A Comparison of Transverse Tined and Longitudinal Diamond Ground Pavement Texturing for Newly Constructed Concrete Pavement

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Paul L. Burgé
Senior Consultant
Acentech Incorporated
33 Moulton St.
Cambridge, MA 02138
Phone: 617-499-8012
Fax: 617-499-8074
E-mail: pburge@acentech.com

Keith Travis, P.E.
Senior Transportation Engineer
Parson Transportation Group
300 Cathedral Park Tower
37 Franklin Street
Buffalo, NY 14202
Phone: 716/853-6940 x221
Fax: 716-853-6192
E-mail: keith.travis@parsons.com

Dr. Zoltan Rado
Pennsylvania Transportation Institute
Penn State University
201 Transportation Research Building
University Park, PA 16802-4710
phone: 814-863-7925
fax: 814-865-3039
e-mail: zxr100@psu.edu

ABSTRACT

The purpose of this study is to provide a comparison of longitudinal diamond ground and transverse tined pavement surface texturing for newly constructed Portland Cement Concrete Pavement (PCCP). The study area is located along a test-section of I-190 in Buffalo, New York. The two PCCP surface treatment types being evaluated in this report are compared based on safety, noise, construction cost, service life, rideability, handling, and maintenance requirements. This paper documents the initial evaluation and also analysis of follow-up noise and skid resistance measurements conducted approximately one year later.

Analysis of the initial testing indicates that the relative skid resistance of the experimental longitudinal diamond ground surface is as good or better than that of the transverse-tined surface. The results of the noise analysis indicate that the longitudinal diamond ground surface is 2 to 5 decibels quieter depending primarily on the traffic vehicle mix. Noise and skid resistance measurements conducted one year later showed little change. While less construction time was required for the transverse tined pavement as compared to the diamond ground pavement, the actual cost difference is not quantifiable. However, a higher initial cost for longitudinal diamond grinding would likely be partially offset by an extended service life.

INTRODUCTION

Surface texturing of concrete pavement is required on projects funded by the Federal Highway Administration (FHWA) to reduce skidding under wet pavement conditions. PCCP surfaces are often finished with a transverse tined texture during construction to increase skid resistance. Alternate pavement surface treatments are occasionally considered in an effort to reduce the tire-pavement noise associated with the traditional finish. However, a compromise in the safety or a reduction in the effective service life along with significant added construction costs would be undesirable side effects resulting from efforts to achieve a reduction in traffic-generated noise levels.

As part of a New York State Thruway Authority (NYSTA) highway reconstruction contract, a new PCCP surface texturing technique was implemented along portions of the Niagara Section of the NYS Thruway, Interstate 190 (I-190). The experimental surface treatment (longitudinal diamond ground texturing) was implemented adjacent to noise-sensitive areas in lieu of the conventional transverse tined concrete surface texturing method currently approved by the FHWA.

The purpose of this study is to provide a comparison of key performance characteristics between longitudinal diamond ground and transverse tined pavement surface texturing for newly constructed PCCP.

The test section of the highway included newly constructed segments of both traditional transversely tined PCCP and the experimental longitudinal diamond ground PCCP. Sample sections of both pavement types were included on both northbound and southbound lanes. The test-section of northbound pavement was opened to traffic in December of 1999. The test-section of southbound pavement was opened to traffic in December of 1998.

Approach

The two PCCP surface treatment types evaluated in this study are compared based on safety, noise, construction cost, service life, rideability, handling, and maintenance requirements. Comparisons are made on a section of highway of the same construction (other than surface treatment) and exposed to the same traffic and weather conditions.

Skid testing and accident reports are used to evaluate safety characteristics. Noise measurements and analytical modeling are used to compare the traffic generated noise levels. The unit price bid by the awarded construction contractor is used to compare relative construction costs. User surveys are used to obtain feedback from highway maintenance personnel, state police and the general traveling public to assess differences in rideability, handling, and maintenance requirements. Each of the aforementioned characteristics will be monitored over a period of five years to assess the service life of each PCCP surface treatment.

This paper reports the results and analysis of construction cost data and the initial set of noise and skid resistance measurements plus follow-up measurements conducted approximately one year later. Additional follow-up noise and skid-resistance measurements will be conducted annually through 2005 in order to continue documenting changes in pavement properties.

MATERIALS AND CONSTRUCTION DETAILS

Construction practices and materials used for the pavement test sections were kept as consistent as possible between the two pavement types except for the actual surface treatments, as detailed below.

Materials

Characteristics of the PCCP used on the portions of the I-190 relative to this study are typical of new PCCP construction in this region.

Construction

Paving

The unreinforced PCCP has transverse joints spaced at 5.5 meters. The transverse joints were saw-cut at a width of approximately 11 mm. Transverse joints were then beveled and a preformed neoprene joint sealer was installed leaving a 6.5 to 9.5 mm finished joint depth. The joint width and depth was kept as small as practical to help reduce wheel noise sometimes referred to as "tire-slap".

Transverse Tined Texturing

Transverse tined texturing was performed as per NYSDOT Special Specification: *Item 25502.070299 - Cement Concrete Pavement, Unreinforced, Class C, Profilographed.*

Immediately after finishing operations were completed and prior to the application of curing compounds, the surface of the concrete was textured with a set of randomly spaced spring steel tines in a direction perpendicular to the centerline of pavement (transverse). The individual tines were 3.1 mm wide, 0.71 mm thick, and 127 mm long. The tine spacing, size, and depth is a result of research that has been performed in an effort to minimize tire-pavement noise or "wheel-whine" characteristic of tined pavement surfaces (*1*). Although acoustical spectral data is not presented in this paper, we note that the randomly spaced tining effectively prevented audible whine and other tonal characteristics.

Longitudinal Diamond Ground Texturing

The longitudinal diamond ground texturing was performed as per NYSDOT Special Specification: *Item 25502.5010 - Full Diamond Grinding and Texturing of Concrete Pavement / Profilographe*d.

Diamond grinding involves the removal of a thin layer of the cured concrete surface using a machine with closely spaced diamond-coated circular saw blades. The diamond blades are spaced such that the thin fins of concrete left between the blade cuts break off during the grinding process, leaving a level surface with longitudinal texture. The grinding head contained 166 saw blades (3.18 mm thick), set at 2.67 mm spacing.

