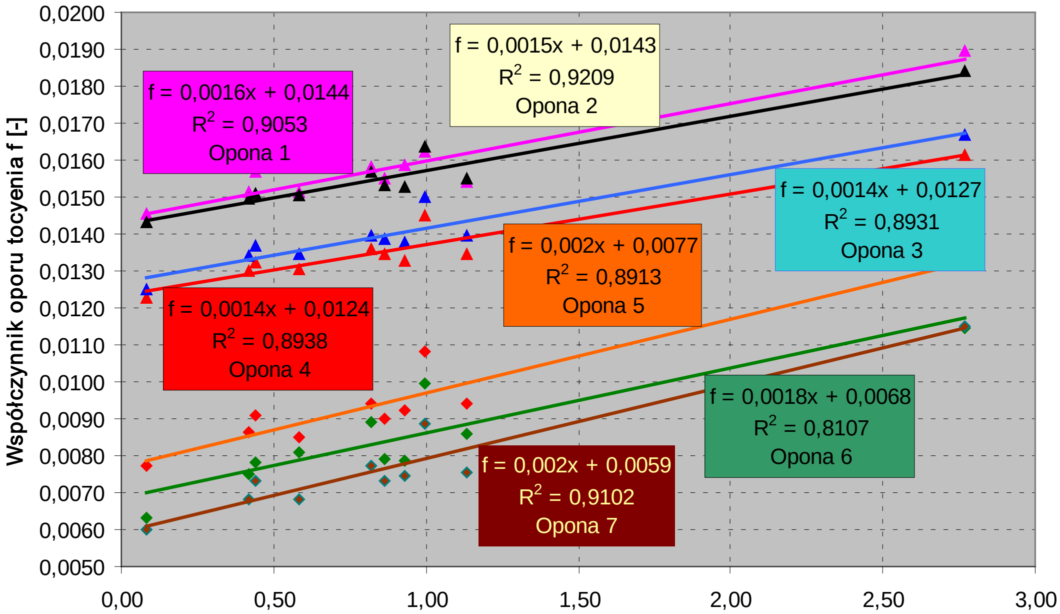


Figure 4-9. Relationship between MPD and RR measured by TUG in Europe for different tires.

The MnROAD staff later supplied texture data obtained by the Robotex measuring system, summarized in Table 4-1, at the beginning of this chapter. The Robotex data were correlated with Rolling Resistance Coefficients (averaged over the 50 and 80 km/h speeds, and all tires). It was also corrected for temperature (CRRt). The relationship between MPD and CRRt for all measured tires are presented in Figure 4-10. The slope of the regression line is still much less than expected (0.0007 versus expected 0.0016 ± 0.0020) and the correlation coefficient is very low, at only 0.156.

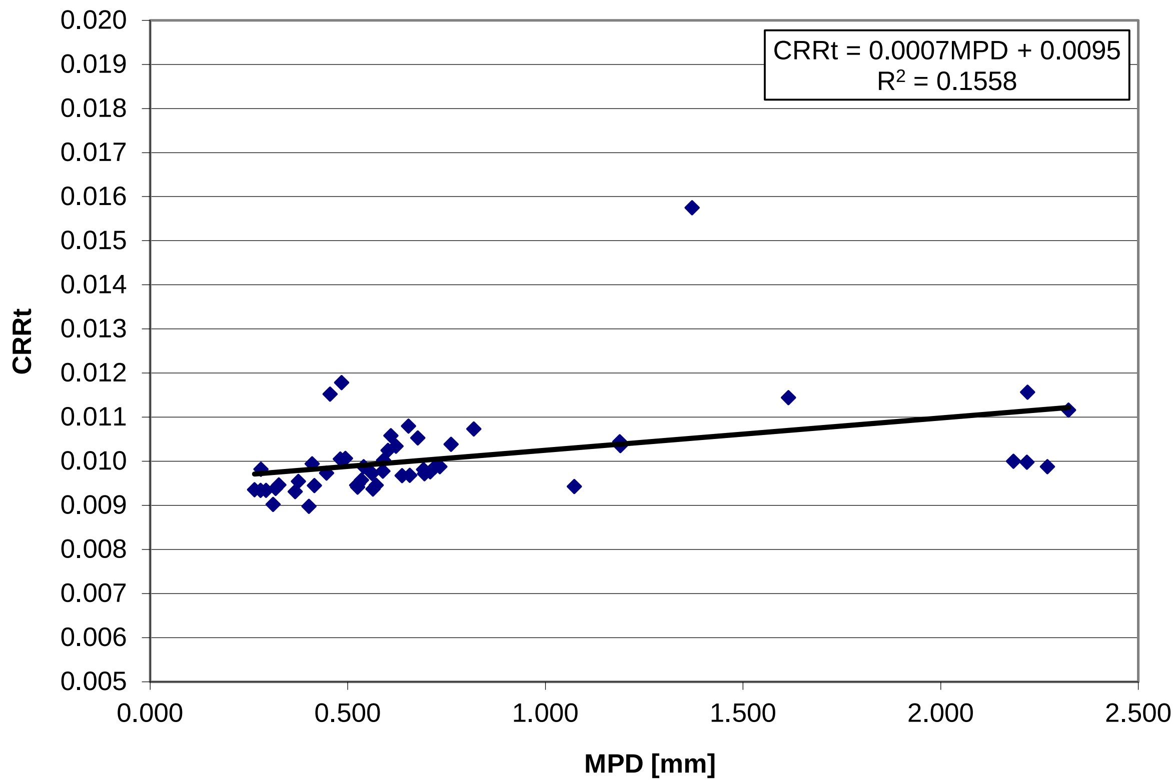


Figure 4-10. Relationship between MPD (Robotex) and average CRRt for all tested tires and speeds.

