FROM CONCEPT TO DEPLOYMENT

(Case Studies for Friction and Noise Improvement at MnROAD Research Facility)

By

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ABSTRACT

Construction and evaluation of transverse drag textures and the development of a quiet grinding configuration with sufficient friction are two surface improvement strategies discussed in this paper. With the growing interest in quiet pavements, prospects for post-construction acceptance of a concrete pavement surface is minimal unless it provides adequate skid resistance and good ride quality as well as good acoustic properties. Acoustic properties of a transverse brooming alternative to longitudinal brooming improved friction in the drag textures but resulted in increased noise.

Efforts at the Herrick Laboratory in Purdue University preceded a full scale experimentation of grinding configurations at the MnROAD research facility. This culminated in development of a quiet grinding configuration. This configuration was subsequently pre-deployed on Highway 94 near St Cloud Minnesota in 2009. Finally this quiet grinding was fully deployed and implemented in a mega project on Interstate 35 in Duluth Minnesota in 2010.

This paper discusses milestones from conceptualization to deployment and compares the acoustic properties of the final diamond grinding configuration to other surfaces in the same research facility. Evidently, a quiet concrete surface with sufficient skid resistance and significant ride improvement has been developed and implemented.

INTRODUCTION

Minnesota Department of Transportation has used drag textures for concrete texturing for 12 years in replacement of transverse tining which was noisy (1). Occasionally there have been isolated safety questions about drag textures. As an initiative to improve friction and noise and friction capacity of the Drag textures., a transverse drag cell was created at the Mn/DOT test facility called MnROAD. Studies showed that wthere were no wet weather increase due to the use of turf drag.The friction improvement and noise observations in the test cell are briefly discussed in this paper.

In a similar initiative the quest for a quiet diamond grinding configuration with sufficient friction was initiated at athe herrick laboratory in Purdue university in 2005. This was followed by gradual field deployment of thegrinding configuration at MnROAD until a successful configuration was deployed in a large construction project. Diamond grinding is the removal of hardened portland cement concrete (PCC) through the use of closely-spaced, diamond saw blades mounted on a rotating drum(3), (4). This process restores or improves ride quality to the pavement. It also changes surface texture, improving friction characteristics. The frictional resistance of easily polished aggregate (or softer aggregate such as limestone) can be improved by increasing the blade-spacing to slightly increase the chip or "land area" between the sawed grooves(5). According to several aothors, (5), (6) one of the advantages of diamond grinding is that it provides long-term improvement of the pavement surface characteristics.

Increase in population and transportation have resulted in increased traffic noise. As the investment exorbitance of noise abatement walls can no longer cope with this challenge, governments are compelled to examine quiet pavement enhancement through pavement surfaces. It is expected that if the bumps and dips of a poorly performing surface are corrected by diamond grinding the surface quietness will improve due to uniform texture and a reduction of excessive tire vibration (9). This quest for quiet pavements has resulted in increased interest in diamond grinding as a pavement surface noise correction measure. Conventional diamond grinding configurations are not optimized for pavement-tire noise properties. Therefore, it is desirable to improve diamond grinding patterns to improve tire-pavement noise characteristics without jeopardizing ride quality and friction properties. In the past decade the United States Federal Highway Administration (FHWA) initiated several studies aimed at developing and deploying a quiet grinding configuration. The Center of Safe Quiet and Durable Highway at Purdue University conducted a series of laboratory tests on various diamond grinding texture configurations and recommended a new diamond grinding texture, referred to in this paper as Innovative Diamond Grinding (IDG), which promised to reduce tire-pavement noise (9).

This paper mainly elucidates the subsequent field development, the predeployment on intersate Highway 94 and the deployment of the new grinding configuration in interstate highway 35, Duluth Minnesota.