Construction Duration and Cost

Both construction duration and bid price were compared to determine the cost differential between the two pavement surface treatments. Construction duration is an important factor because additional construction time would result in additional delays to the traveling public. Also, the contractor would include the cost of extended construction duration in the bid prices for maintenance and protection of traffic (MPT) and related construction items.

Construction Duration

For the subject contract (TAN 97-91), less construction time was required for the transverse tined pavement as compared to the diamond ground pavement.

The operation of tining was automated. It was performed from the same work-bridge and during the same work operation as the floating/finishing. Therefore, the production rate is only slightly increased over that where no tining is required (as would be the case in preparing the surface for diamond grinding).

The rate of the diamond grinding process varies depending on equipment horsepower, aggregate hardness, condition of the cutting blades, and the depth of the cut. For this project, the grinding rate was approximately 0.6 lane-Km per day (0.4 lane-miles/day). In addition there was a 7-day minimum curing time required prior to grinding. The diamond grinding process was completed over continuous highway sections during an independent construction sequence.

Cost

From the information available on the subject contract, there is inadequate information to determine the precise cost difference between the two surfacing techniques.

The price bid for the diamond grinding item on this project was $\$3.15/m^2$ ($\$3.75/yd^2$). The average industry cost is $\$2.10/m^2$ ($\$2.50/yd^2$) (*2*). The increased cost above the industry average is likely due to the fact that diamond grinding is a relatively new industry to the area. The subcontractor was brought in from out-of-state, and the test areas for grinding were relatively small, both of which cause the cost per square yard to be higher. Also, additional time to grind or float finish the pavement is sometimes needed to achieve required tolerances before tining.

PAVEMENT NOISE ANALYSIS

Research has shown that different commonly used pavement materials and treatments can have a significant influence on highway-generated noise levels (*3,4*). The pavement noise analysis for this study uses a combination of noise measurements and analytical noise modeling to evaluate the relative acoustical performance for the two candidate pavement types for both empirical and theoretical highway traffic conditions.

Noise Measurements

A series of traffic noise measurements were conducted along the northbound lanes of the test section between April 11 and April 20, 2000. Noise measurement and analysis procedures were consistent with specifications in *Measurement of Highway-Related Noise* (*5*) and *Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model* (*4*). The measurement program included single vehicle pass-by measurements, drop-off vehicle noise measurements, and aggregate traffic noise measurements.

Single Vehicle Pass-by Measurements

Single vehicle pass-by measurements were conducted for both longitudinal ground, and transverse tined pavement types. Measurements were conducted between 11 PM and 6 AM, in order to better capture isolated individual vehicle events.

The single vehicle pass-by measurements were conducted in accordance with documented procedures for the development of Reference Energy Mean Emission Levels (REMEL's) used in the FHWA Traffic Noise Model. Due to project terrain constraints, the recommended 15 meter (50 foot) reference measurement positions were not available for both pavement types. Therefore, the single vehicle pass-by measurements were conducted at a distance of 7.5 m (25 ft) and adjusted to the 15 m (50 ft) reference distance using the measured drop-off correction.

The results of the single vehicle pass-by measurements (adjusted for the reference distance) were graphed to show individual vehicle data points. Linear regressions representing each pavement surface type were calculated for automobile, medium truck, and heavy truck types. An example of the data and regression curves for autos and light trucks care shown in Figure 1. Similar graphs were generated for medium trucks and heavy trucks.

Drop-off Noise Measurements

The primary single vehicle measurement site, near the interface of the two pavement types did not allow for the required 15 meter wayside measurement position due to an existing embankment. A secondary measurement location was selected in order to measure the single vehicle drop-off correction. An average drop-off correction value of 6.2 dB was measured for all vehicle types.

Aggregate Traffic Measurements

Long-term (24 hour) aggregate traffic noise measurements were taken in order to determine the loudest hour of the day for the study area.

Short-term (1-hour) aggregate traffic noise measurements were collected during the loudest hour of the day concurrently with classified traffic counts to identify time-averaged noise level for both pavement types and associated traffic mix.

Traffic Noise Model Analysis

The FHWA Traffic Noise Model (TNM) is a Windows computer based analytical model that predicts traffic generated noise levels. The program predicts hourly average noise levels in A-weighted decibels (dBA) based on traffic volumes and mix, roadway and landscape topography, and other factors. The program uses Reference Energy Mean Emission Levels (REMELs) for a variety of vehicle types (autos, medium trucks, heavy trucks, buses and motorcycles) for a number of standard pavement types, including standard PCCP, dense grade asphalt, open grade asphalt, and an average of all pavement types. The program also provides for the input of user-defined REMELs for special vehicle types.

TNM User Defined Vehicles Parameters

Using single vehicle pass-by measurement data for each pavement type, parameters required to specify user-defined vehicles in FHWA's Traffic Noise Model (TNM) were developed for each of the three primary vehicle types (autos, medium trucks, heavy trucks) . User-defined vehicle parameters were developed for both pavement types. Table 1 summarizes input parameters developed from the noise measurements, along with 95% confidence limits for the linear regression of each vehicle/pavement type.

The "minimum level" parameter specified in Table 1 is representative of low speed vehicle noise, where the noise level is assumed to be dominated by engine/exhaust noise (independent of tire-pavement noise contributions). Because the data collected for this study is limited to vehicles traveling at highway speeds (80 to 140 km/h), the published TNM standard minimum levels for each of the three vehicle types is used.

TNM runs using new REMEL parameters for the candidate pavement types were validated to within approximately one decibel when compared to aggregate noise measurements.

TNM Vehicle Mix Scenarios

Four theoretical traffic mix scenarios were developed as a comparison parameter for pavement noise levels as follows:

1. Parkway: 100% autos and light trucks.
2. Light truck usage: 95% autos and light trucks, 5 % medium and heavy trucks.
3. Moderate truck usage: 80% autos and light trucks, 20 % medium and heavy trucks.
4. Heavy truck usage: 60% autos and light trucks, 40 % medium and heavy trucks.