To improve correlation the surfaces were divided to the following classification:

- Bituminous surfaces,
- PCC with unidirectional texture or very fine drag,
- PCC with transverse grooves, and
- PCC with longitudinal grooves.

Each classification was considered separately and the final relationships are presented in Figure 4-11. The slope of the regression line for bituminous surfaces is 0.0013, and this value corresponds much better with results obtained in Europe (where only a few Portland cement concrete surfaces have been tested). For concrete surfaces the slope was much smaller and in the case of grooved surfaces even negative (it must be noticed, however, that the range of MPD values for transverse grooved PCC was so small that the regression line becomes meaningless). Nevertheless, the categorization of surfaces shows that results for bituminous surfaces obtained in the USA correspond to some degree with relationships established in Europe. As the data presented in Figure 4-11 include the Cell 28 that was a clear outlier, the evaluation for bituminous surfaces was also repeated without Cell 28. The results of this analysis are presented in Figure 4-12.

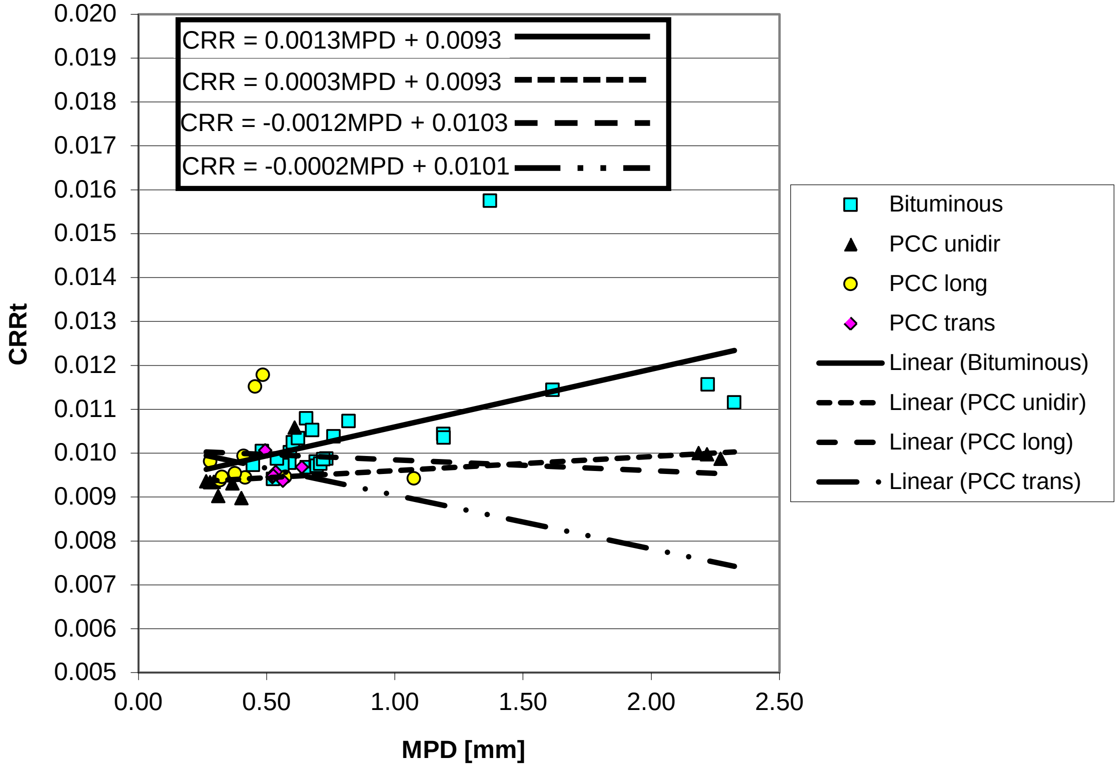


Figure 4-11. Relationships between MPD (Robotex) and average CRRt for different pavement types.

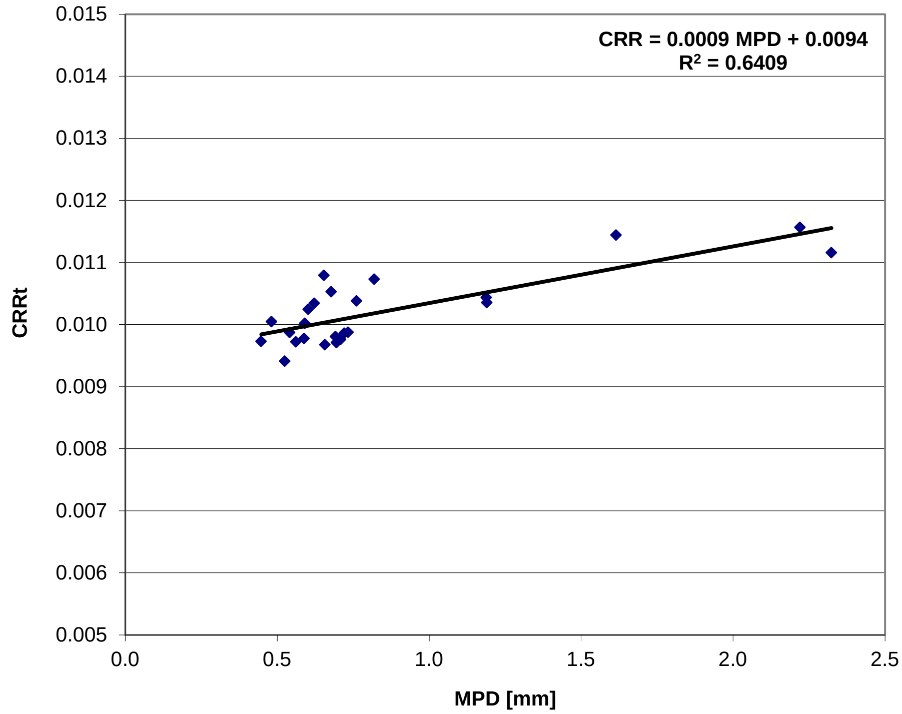


Figure 4-12. Relationship between MPD (Robotex) and averaged CRRt for bituminous surfaces, Cell 28 excluded.