PRELIMINARY LABORATORY DEVELOPMENT

The Federal Highway Administration (FHWA) The International Grinding and Grooving Association (IGGA), American Concrete Paving Association (ACPA) and Purdue University initiated laboratory studies towards a diamond grinding texture with improved noise characteristics. The research began by attempting to optimize blade width and spacer configurations. Traditionally, this had been thought to control resulting noise characteristics. Earlier investigations indicated that fin (landing) profile was the controlling variable and not the blade/spacer configuration.

The main process involved creation and testing of various configurations of diamond grinding. The experimentation entailed a variation of blades and spacer stacking to create configuration types. The Purdue research uses the Purdue Tire Pavement Test Apparatus (TPTA) to evaluate the various textures. This laboratory based device, shown in FIGURE1, consists of a twelve foot diameter drum upon which cast segments are placed around the circumference as shown. IGGA developed grinding head was used to grind the various textures and is shown in the right hand side of FIGURE1.

This was simulated with the use of smaller sized cutters. The texture resulting from the grooving were then attached to the large diameter drium on which a standard tire moving at 40 miles aper hour ran in a circular m,motion. Various configurations were tested until a range of configuaration became evident as quiet alternatives. The tests included groove, depth, groove width and land width combinations aimed at ascertaining the quietest range of configurations.The process did not create or use a parallel laboratory equivalent for friction measuremnent. Neither did it simulate actual OBSI speeds and linear motion.

FIGURE1. Top: Laboratory Diamond Grinder and Top Track Purdue Testing Wheel

Bottom: Rotating Drum of Blades and Spacer of Diamond Grinding Equipment.

Noise testing, using Sound Intensity (SI) techniques could only be conducted to 30 mph in the laboratory although field evaluations are typically conducted at 60 mph.

SUBSEQUENT FIELD EVALUATION STRATEGIES

The MnROAD research facility was the site for friction and noise improvement studies for drag and for ground pavements.

The Minnesota Department of Transportation (Mn/DOT) constructed the Minnesota Road Research Project (MnROAD) between 1990 and 1994. MnROAD is located along Interstate 94 forty miles northwest of Minneapolis/St. Paul 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. Parallel and adjacent to Interstate 94 and the Mainline is the Low Volume Road (LVR). The LVR is a 2-lane, 2½-mile closed loop that contains 20 test cells. Traffic on the LVR is restricted to a MnROAD operated vehicle, which is an 18-wheel, 5-axle, tractor/trailer with two different loading configurations. The "legal" load configuration has a gross vehicle weight of 80 kips. The tractor/trailer travels on the inside lane of the LVR loop in the 80K configuration on five weekdays. It was hypothesized at the inception of MnROAD that the 2 load spectra would yield similar damage ESALs on the LVR is determined by the number of laps (80 per day on average) for each day and are entered into the MnROAD database.

The mainline consists of a 3.5-mile 2-lane interstate roadway carrying "live" traffic. The mainline consists of both 5-year and 10-year pavement designs. The 5-year cells were completed in 1992 and the 10-year cells were completed in 1993. Originally, a total of 23 cells were constructed consisting of 14 HMA cells and 9 Portland Cement Concrete (PCC) test cells. Traffic on the mainline comes from the traveling public on westbound I-94. Typically the mainline traffic is switched to the old I-94 westbound lanes once a month for three days to allow MnROAD researchers to safely collect data. The mainline

ESALs are determined from an IRD hydraulic load scale was installed in 1989 and a Kistler Quartz sensor installed in 2000.Currently the mainline has received roughly seven million flexible Equivalent Single Axle Loads (ESALS) and 13million Rigid ESALS as of December 31, 2010.

Friction Improvement Strategy in Drag Textures

The first turf drag cells 32 and 52 were was built in the low volume track in 2000. Friction and ride quality were measured periodically to monitor texture survival. OBSI measurements that later commenced in 2007 in these cells facilitated noise evaluation. There was no prior laboratory work in the development of the drag textures but it was borne out of a state legislative moratorium on (noisy) transverse tined pavements in 1999 which led to the transitioning to turf or broom drag as a quiet alternative (1). Gradually theere have been occasional friction challenges with this alternative. To study friction improvement in drag textures, a transverse drag cell and more longitudinal drag cells (13) (14) were built in 2008 at the MnROAD test facility. A 60 year design cell (cell 53) was finished with transverse drag textures. This cell was also monitored to ascertain if there was any friction improvement or if the acoustic properties of the transverse drag was similar.