TNM Predicted Noise Levels

Employing the user-defined vehicle parameters generated from the pavement specific pass-by data (presented above), TNM was used to predict traffic noise levels for a variety of conditions. The scenarios evaluated include variations of the following factors:

- Pavement Type - Two candidate pavement surfaces (longitudinally ground and transverse tined) plus the standard TNM “average” pavement type.

- Vehicle Mix - Four different vehicle mix scenarios, as defined above. All vehicles are assumed to be traveling at a steady cruise speed of 108 km/h (65 mph).

- Receiver Distance - Receiver distances of 30, 60, and 90 meters from mainline traffic lanes.

- Line of Sight Obstructions - For each pavement type and receiver distance, both obstructed and unobstructed line of sight conditions are evaluated. For the unobstructed case, a clear line-of-site from traffic to the receivers is assumed. For the “obstructed” case, a typical 1 meter high “jersey barrier” at the edge of the pavement between the traffic and the receivers is assumed. Aside from the jersey barrier, all other elements (roadways, receivers) are modeled at zero elevation (all receivers are modeled to be 1.5 meters above the nominal elevation).

For modeling purposes using TNM, it is assumed that a total of 6000 vehicles per hour split evenly between northbound and southbound directions. Table 2 shows the predicted TNM noise levels at the modeled receiver locations for each of the modeled scenarios.

The results of the TNM modeled scenarios are shown in Figures 2, 3 and 4. Figure 2 shows the relative difference in noise level as a function of receiver distance from the roadway centerline. Two curves show the predicted difference for an unobstructed observer’s view of the roadway and for a view partially obstructed by a 1 meter high jersey barrier at the near edge of the roadway. Figure 3 shows the relative difference in noise level as a function of average vehicle speed, with difference curves for each of the four vehicle mix scenarios. Figure 4 shows the noise level difference as a function of percent heavy truck usage for typical highway speed.

Noise Data Analysis and Results

The results of the analysis conclude that the longitudinally ground pavement is quieter than the transverse tined pavement by approximately 2 to 5 dBA, depending primarily on the vehicle mix.

The short-term aggregate traffic noise measurements conducted along the study test section during the peak noise hour (which generally corresponds to a light to medium truck usage mix scenario) show that the longitudinal ground pavement is about 3.0 dBA quieter than the transverse tined pavement. Aggregate traffic noise measurement conducted approximately one year later showed essentially no change in absolute or relative noise levels.

The single vehicle pass-by regression analysis indicates that the longitudinally ground pavement does not provide the same acoustic benefit to all vehicle types uniformly. The longitudinally ground pavement provides approximately 5 dBA noise improvement for automobiles and light trucks relative to the transverse tined pavement, but only about 2 dBA improvement for medium and heavy trucks. This result was expected since automobile noise levels are dominated by tire-pavement noise at highway speeds, while engine and exhaust noise (which is independent of pavement type) makes a significant contribution for heavy and medium trucks at highway speeds. This suggests that higher percentages of heavy and medium trucks using the roadway would diminish the relative acoustical advantage of the longitudinally ground pavement. This conclusion is supported by the TNM predicted noise levels, which indicate that the longitudinal ground pavement would be approximately 5.4 dBA quieter than the transverse tined pavement the parkway scenario (100% autos) but only about 2.2 dBA quieter for the heavy truck usage scenario (Figure 4). A 2 dBA difference in noise level is generally below the threshold of a perceptible difference to the average human ear.

The comparison of TNM predicted noise levels also suggests that receiver distance and small line of sight obstructions (such as a jersey barrier) play a lesser role in the relative noise levels of the two pavement types (Figure 2). The presence of a jersey barrier reduced the relative benefit of the longitudinally ground pavement by less than 0.5 dBA. The influence of distance on the relative difference in noise levels of the two pavement types was 0.3 dBA or less. The influence of vehicle speed on relative noise level was generally less than 0.5 dBA depending on vehicle mix, over the range of typical highway speeds (Figure 3).

SKID TESTS AND MACROTEXTURE MEASUREMENTS

Skid resistance and macrotexture measurements were performed in April, 2000 and June, 2001. Tests were conducted on the longitudinal diamond ground and transverse tined PCCP surfaces in the northbound lanes (constructed in 1999) and the southbound lanes (constructed in 1998). Tests were performed in both the driving lane and passing lane.

Skid resistance measurements were made at 67, 83 and 100 km/h (40, 50, and 60 mph) on each surface treatment with both blank and ribbed test tires. Skid resistance is defined as the retarding force generated by the interaction between a pavement and a tire under a locked-wheel condition (*6*). To ensure that measurements made at various times and places can be compared with each other, a standardized tire was used and a standard amount of water was applied to the dry pavement ahead of the tire. The details of the skid resistance test procedure are described in the *ASTM E 274* (*7*). The details of the blank and ribbed standard test tires are described in the *ASTM E 524* (*8*) and the *ASTM E 501* (*9*) respectively. A minimum of five measurements per test section were conducted and used to calculate an average for each test section. The results of the pavement skid test are reported in Table 3 as the skid number (SN).

The values reported in Table 3 are reasonable and are considered accurate in accordance with ASTM standards. The effect of speed is consistent and as expected (SN decreases when speed increases) for the average SN. The acceptable precision of SN units can be stated in the form of repeatability. ASTM E 274 suggests an acceptable standard deviation of 2 SN units.

The two different test tires were used to measure two different pavement surface characteristics. Tests performed using the blank (smooth) test tire represent the pavement's macrotexture, while measurements made with the ribbed test tire best represent the pavement's microtexture. In general, microtexture provides the frictional capability of dry pavement. Macrotexture provides the drainage capability at the tire-pavement interface and therefore how effective the microtexture will be when the pavement is wet.

Good microtexture is obtained by using suitable aggregate in the pavement surface. Fine aggregates containing a minimum of 25% siliceous sand; durable non-polishing coarse aggregates, a low water to cement ratio, adequate air content, adequate cement factor, and good curing practices are all necessary to obtain high-quality durable concrete (*10*).