The slope of the regression line for bituminous surfaces when Cell 28 was excluded decreased to 0.0009, which is roughly half of the expected value. It is interesting to note that the correlation between MPD measured by CTM and Robotex is not very high, as indicated in Figure 4-13. Problems with texture measurements may contribute to the differences in the relationship between MPD and CRR that are seen between Europe and USA.

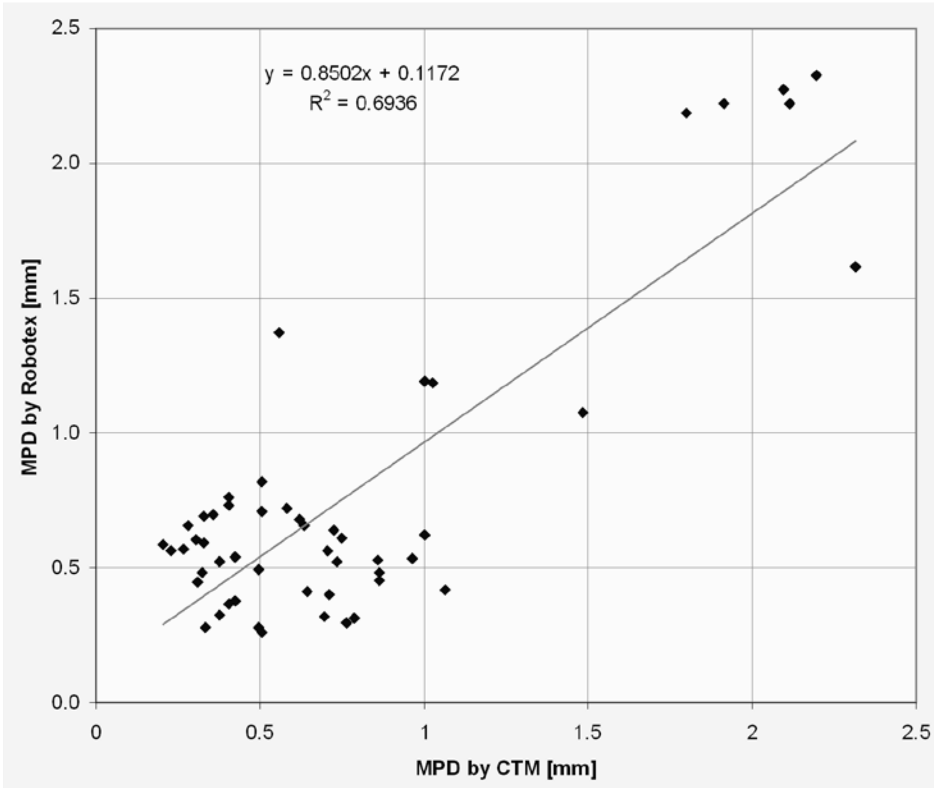


Figure 4-13. Relationship between MPD (CTM) and MPD (Robotex).

Since correlations between CRR and texture were not obvious when making simple regression analyses, multiple regression analyses have been made, resulting in ANOVA tables for each analysis. The analyses were based on CRR values not corrected for temperature, as the correction that is applied according to ISO 28580 may be not representative. Instead, a new variable indicating the day of measurement (DAY) was introduced. The most significant variable is the measurement DAY ($p << 0.1$ %). This might be an indication of differences of properties for surface sets tested each day, temperature influence or problem in calibration stability.

The second most significant variable is pavement type – asphalt concrete or Portland cement concrete (AC or CC, respectively) at a significance of $p << 0.1$ %. Portland cement concrete gives lower CRR values than AC by approximately 5 % at MPD values of 1 mm for this dataset. It is important to be careful when interpreting this in a wider sense, as it may be limited to the special test roads here. The third most significant variable is MPD ($p << 0.1$ %). However, it is significant only for AC pavements.

Skew in the texture and profile smoothness (IRI) are not statistically significant variables (95 % confidence was used, but these variables are far from that level). The skew in a pavement texture relates to the predominance of peaks in the texture directed upward or downward. A positive skew would indicate more peaks directed upwards (spikes in the texture) and negative skew is an indication that more peaks are directed downward (depressions in the texture).

It is surprising that skew and IRI are not as significant as would be expected, as the variation in skew and especially IRI were very high (7 out of 50 pavements had IRI > 3 m/km with the highest at 5.6 m/km). This is not to say that IRI does not affect CRR. It may be that just the TUG trailer is not sensitive to variations in pavement roughness. The lack of effect of skew may be explained by the fact that the MPD is already sensitive to the vertical orientation of the texture, by definition (which is related to skew) and the skew parameter is not significantly more effective than MPD in describing this orientation. The best model for the effect of the significant parameters, and using all data, follows.

$$CRR = 0.009063 + 0.00062 * Day - 0.00065 * (AC\ or\ CC) + 0.000566*MPD \qquad \text{Equation 2}$$

where:

Day = 1 for the 1st day, 2 for 2nd day and 3 for 3rd day,
AC or CC = 1 for AC and 2 for CC, and
CRR = coefficient of rolling resistance.

This model, which is based on 50 observations, explains approximately 55 % of the data variance (R^2), so much of the variance remains unexplained. If only the subset of 27 observations for which skew values are available is used, a corresponding model explains approximately 70 % of the variance. This is not related to the inclusion of the skew parameter, but rather it is since this reduced data set seems to be more "kind" and excludes pavements which contribute to highly deviating data.