Summer 2007 MnROAD Proof of Concept Grind and Evaluation

Diamond grinding was performed with large equipment (FIGURE1) that consists of a large rotary drum with diamond-tipped cutters, a large water receptacle for wet grinding and a delivery pipe for the slurry produced. The process of diamond grinding begins with the design of an anticipated configuration as this determines how the grinder will stack the blades and spacers on the grind shaft. The blades are stacked to cut the groves and the spaces are stacked to facilitate the inter-groove spacing known as land width or land area. Cutting depth is enhanced by setting the radial or annular difference between the blade and spacer to correspond to the expected grind depth while the thickness of the spacers determines the land width. The proof-of-concept grinding validated the feasibility of producing the innovative grind at a production level. Although it was not a full width grinding, the process created four test strips.

- TS1 was a flush grind and groove in one pass, TS2 was the flush grind and groove in 2 passes,
- TS3 was the conventional grind of .125X .125 X 0.066 inch grove land, depth configuration TS1 and
- TS2 represented the innovative configuration with the difference of the number of passes to achieve each configuration.
- TS4 was the original non-uniform transverse tine that was in the entire lane before grinding. ACPA measured on Board sound intensity on each strip and

Mn/DOT measured Ride quality, Friction, and Texture before and after grinding. Subsequent OBSI were measured by Mn/DOT every season after summer 2007 is available in the MnROAD data base. Additionally the surfaces were evaluated for mean profile depth, friction and ride quality. Due to the width of the strips (18 inches wide and 2 ft apart) pavement smoothness and friction measurements with the light weight profiler and friction measurements with the lock wheel skid tester were challenging in the test strips but easily achieved in the subsequent full width grind discussed in a later section.

Pavement noise, mean profile depth and international roughness are measured at each stage of the grinding development. Ribbed tire and smooth tire friction were also measured. The standards and procedure for friction and was standard. However, sound intensity test procedure is discussed here.

Tire Pavement Interaction Noise: On Board Sound Intensity (OBSI) Tire-pavement noise was evaluated with the on board sound intensity (OBSI) test according to the AASHTO TP 79-08 (11) procedure. The process records and analyzes data with microphones located close to the tire-pavement contact. OBSI is a single value representing tire-pavement noise. The test is conducted on a 440-ft stretch of pavement when the test vehicle moves at a constant speed of 60 miles per hour.

The test set-up consists of a sedan outfitted with four GRAS sound intensity meters, a BRUEL AND KJAER front-end four-channel frequency analyzer and a standard reference test tire (SRTT). The microphones are suspended of the vehicle frame and positioned 3 inches vertical displacement and 2 inches lateral displacement from the leading and trailing end of the standard reference tire and pavement contact. The microphones are anchored to a free rotating ring mounted on the right wheel that allow the microphone assembly to be fixed in position and direction without inhibiting the rotation of the tire when the vehicle runs at the test speed. PULSE noise-and-vibration software installed in a connected computer receives and analyzes the data categorizing the response into component third octave frequency output.

Pavement noise response from the microphones is condensed into a third octave frequency –sound intensity plot and averaged for the leading edge and trailing edge. The OBSI parameter is the average of the logarithmic sum of the sound intensity in 12 frequencies **(**400, 500, 630, 800, 1000, 1250, 1600, 2000, 2500, 3150, 4000, and 5000 Hz) computed for the two microphones as follows:

Where SI_i (i=1, 2, 3, 12) are sound intensities in dB at each of the frequencies. The OBSI analysis is based on the AASHTO TP 76-09 protocol.

$$\mathbf{OBSI} = 10 * \log_{10} \sum_{I=1}^{12} [\, 10^{\{SI\,i/10\}} \,] \qquad \text{(Equation 1)}$$

Where $SI_{1,}$ SI_2 …, SI_{12} are sound intensities in dB at each of the 12 third octave frequencies denoted by subscripts 1 to 12.