To further investigate the pavement surface's macrotexture, mean texture depth (MTD) measurements were performed. This measurement involves spreading a known volume of glass spheres on a clean, dry pavement surface, measuring the area covered, and calculating the average depth between the bottom of the pavement surface voids and the top of surface aggregate. Ten mean texture depth measurements were made in each of the eight test sections. The tests were conducted in accordance with *ASTM E 965* (*11*). The average mean texture depth for the longitudinal diamond ground surfaces was 0.58 mm in 2000 and 0.46 mm in 2001. The average mean texture depth for the transverse tined surfaces was 0.58 mm in 2000 and 0.53 mm in 2001. Data for both surfaces indicate a small drop in macrotexture for the one-year period.

The standard deviation of repeated MTD measurements by the same operator on the same surface can be as low as 1% of the average texture depth. The standard deviation of different measurements within the same site (pavement surface) may be as large as 27% of the average texture depth (*11*).

Analysis of Data

Skid resistance becomes a major factor in traffic safety when the pavement is wet. However, skid resistance is not the only factor affecting wet pavement safety. Other factors include: traffic characteristics (speed, density, percentage of trucks), road geometric configuration (horizontal curvature, vertical alignment, and super-elevation), driving difficulty (signalization, presence of turning lanes and weaving movements, surrounding land use, and number of access points), and pavement wet time (average period of time during a year when the pavement is wet) (*12*). All of these factors interact in a manner that is very difficult to analyze in quantitative terms. This is the main reason for the lack of nationally accepted minimum skid resistance values that could be used as safety thresholds.

Having recognized that skid resistance alone does not determine the level of wet pavement safety, the ranges of 35 to 40 for ribbed tire skid resistance and 20 to 25 for blank tire skid resistance, (both measured at 65 km/h) have been recommended in the past as the minimum values that should apply to highway pavements in general (*13*). These values were based on a trend that was observed in a study of wet-to-dry pavement accidents versus skid number in the State of Kentucky. The Pennsylvania State Department of Transportation uses the recommended lower values (35 and 20) in addition to certain accident criteria as thresholds to erect "Slippery When Wet" signs until the pavement surface friction characteristics could be improved. All sites in this study have skid resistances above those ranges.

When arranging the mean texture depth data in an order from the most to the least exposure to traffic, the 2000 MTD data of the experimental longitudinal diamond ground surface demonstrate a decline from 0.71 to 0.53 mm. The transverse tined surface remained virtually unchanged at 0.56 mm. The data from 2001 testing shows the same trend for the experimental longitudinal diamond ground surface (0.51 to 0.43 mm); however, the transverse-tined surface demonstrates a reverse trend (0.48 mm on the least-traveled surface to 0.56 mm on the most-traveled surface). It should be noted that the operators reported a large variability in the surface macrotexture within a single test section. The 2001 measurements were obtained in the section as the previous year, but not in the exact same location (as it is difficult to locate the lock-up in the precise same location from year to year). However, many actual skid tests were performed within each section and were averaged to give the nominal values for the corresponding sections. The difference between 2001 measurements on all surfaces might simply demonstrate the variability of the surfaces rather than a trend related to traffic level. Initially, it appeared that the experimental surface was being affected more by traffic than the transverse tined surface. However, it is too early to speculate whether this is representative of a trend that might continue or level out over a period of time.

As seen in Figure5, the skid resistance levels of the driving lane ($SN_{D)}$ are generally lower than the skid resistance levels of the passing lane ($SN_{P)}$. This relationship is illustrated by the fact that almost all data points on the graphs are above the line traversing the plot at a 45-degree angle which represents the points at which the SN_P and SN_D are equal. This data is consistent with the general trend that higher average daily traffic levels are found in the driving lane rather than in the passing lane. Larger average daily traffic levels increase the rate at which the pavement surface becomes polished and thereby lowers the microtexture value of the surface at a faster rate.

As shown in Figure 6, there is an equal distribution of the ribbed tire SN data points about the line traversing the plot at a 45-degree angle. The line represents the points at which the $SN_{Longitudinal}$ and $SN_{Transverse}$ are equal. The 2000 blank tire SN data points are consistently higher for the longitudinal diamond ground pavement compared to those of the transverse-tined. The 2001 blank tire SN data show a general shift toward the line of equality with the exception of the data for the southbound passing lane. This suggersts that LDG macrotexture starts out better that TT but deteriorates more quickly, so that after one year, LDG and TT macrotextures are more equal."

In summary, initial results show a greater loss of macrotexture (MTD and SN_B) for the experimental longitudinal diamond ground surface than for the transverse tined surface. However, the relative skid resistance of the experimental longitudinal diamond ground surface tends to be higher than that of the transverse tined surface using a blank tire (representative of the surface macrotexture / resistance to wet pavement accidents). There is no significant difference in the skid resistance measured with the ribbed tire (representative of the surface microtexture), as would be expected since both pavements were constructed using the same mix design.

DISCUSSION OF RELATIVE SERVICE LIFE

The pavement skid resistance is expected to change over a period of several years. Comparing the data for the experimental longitudinal diamond ground surface constructed in 1998 with that constructed in 1999 yields no significant difference in mean SN value (Table 3). Comparing the data for the transverse-tined surface constructed in 1998 with that constructed in 1999 yields a small difference in mean SN. The 2001 data shows even less difference in mean SN between the different construction years for the transverse tined surface. This would indicate that the small difference in skid resistance between the northbound surface and the southbound surface is diminishing.

Another consideration is the life-cycle cost. Similar studies (*14,15*) have shown a long-term benefit from diamond grinding. The studies speculate that the benefit is realized from reduced pavement joint fatigue that results from the smooth surface created by diamond grinding. Profilograph readouts from this project show that the diamond grinding creates a significantly smoother profile, so the diamond grinding process may show a long-term (20+ years) benefit due to the increased service life.

Note that this data was collected from 177 rehabilitated highway sections in 26 states throughout the country. To date no known data is available on the longevity of newly constructed diamond ground pavements, which may differ from the rehabilitated highways in that the concrete is harder due to the additional curing time.

FUTURE RESEARCH (YEAR 2001)

Pavement noise and skid resistance testing is to be continued over the next several years on an annual basis in order to further document changes in these parameters over time. The data should be measured at the same time of the year (i.e., spring) to avoid changes in measured values caused by short-term and long-term seasonal variations. Traffic volumes and accident data will also be collected. Interviews with various highway users such as state troopers, maintenance personnel, and others will be conducted to determine if there are noticeable differences in maintenance requirements, vehicle operation, or rider comfort while traveling over the different pavement surfaces.