CHAPTER 5. CONCLUSIONS

What is surprising and inconsistent with European experience is the relatively low correlation between CRR and MPD. Possible reasons may include the following:

- Variation of temperature may be obscuring the correlation because of the possibility of a non-representative temperature correction procedure based on ISO28580.
- The macro texture values do not seem to be robust, as there is such poor correlation between the CTM and the Robotex measurements. Partly, this is understandable as some of the textures are very special.

The MPD value may not be the best parameter to represent texture. Another variant of MPD, namely when the profile has first been modified by a mathematical function (enveloped) to simulate tire deflection, the calculated MPD on this modified profile is likely to be better, and this may be especially important for the many special textures included in this dataset (grooved concrete).

It may also be that the precision and repeatability of the rolling resistance measurements at MnROAD were lower than has been common in measurements in Sweden and Denmark, where distances of several hundred meters have generally been used for each test section. However, the MnROAD facility permitted undisturbed measurements in both directions (3x2 runs for each combination of surface type, tire, and speed, and that should make them equivalent to longer test sections with some traffic disturbances.

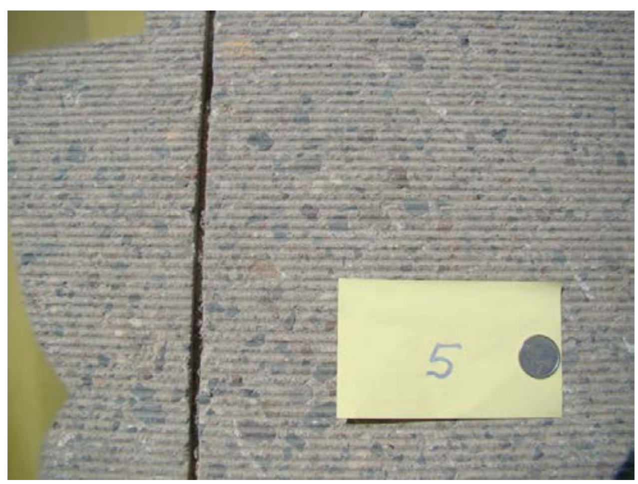
REFERENCES

1. Izevbekhai, B., and W. J. Wilde, *Innovative diamond grinding on MnROAD cells 7, 8, 9, and 37*, Report No. 2011-05, Minnesota Department of Transportation, St. Paul, MN, 2011.

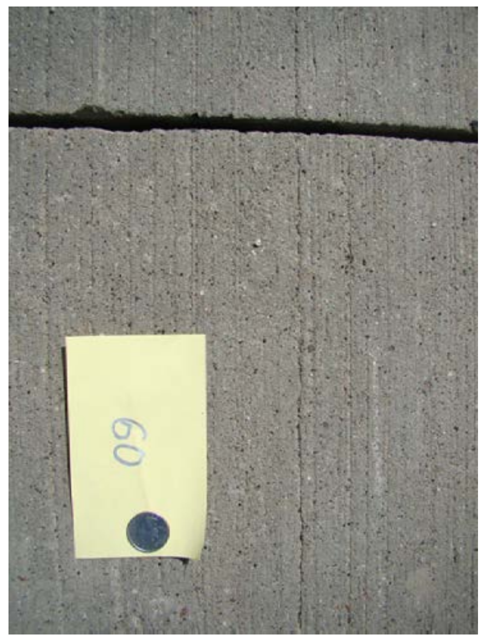
APPENDIX A. SUMMARY OF PAVEMENT SURFACE TYPES AT MNROAD

Table A-1. Characteristics of MnROAD Cells and Pavement Surfaces.

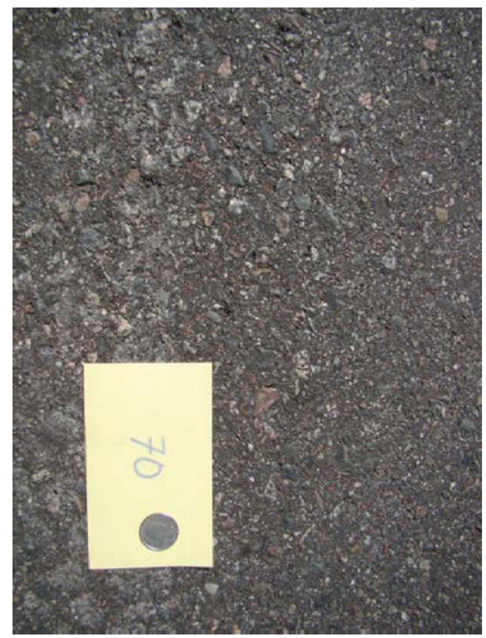
Cell	SubCell	Experiment	Surface Type	Picture
2		SemMaterials FDR Study	Ultra Thin Bonded Wearing Course	
3		SemMaterials FDR Study	Ultra Thin Bonded Wearing Course	