The same scope and set of testing was repeated in the subsequent stages of grinding configuration.

PAVEMENT IMPROVEMENT AND EVALUATION (DRAG TEXTURES)

Improvements in the surface properties of drag textures and grind textures are discussed in this section. Due to the remarkable success achieved in the grind improvement, the latter is discussed in detail.

For OBSI measurements conducted between 2009 and 2010, FIGURE2 shows the comparison of the transverse broom cell to longitudinal broom cell. OBSI change of 3-dB will be detected by the human ear. A difference of 2 may be detected by a little child. The results show the longitudinal texture to be much quieter in most cases. The aggressive broom texture that was a true friction enhancement was averagely 2.5 dB louder than the moderately textured inside lane. While average ribbed tire friction number (FN) (11) of longitudinal texture was 40 and the smooth tire friction number was 25, the ribbed tire friction number of the moderate transverse tine was 43 and the smooth tire FN was 25. By contrast the Average FN (ribbed) of the aggressive transverse texture was 49 and its Average FN (smooth) was 40.

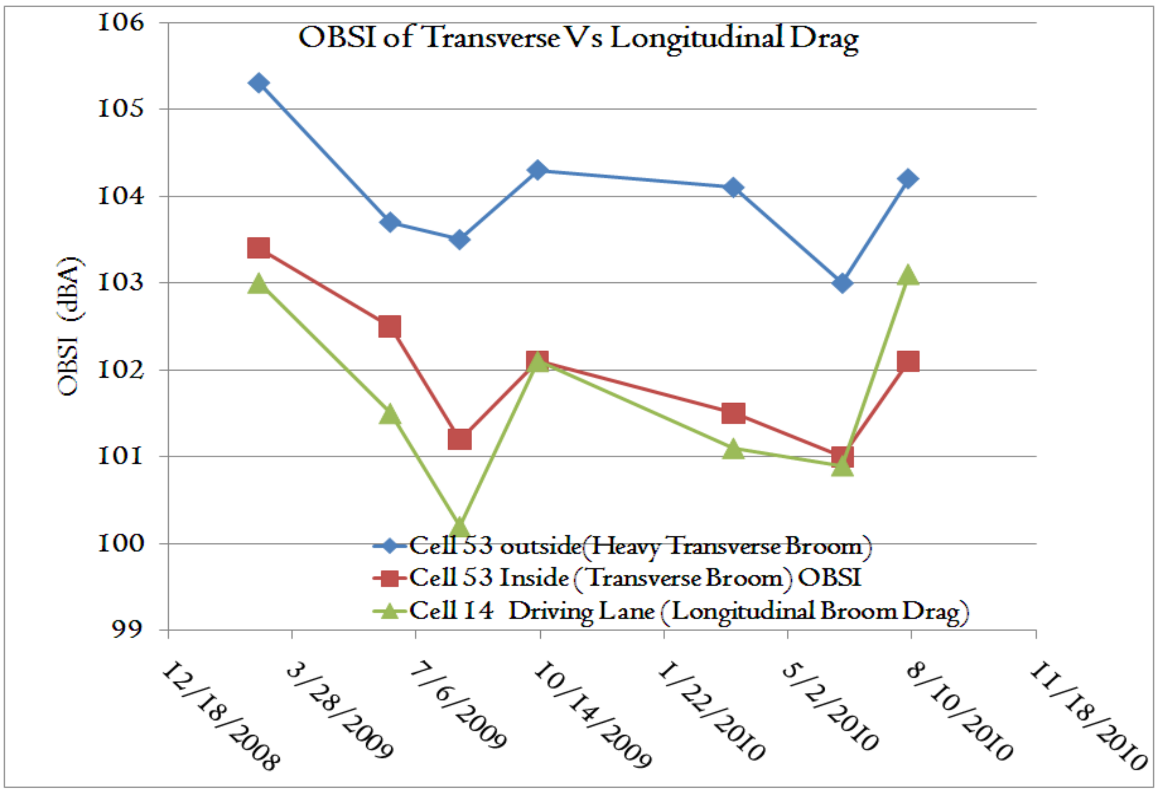


FIGURE 2: Result of OBSI Measurements Conducted Between 2009 and 2010 in Drag Cells