CONCLUSIONS

Construction Time and Cost

The longitudinal diamond ground pavement will require more construction time and will cost more than transverse tining. However, a higher initial cost for longitudinal diamond grinding would likely be partially offset by an extended service life.

Pavement Noise

The longitudinally diamond ground pavement was shown to be 2 to 5 dBA quieter than the transverse tined pavement, depending mostly on the percentage of heavy trucks in the vehicle mix. The longitudinally ground pavement was approximately 3 to 4 dBA quieter for typical highway traffic mix and speed. Aggregate traffic noise measurements made after approximately one year showed virtually no difference in relative or absolute noise levels.

Skid Resistance

Initial measurements show a greater wet skid resistance for the longitudinal diamond ground surface than for the transverse tined surface. The difference was shown to be less after about one year, but with the longitudinal diamond ground pavement still superior. The dry skid resistance for both pavement surface treatments was essentially the same.

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REFERENCES

1. FHWA PCC Surface Texture Technical Working Group Findings - www.bts.gov/ntl/docs/79_tpave.html.
2. American Concrete Pavement Association, "*Diamond Grinding and Concrete Pavement Restoration*", ACPA Technical Bulletin TB-008P, 1990.
3. Wayson R.L. *Relationship Between Pavement Surface Texture and Highway Traffic Noise*, NCHRP Synthesis 268, TRB, National Research Council, Washington D.C. 1998.
4. Fleming, G.G., A.S. Raposa, and C.S. Lee. 1995. *Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model (FHWA TNM), Version 1.0.* Cambridge, MA: John A. Volpe National Transportation Systems Center, Acoustics Facility. FHWA-PO-96-008
5. Lee, C.S. and G.G. Fleming. 1996. *Measurement of Highway Related Noise*. Cambridge, MA: John A. Volpe National Transportation Systems Center, Acoustics Facility. FHWA-PO-96-046
6. American Society for Testing and Materials, "*Standard Definitions of Terms Relating to Traveled Surface Characteristics, Designation: E 867,*" in Annual Book of ASTM Standards, Vol. 04.03 (Philadelphia, PA: ASTM, 1999).
7. American Society for Testing and Materials, "*Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire, Designation: E 274,*" in Annual Book of ASTM Standards, Vol. 04.03 (Philadelphia, PA: ASTM, 1999).
8. American Society for Testing and Materials, "*Standard Specification for Standard Smooth Tire for Pavement Skid-Resistance Tests, Designation: E 524,*" in Annual Book of ASTM Standards, Vol. 04.03 (Philadelphia, PA: ASTM, 1999).
9. American Society for Testing and Materials, "*Standard Specification for Standard Rib Tire for Pavement Skid-Resistance Tests, Designation: E 501,*" in Annual Book of ASTM Standards, Vol. 04.03 (Philadelphia, PA: ASTM, 1999).
10. U.S. Department of Transportation Federal Highway Administration, "*Portland Cement Concrete Mix Design and Field Control,*" FHWA Technical Advisory T 5080.17, - 1994.
11. American Society for Testing and Materials, "*Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique, Designation: E 965,*" in Annual Book of ASTM Standards, Vol. 04.03 (Philadelphia, PA: ASTM, 1999).
12. B. T. Kulakowski, et. al. Skid Resistance Manual, Report No. FHWA-IP-90-013 (Washington, DC: Federal Highway Administration, 1990).
13. W. E. Meyer and J. J. Henry. "*Tire-Pavement Traction, Demand and Availability,*" SAE Technical Paper Series, Paper No. 840071, 7 pp., 1984.
14. Snyder, M.J. Reiter, K.T. Hall, and M.I. Darter, "Rehabilitation of Concrete Pavements, Volume I: Repair Rehabilitation Techniques," Report FHWA-RD-88-071, 1989.
15. S. Rao, H.T. Yu, and M.I. Darter, "*The Longevity and Performance of Diamond-Ground Pavements,*" Research and Development Bulliten RD118, 1999.

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TABLE 1 TNM User-Defined Input Data

Pavement Type	***Vehicle Type***	***Min. Level***	***Intercept***	***Slope***	***95% Confidence Limit (dB)***
Longitudinally Diamond Ground	Auto	50.1	31.6	25	± 0.15
	Medium Trucks	68.0	66.3	9.5	± 0.90
	Heavy Trucks	74.3	8.6	43.7	± 0.30
Transverse Tined	Auto	50.1	28.3	29.8	± 0.12
	Medium Trucks	68.0	59.6	14.2	± 0.64
	Heavy Trucks	74.3	15.9	40.7	± 0.23

TABLE 2 Predicted Absolute Noise Levels

Prediction Scenario		***Receiver***					
		Unobstructed			***Jersey Barrier***		
Pavement	***Traffic Mix***	***30m***	***60m***	***90m***	***30m***	***60m***	***90m***
TNM Average	Parkway	72.0	67.4	64.7	69.8	64.2	60.3
TNM Average	Lt. Truck	73.8	69.6	66.9	72.2	67.2	63.9
TNM Average	Med. Truck	76.8	73.0	70.4	75.7	71.3	68.2
TNM Average	Hvy. Truck	79.1	75.4	72.9	78.2	73.9	71.0
Longitudinal Ground	Parkway	72.2	67.6	64.9	70.1	64.4	60.6
Longitudinal Ground	Lt. Truck	74.6	70.4	67.8	73.1	68.3	65.0
Longitudinal Ground	Med. Truck	78.1	74.3	71.7	77.0	72.7	69.7
Longitudinal Ground	Hvy. Truck	80.6	76.9	74.4	79.7	75.5	72.6
Transverse Tined	Parkway	77.6	73.0	70.3	75.5	69.8	66.0
Transverse Tined	Lt. Truck	78.7	74.4	71.7	76.9	71.8	68.4
Transverse Tined	Med. Truck	80.9	77.0	74.4	78.6	75.1	72.0
Transverse Tined	Hvy. Truck	82.9	79.1	76.5	81.9	77.6	74.6

TABLE 3 Summary of Calculated Skid Numbers.