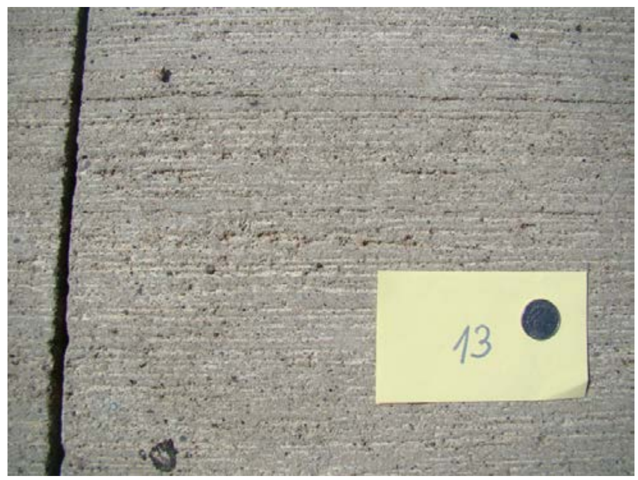
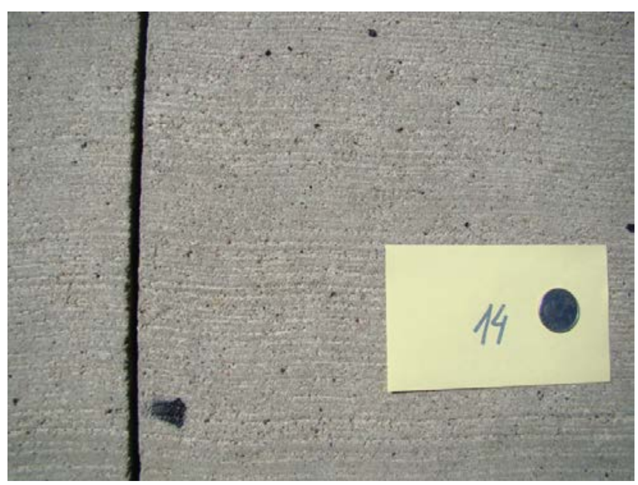
4		SemMaterials FDR Study	12.5 mm Dense Graded Superpave	
5	505 605		Transverse Broom	
	305 405		Longitudinal Tine + Conventional Grind	

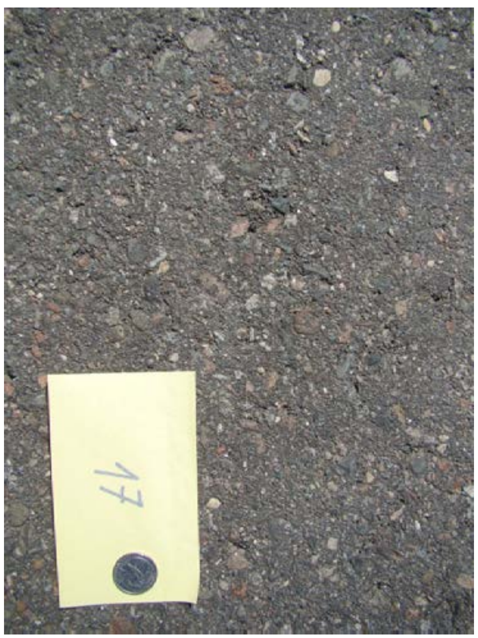
6	306 406		Longitudinal Tine + Turf	
7		5 year design PCC - Widened lane - PASB - longer panel	Innovative Diamond Grind	
8		5 year design PCC - Widened lane - PASB - Supplemental Steel	Conventional Diamond Grind	

9		5 year design PCC - Widened lane - PASB	Ultimate Diamond Grind (2008)	
60		Thin Bonded Concrete Overlay of HMA - 5 inch - sealed	Turf	
61		Thin Bonded Concrete Overlay of HMA – 5 inch - unsealed	Turf	

62		Thin Bonded Concrete Overlay of HMA - 4 inch - sealed	Turf	
63		Thin Bonded Concrete Overlay of HMA - 4 inch - unsealed	Conventional Diamond Grind	
96		Thin Bonded Concrete Overlay of HMA - 5 by 6 panels	Conventional Diamond Grind	

70		SHRP II Composite Pavement Study - DL Doweled, PL Not Doweled	12.5 mm Dense Graded Superpave	
71		SHRP II Composite Pavement Study - Diamond Grind Surface	2010 Ultimate Diamond Grind (Driving) Conventional Diamond Grind (Passing)	
72		SHRP II Composite Pavement Study - EAC Surface	Exposed Aggregate	

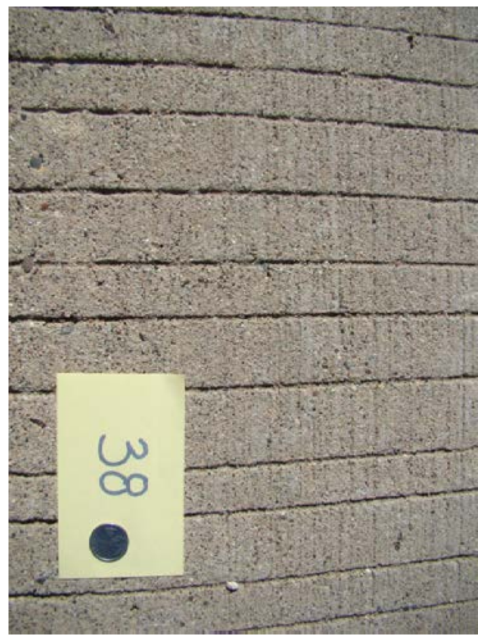
12		10 year design PCC - Drained base	Transverse Tine	
13	513 413 313 213 113	PCC Thickness Optimization - 5 inch - Flat Plate Dowels - 12 and 15 foot panel lengths	Longitudinal Turf Drag	
14	914 814 714 614 514 414 314 214 114		Longitudinal Broom Drag	

15		Warm Mix Asphalt Overlay	12.5 mm Dense Graded Superpave	
16		Recycled Unbound Base Study, Warm Mix Asphalt Surface	12.5 mm Dense Graded Superpave	
17		Recycled Unbound Base Study, Warm Mix Asphalt Surface	12.5 mm Dense Graded Superpave	

18		Recycled Unbound Base Study, Warm Mix Asphalt Surface	12.5 mm Dense Graded Superpave	
19		Recycled Unbound Base Study, Warm Mix Asphalt Surface	12.5 mm Dense Graded Superpave	
20		Low Temperature Cracking, RAP Study	12.5 mm Dense Graded Superpave	

21		Low Temperature Cracking, RAP Study	12.5 mm Dense Graded Superpave	
22		Low Temperature Cracking, RAP Study	12.5 mm Dense Graded Superpave	
33		Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave	

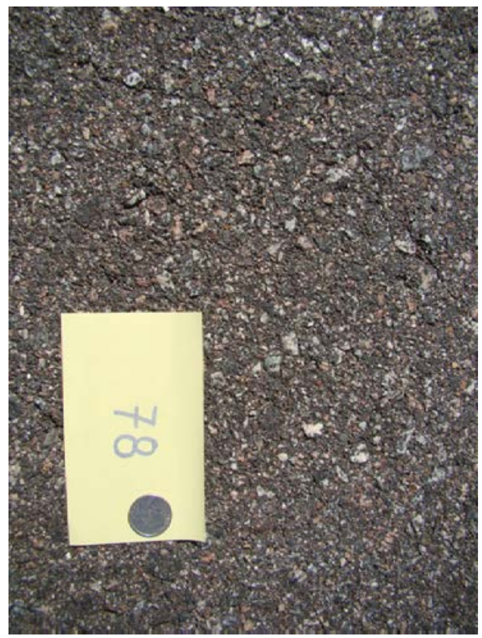
34		Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave	
35		Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave	
36		LVR design PCC - SUBGRADE R70 subgrade - doweled	Transverse Tine	

37		LVR design PCC - SUBGRADE R70 subgrade -undoweled	Conventional Diamond Grind (TS3) Innovative Diamond Grind (TS 1 and 2) 2010 Diamond Grind (TS 5) Transverse Tine (TS 4 and Inside)	
38		LVR design PCC - Standard base - doweled	Transverse Tine	
39		Porous Concrete Overlay Experiment	Pervious Overlay	

85	24	40
Pervious Concrete Experiment - Low Volume Road - Sand subgrade	Aging Study, WMA Control	LVR design PCC - 7-5.5-7 inch Trapezoidal - undoweled
Pervious Concrete	12.5 mm Dense Graded Superpave, Fog seals each year in 100-ft sections	Transverse Tine
		

86		Porous HMA Study	Porous Hot Mixed Asphalt	
87		Porous Pavement Study - Control Section	12.5 mm Dense Graded Superpave	
88		Porous HMA Study	Porous Hot Mixed Asphalt	

28	**27**	**89**
Stabilized Full Depth Reclamation	Geocomposite Capillary Barrier Drain	Pervious Concrete Experiment - Low Volume Road - Clay subgrade
Double Chip Seal	Chip Seals (FA-2 and FA-3)	Pervious Concrete
		

77		Fly Ash Study, Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave	
78		Fly Ash Study, Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave	
79		Fly Ash Study, Polyphosphoric Acid Study	12.5 mm Dense Graded Superpave	

31		2004 LVR Taconite Superpave	12.5 mm Dense Graded Superpave	
32		LVR design PCC - Thin Slab	Longitudinal Turf Drag	
52		5 year design PCC - Load testing - FRP dowels	Longitudinal Turf Drag	

53		60- year PCC	Transverse Broom	
54		PCC mix experiment - Mesabi Select aggregates	Longitudinal Turf Drag	
R212		Stone Matrix Asphalt	Stone Matrix Asphalt	

APPENDIX B. SUMMARY OF ROLLING RESISTANCE RESULTS

Table B-1. Coefficient of Rolling Resistance (SRTT), with and without Temperature Correction.

SRTT	Without Temperature Correction				With Temperature Correction			
Cell	**31 mph (50 km/h)**	**50 mph (80 km/h)**	**68 mph (110 km/h)**	**81 mph (130 km/h)**	**31 mph (50 km/h)**	**50 mph (80 km/h)**	**68 mph (110 km/h)**	**81 mph (130 km/h)**
2	0.0085	0.0090	0.0099	0.0104	0.0082	0.0087	0.0096	0.0101
3	0.0085	0.0088	0.0098	0.0105	0.0083	0.0086	0.0095	0.0102
4	0.0079	0.0080	0.0086	0.0096	0.0077	0.0077	0.0083	0.0093
505/605	0.0082	0.0087	0.0098	0.0105	0.0080	0.0084	0.0095	0.0102
305/405	0.0080	0.0083	0.0090	0.0098	0.0078	0.0080	0.0087	0.0095
6	0.0080	0.0073	0.0090	0.0100	0.0078	0.0071	0.0087	0.0097
7	0.0076	0.0079	0.0086	0.0095	0.0073	0.0076	0.0083	0.0092
8	0.0081	0.0084	0.0091	0.0102	0.0079	0.0081	0.0088	0.0099
9	0.0075	0.0080	0.0086	0.0096	0.0072	0.0077	0.0083	0.0093
60	0.0068	0.0069	0.0072	0.0092	0.0073	0.0074	0.0077	0.0098
61	0.0067	0.0069	0.0072	0.0092	0.0071	0.0073	0.0077	0.0098
62	0.0066	0.0069	0.0071	0.0093	0.0070	0.0073	0.0075	0.0099
63	0.0088	0.0089	0.0093	0.0117	0.0094	0.0095	0.0099	0.0124
96	0.0093	0.0091	0.0097	0.0122	0.0099	0.0097	0.0103	0.0129
70	0.0076	0.0077	0.0079	0.0099	0.0081	0.0082	0.0084	0.0105
71	0.0068	0.0072	0.0074	0.0093	0.0072	0.0076	0.0078	0.0099
72	0.0078	0.0081	0.0082	0.0105	0.0082	0.0086	0.0087	0.0111
12	0.0070	0.0071	0.0072	0.0093	0.0074	0.0075	0.0076	0.0099
13	0.0071	0.0070	0.0077	0.0097	0.0075	0.0075	0.0082	0.0103
14	0.0068	0.0070	0.0075	0.0098	0.0072	0.0074	0.0080	0.0104
15	0.0074	0.0077	0.0081	0.0100	0.0079	0.0082	0.0086	0.0106
16	0.0078	0.0079	0.0082	0.0101	0.0082	0.0084	0.0087	0.0107
17	0.0078	0.0080	0.0082	0.0101	0.0083	0.0085	0.0087	0.0107
18	0.0086	0.0086	0.0087	0.0103	0.0092	0.0091	0.0093	0.0109
19	0.0082	0.0082	0.0084	0.0099	0.0087	0.0087	0.0089	0.0105
20	0.0071	0.0074	0.0077	0.0098	0.0075	0.0079	0.0082	0.0104
21	0.0072	0.0074	0.0079	0.0095	0.0076	0.0078	0.0084	0.0101
22	0.0074	0.0075	0.0077	0.0093	0.0079	0.0079	0.0082	0.0099