Test Tire	Lane	SN_{40}				SN_{50}				SN_{60}			
		LDG		TT		LDG		TT		LDG		TT	
		2000	2001	2000	2001	2000	2001	2000	2001	2000	2001	2000	2001
Blank	SB DRV	37.2	35.7	30.6	33.7	30.5	24.4	23.8	20.0	27.0	18.6	24.2	20.1
	NB DRV	37.6	29.9	32.5	29.1	31.6	24.6	27.7	25.6	25.8	19.3	22.7	19.4
	SB PAS	44.7	39.8	33.7	29.9	37.1	36.7	26.5	24.9	31.3	23.8	22.4	19.1
	NB PAS	46.8	34.6	34.4	34.3	36.3	31.2	31.7	27.6	29.1	22.3	30.5	21.3
	Average	41.6	35.0	32.8	31.8	33.9	29.2	27.4	24.5	28.3	21.0	25.0	20.0
Ribbed	SB DRV	41.5	38.0	40.6	39.7	39.2	35.0	38.9	35.6	35.4	31.2	36.2	33.0
	NB DRV	41.4	40.9	42.9	42.1	38.4	35.5	43.4	36.9	40.1	34.2	38.1	34.7
	SB PAS	48.5	45.3	43.5	45.5	43.2	43.9	39.7	42.9	38.5	35.6	38.8	38.0
	NB PAS	49.1	45.0	49.7	46.8	44.6	40.5	47.4	43.3	40.0	38.0	45.0	43.4
	Average	45.1	42.3	44.2	43.5	41.4	38.7	42.4	39.7	38.5	34.8	39.5	37.3

LDG = longitudinal diamond ground
TT = transverse tined
SB = southbound
NB = northbound
DRV = driving lane
PAS = passing lane

Southbound lanes opened to traffic December, 1998.
Northbound lanes opened to traffic December, 1999.