Table B-1, continued. Coefficient of Rolling Resistance (SRTT), with and without Temperature Correction.

SRTT	Without Temperature Correction				With Temperature Correction			
Cell	31 mph (50 km/h)	50 mph (80 km/h)	68 mph (110 km/h)	81 mph (130 km/h)	31 mph (50 km/h)	50 mph (80 km/h)	68 mph (110 km/h)	81 mph (130 km/h)
33	0.0069	0.0070			0.0074	0.0075		
34	0.0069	0.0069			0.0074	0.0074		
35	0.0070	0.0070			0.0075	0.0075		
36	0.0065	0.0066			0.0069	0.0071		
37	0.0061	0.0062			0.0065	0.0066		
38	0.0066	0.0065			0.0071	0.0070		
39	0.0073	0.0067			0.0079	0.0071		
40	0.0069	0.0067			0.0074	0.0072		
24	0.0070	0.0071			0.0075	0.0076		
85	0.0076	0.0070			0.0081	0.0075		
86	0.0086	0.0086			0.0092	0.0093		
87	0.0066	0.0068			0.0071	0.0073		
88	0.0090	0.0091			0.0097	0.0097		
89	0.0075	0.0073			0.0080	0.0078		
27	0.0090	0.0088			0.0096	0.0095		
28	0.0129	0.0132			0.0138	0.0142		
77	0.0081	0.0081			0.0087	0.0087		
78	0.0076	0.0078			0.0082	0.0083		
79	0.0069	0.0072			0.0074	0.0077		
31	0.0072	0.0071			0.0077	0.0076		
32	0.0067	0.0066			0.0071	0.0071		
52	0.0063	0.0064			0.0067	0.0068		
53	0.0067	0.0069			0.0072	0.0074		
54	0.0065	0.0060			0.0069	0.0065		
R212	0.0075	0.0079			0.0079	0.0083		

Table B-2. Coefficient of Rolling Resistance (AV4), with and without Temperature Correction.

AV4	Without Temperature Correction			With Temperature Correction		
Cell	**31 mph (50 km/h)**	**50 mph (80 km/h)**	**68 mph (110 km/h)**	**31 mph (50 km/h)**	**50 mph (80 km/h)**	**68 mph (110 km/h)**
2	0.0145	0.0146	0.0152	0.0141	0.0142	0.0148
3	0.0145	0.0145	0.0152	0.0141	0.0141	0.0148
4	0.0139	0.0139	0.0144	0.0135	0.0135	0.0140
505/605	0.0141	0.0142	0.0148	0.0137	0.0137	0.0144
305/405	0.0139	0.0139	0.0145	0.0135	0.0135	0.0140
6	0.0140	0.0132	0.0145	0.0136	0.0129	0.0141
7	0.0136	0.0136	0.0141	0.0133	0.0132	0.0137
8	0.0140	0.0140	0.0146	0.0136	0.0136	0.0141
9	0.0136	0.0136	0.0142	0.0133	0.0132	0.0138
60	0.0131	0.0133	0.0135	0.0134	0.0136	0.0138
61	0.0131	0.0133	0.0138	0.0134	0.0136	0.0141
62	0.0130	0.0135	0.0139	0.0133	0.0138	0.0143
63	0.0148	0.0152	0.0157	0.0151	0.0155	0.0161
96	0.0151	0.0153	0.0158	0.0155	0.0156	0.0162
70	0.0135	0.0138	0.0143	0.0138	0.0141	0.0146
71	0.0131	0.0134	0.0136	0.0134	0.0137	0.0139
72	0.0141	0.0144	0.0147	0.0144	0.0147	0.0150
12	0.0133	0.0135	0.0140	0.0136	0.0138	0.0143
13	0.0134	0.0132	0.0142	0.0137	0.0135	0.0145
14	0.0132	0.0134	0.0140	0.0135	0.0137	0.0143
15	0.0135	0.0138	0.0144	0.0138	0.0141	0.0147
16	0.0137	0.0140	0.0145	0.0140	0.0143	0.0148
17	0.0137	0.0142	0.0146	0.0140	0.0145	0.0149
18	0.0140	0.0142	0.0148	0.0143	0.0145	0.0152
19	0.0140	0.0142	0.0146	0.0143	0.0145	0.0149
20	0.0134	0.0137	0.0144	0.0137	0.0140	0.0147
21	0.0133	0.0136	0.0142	0.0136	0.0139	0.0145
22	0.0134	0.0137	0.0142	0.0137	0.0140	0.0145

Table B-2, continued. Coefficient of Rolling Resistance (AV4), with and without Temperature Correction.

AV4	Without Temperature Correction			With Temperature Correction		
Cell	**31 mph (50 km/h)**	**50 mph (80 km/h)**	**68 mph (110 km/h)**	**31 mph (50 km/h)**	**50 mph (80 km/h)**	**68 mph (110 km/h)**
33	0.0135	0.0131		0.0143	0.0138	
34	0.0135	0.0130		0.0143	0.0138	
35	0.0137	0.0131		0.0145	0.0139	
36	0.0132	0.0128		0.0140	0.0136	
37	0.0131	0.0125		0.0139	0.0133	
38	0.0135	0.0127		0.0143	0.0135	
39	0.0140	0.0130		0.0148	0.0138	
40	0.0134	0.0130		0.0142	0.0137	
24	0.0133	0.0132		0.0141	0.0140	
85	0.0138	0.0133		0.0146	0.0142	
86	0.0144	0.0144		0.0153	0.0153	
87	0.0129	0.0132		0.0137	0.0140	
88	0.0148	0.0147		0.0157	0.0156	
89	0.0134	0.0133		0.0142	0.0141	
27	0.0146	0.0143		0.0155	0.0152	
28	0.0181	0.0177		0.0193	0.0188	
77	0.0139	0.0139		0.0147	0.0148	
78	0.0137	0.0137		0.0146	0.0146	
79	0.0131	0.0132		0.0139	0.0140	
31	0.0134	0.0133		0.0142	0.0141	
32	0.0129	0.0129		0.0137	0.0137	
52	0.0126	0.0128		0.0134	0.0136	
53	0.0129	0.0131		0.0137	0.0139	
54	0.0126	0.0127		0.0134	0.0134	
R212	0.0142	0.0145		0.0150	0.0153	

Table B-3. Coefficient of Rolling Resistance (ME16), with and without Temperature Correction.

ME16	Without Temperature Correction			With Temperature Correction		
Cell	31 mph (50 km/h)	50 mph (80 km/h)	68 mph (110 km/h)	31 mph (50 km/h)	50 mph (80 km/h)	68 mph (110 km/h)
2	0.0087	0.0093	0.0101	0.0084	0.0090	0.0098
3	0.0085	0.0091	0.0106	0.0083	0.0088	0.0103
4	0.0080	0.0081	0.0094	0.0077	0.0079	0.0091
505/605	0.0083	0.0088	0.0101	0.0080	0.0085	0.0098
305/405	0.0081	0.0084	0.0094	0.0079	0.0082	0.0091
6	0.0080	0.0078	0.0094	0.0078	0.0076	0.0091
7	0.0075	0.0078	0.0088	0.0073	0.0076	0.0086
8	0.0082	0.0086	0.0097	0.0080	0.0084	0.0094
9	0.0077	0.0078	0.0089	0.0075	0.0075	0.0087
60	0.0068	0.0069	0.0073	0.0072	0.0073	0.0078
61	0.0068	0.0069	0.0075	0.0072	0.0074	0.0079
62	0.0068	0.0069	0.0077	0.0072	0.0074	0.0082
63	0.0091	0.0093	0.0100	0.0097	0.0099	0.0107
96	0.0095	0.0093	0.0102	0.0101	0.0100	0.0108
70	0.0074	0.0077	0.0081	0.0079	0.0082	0.0086
71	0.0067	0.0071	0.0074	0.0072	0.0075	0.0079
72	0.0081	0.0083	0.0084	0.0087	0.0089	0.0090
12	0.0071	0.0072	0.0075	0.0075	0.0076	0.0080
13	0.0071	0.0070	0.0077	0.0075	0.0075	0.0082
14	0.0069	0.0071	0.0076	0.0074	0.0075	0.0080
15	0.0075	0.0077	0.0081	0.0079	0.0082	0.0086
16	0.0077	0.0078	0.0083	0.0082	0.0083	0.0088
17	0.0077	0.0080	0.0084	0.0082	0.0085	0.0090
18	0.0082	0.0084	0.0088	0.0087	0.0090	0.0094
19	0.0079	0.0081	0.0085	0.0084	0.0086	0.0091
20	0.0071	0.0074	0.0079	0.0076	0.0079	0.0084
21	0.0071	0.0073	0.0078	0.0075	0.0077	0.0084
22	0.0073	0.0074	0.0075	0.0077	0.0079	0.0080

Table B-3, continued. Coefficient of Rolling Resistance (ME16), with and without Temperature Correction.

ME16	Without Temperature Correction			With Temperature Correction		
Cell	**31 mph (50 km/h)**	**50 mph (80 km/h)**	**68 mph (110 km/h)**	**31 mph (50 km/h)**	**50 mph (80 km/h)**	**68 mph (110 km/h)**
33	0.0071	0.0076		0.0077	0.0081	
34	0.0071	0.0074		0.0076	0.0079	
35	0.0072	0.0075		0.0078	0.0080	
36	0.0068	0.0069		0.0073	0.0074	
37	0.0063	0.0066		0.0067	0.0071	
38	0.0069	0.0070		0.0074	0.0075	
39	0.0075	0.0070		0.0080	0.0075	
40	0.0072	0.0073		0.0077	0.0078	
24	0.0073	0.0069		0.0078	0.0073	
85	0.0077	0.0068		0.0082	0.0072	
86	0.0085	0.0082		0.0091	0.0088	
87	0.0067	0.0067		0.0072	0.0071	
88	0.0088	0.0086		0.0095	0.0092	
89	0.0076	0.0072		0.0081	0.0077	
27	0.0089	0.0087		0.0095	0.0093	
28	0.0134	0.0132		0.0143	0.0141	
77	0.0081	0.0082		0.0087	0.0088	
78	0.0079	0.0077		0.0084	0.0082	
79	0.0073	0.0072		0.0078	0.0077	
31	0.0074	0.0071		0.0079	0.0076	
32	0.0068	0.0065		0.0072	0.0070	
52	0.0064	0.0063		0.0069	0.0068	
53	0.0070	0.0067		0.0075	0.0072	
54	0.0066	0.0061		0.0071	0.0065	
R212	0.0075	0.0082		0.0079	0.0087	