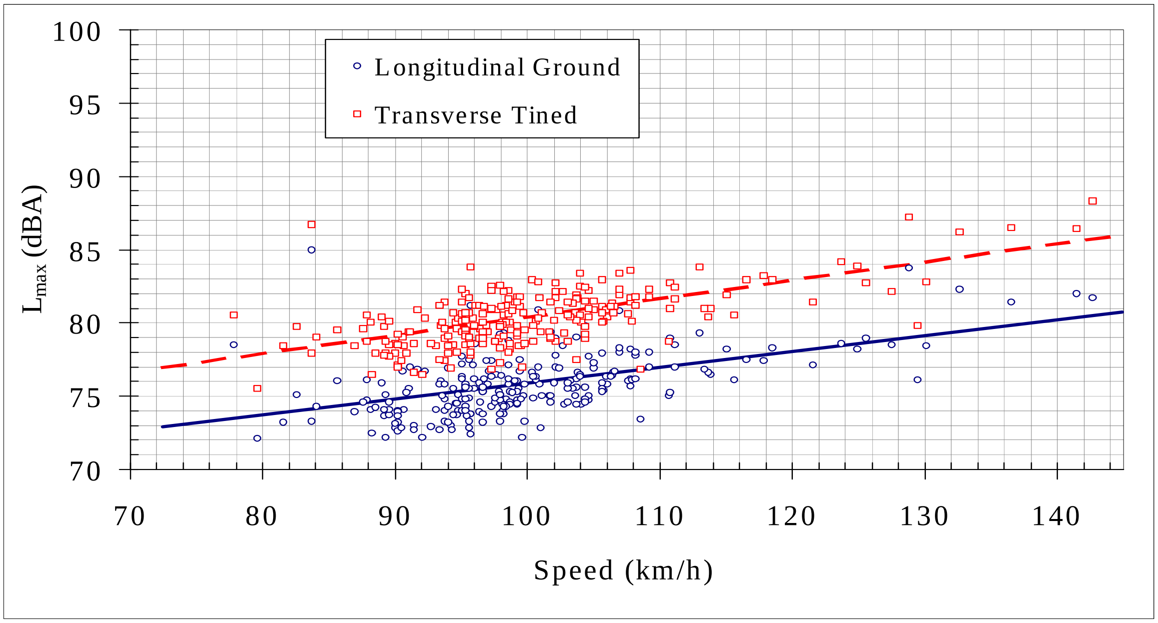

FIGURE 1. Single Vehicle Pass-by Noise Measurements for Automobiles

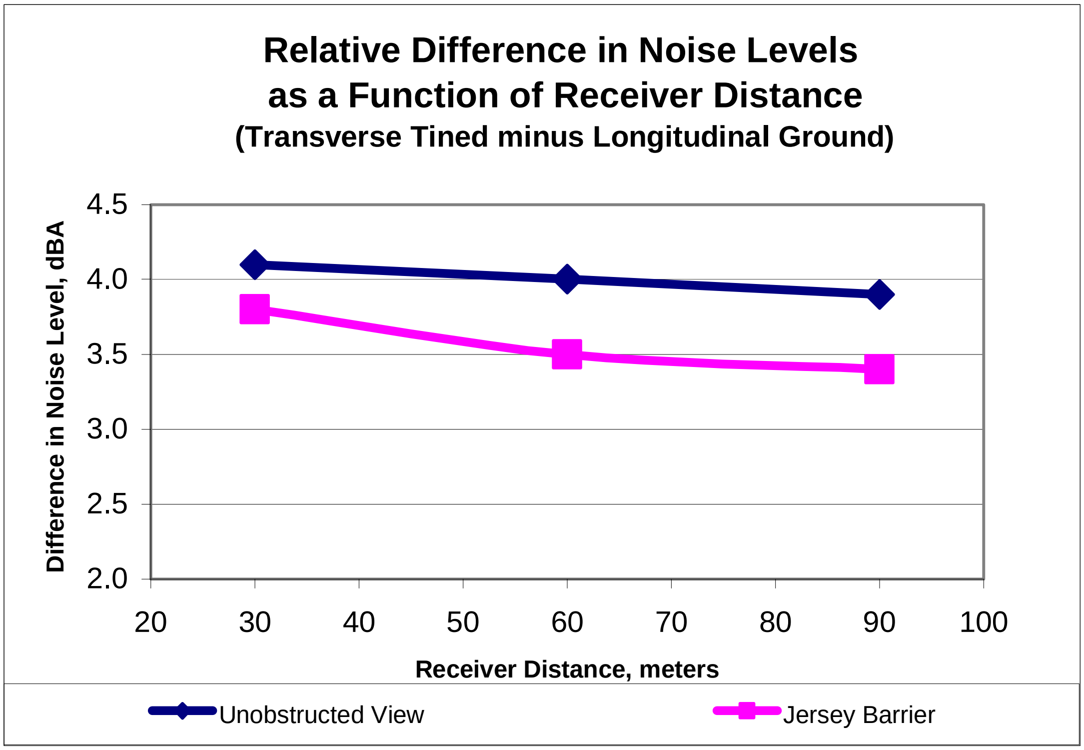

FIGURE 2. Relative Difference in Noise Level as a Function of Receiver Distance

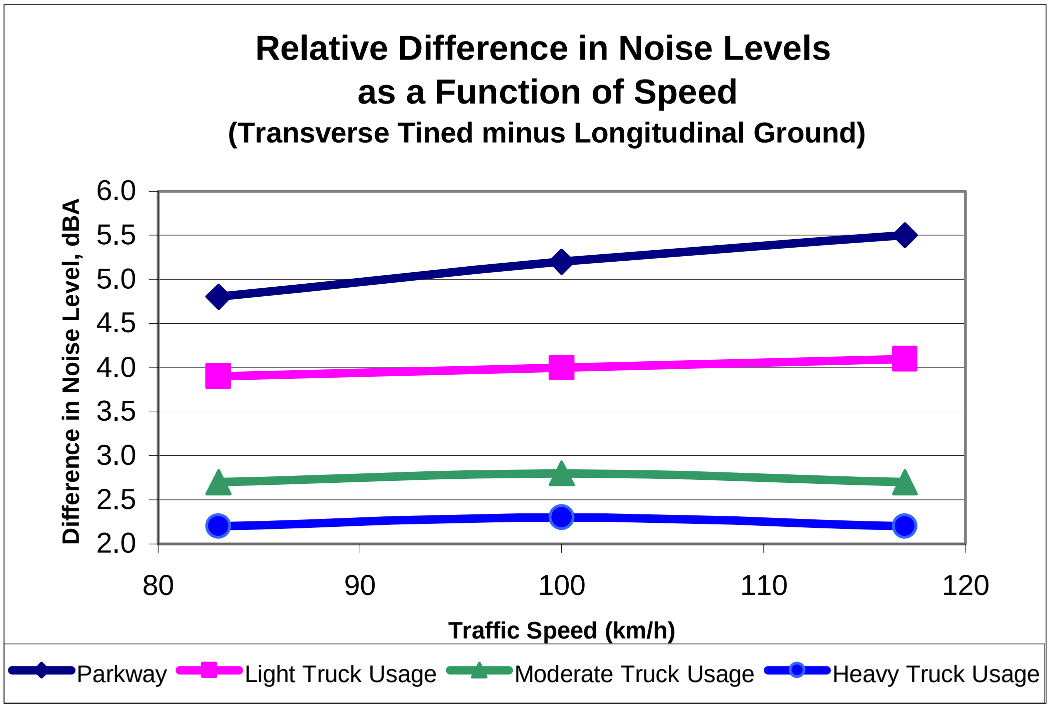

FIGURE 3. Relative Difference in Noise Level as a Function of Vehicle Speed

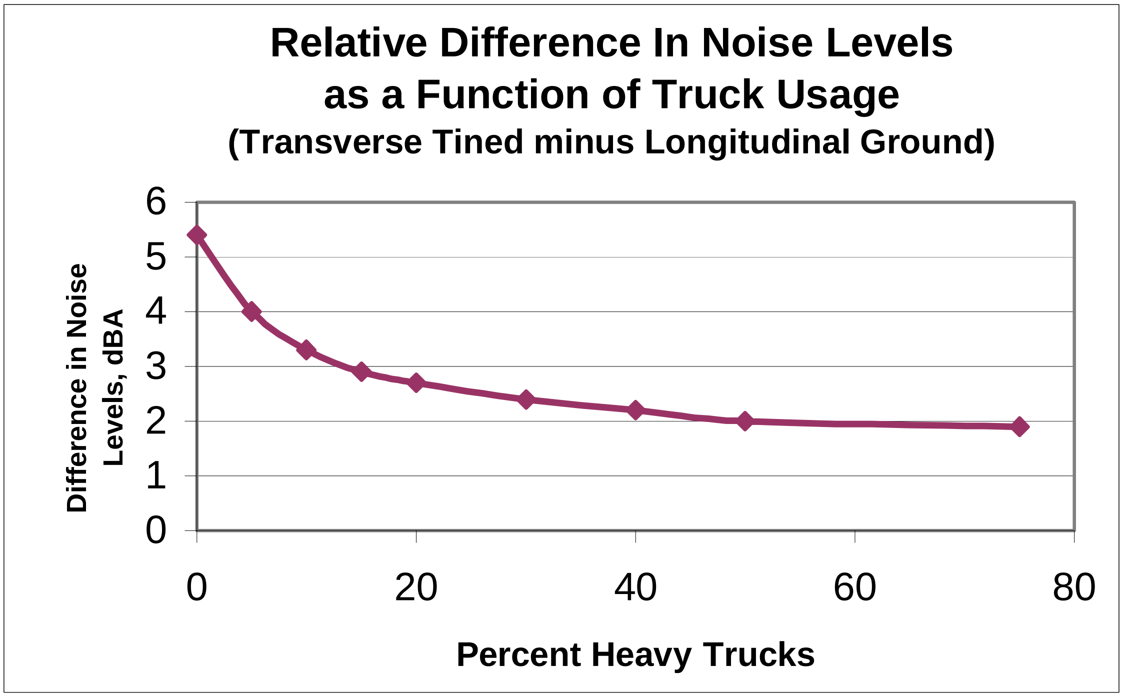

FIGURE 4. Relative Difference in Noise Level as a Function of Heavy Truck Usage

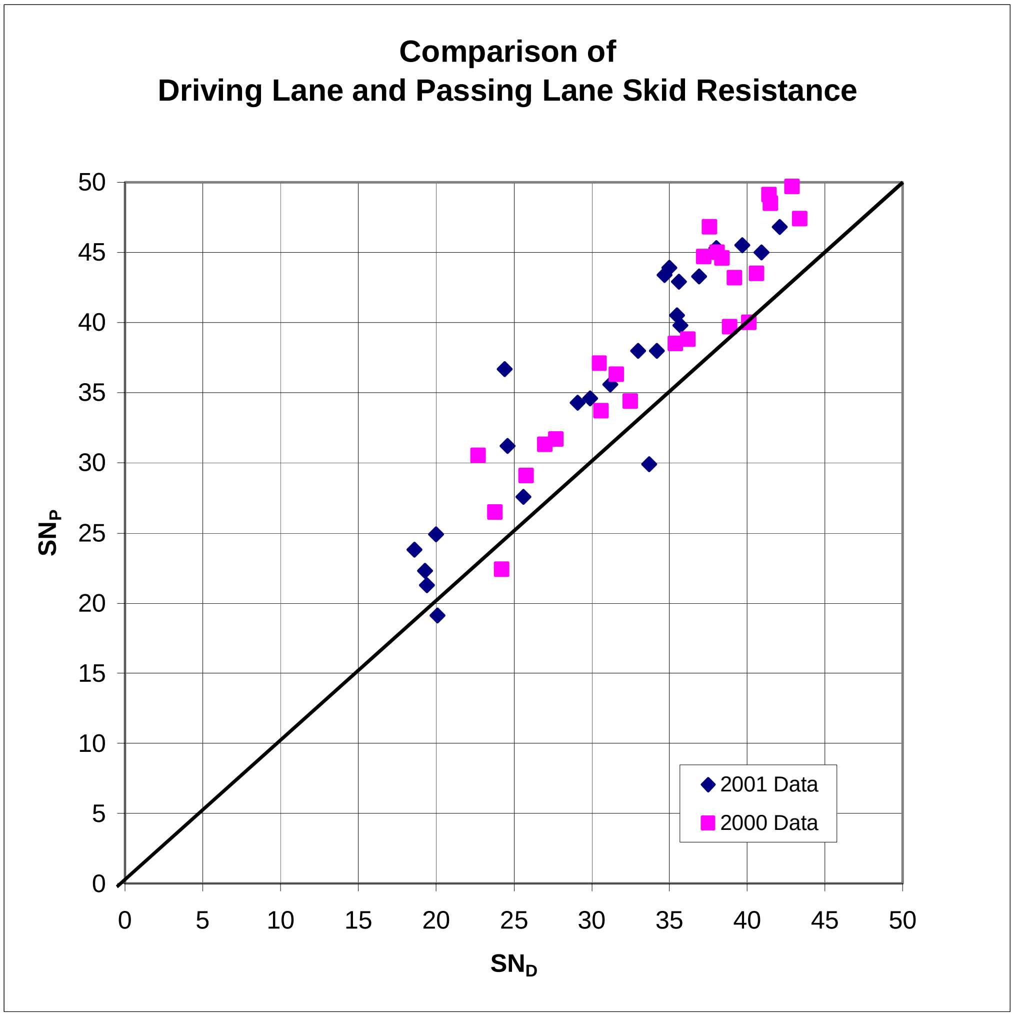

FIGURE 5. Skid Resistance for Driving Lane versus Passing Lane

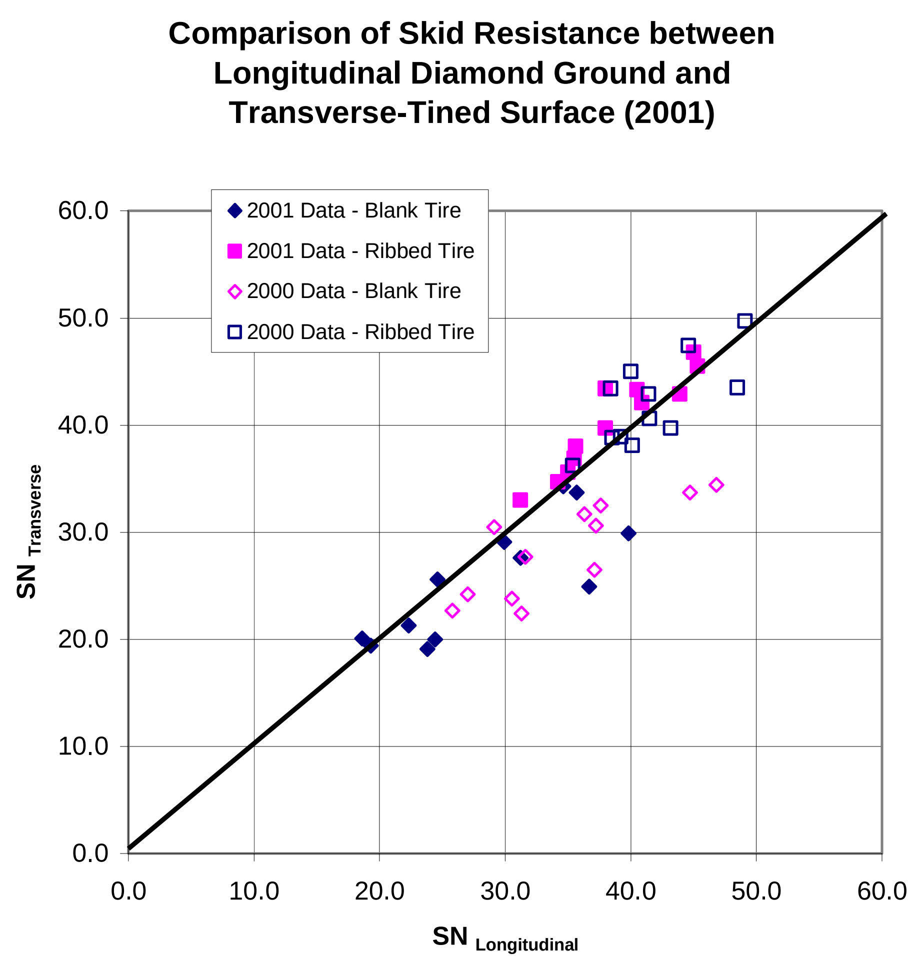

FIGURE 6. Skid Resistance for Longitudinal Diamond Ground versus Transverse Tined PCCP