Sampling all the longitudinal and transverse drag cells in the MnROAD facility, it was determined from a one-tailed analysis, based on a 95 % confidence level the probability that the data set of the transverse and the longitudinal textures are similar is 0.00179. For a 2 tailed perspective, the probability that the data set is similar is 0.0037. These compared to α of 0.05 determined that transverse drag texturing thus has an effect on OBSI by producing increased noise. However, the friction benefits outweighed the increased noise demerit. These observations were in consonance with the effect of texture direction on noise as observed [12].

PAVEMENT SURFACE IMPROVEMENT & EVALUATION (DIAMOND GRIND)

Full Width Grind and Evaluation in Autumn of 2007

After pre-grind measurements the mainline Cells 7 and 8 grinding was done between 10/18/07 and 10/20/07 and the respective testing for post grind friction texture ride and noise followed shortly after. Cell 7 received the innovative grind while cell 8 received the conventional grind in minimally overlapping adjacent longitudinal 4ft strips. Two cells 500 ft long with 2 lanes (driving and passing lanes were ground with the conventional grinding. That was the full grind for cell 8 and the primary grind for cell 7. The secondary grind for cell 7 was the innovative diamond grinding configuration that is the subject of this study. Conventional Configuration (3) (MnROAD Cell 8) consists of groove and landing similar to the square box car configuration with equal land and groove area but the depth is 1/20th of an inch. Innovative grind in cell 7 consisted of groove and landing similar to the box car configuration with unequal land and groove area but the depth is 1/16 of an inch. Land is much wider than groove for quiet pavement enhancement.

Results showed that ribbed tire friction for the innovative grind ranging from 47 to 59. The disparity between ribbed and smooth tire friction was less than 5 in the innovative configurations.

At 98.5 dB (A) the innovative grind was much quieter than the conventional grind where OBSI was 102.7 dB (A) and quieter than the un-ground tine where measured OBSI was104 dB (A).

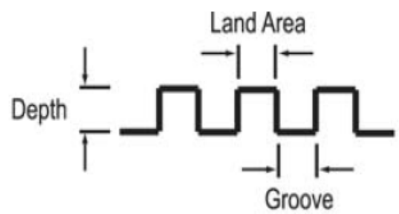
	
a) General Configuration	**Conventional Grind Cell 8**
	
c)Innovative Grind Cell 7	**d)Ultimate Grind Cell 9**

FIGURE3: Grinding Configuration of Conventional and Innovative Grinding.

Table 1 shows the relevant dimensions

TABLE 1: SUMMARY OF Full Width Grind (2007) and Grind Improvement (Cell 9) 2009OBSI, and Ride Quality tests on Cells 7 TIMELINE

	Cell 37 Multiple Strips 2007		Cell 7 Innovative 2007		Cell 8 Conventional 2007		Cell 9 Trans tine Pre-grind 2008		Cell 9 Ultimate 2008		Pre-deployment 2009		Duluth grind 2010	
	Inch	Mm	Inch	mm	Inch	mm	Inch	mm	Inch	mm	Inch	mm	Inch	mm
Mean Land Width	0.375	9.5	0.375	9.50	0.125	3.175	0.5	12.5	0.502	12.75	0.375	9.5	0.375	9.5
Mean Groove Depth	0.1	2.54	0.120	3.048	0.125	3.175	0.15	3.8	0.309	7.85	0.309	8.0	0.309	
Mean Groove Width	0.125	3.175	0.125	3.125	0.125	3.175	0.15	3.8	0.129	3.28	0.129	3.28	0.129	3.28
Mean Texture E-965	0.047	1.2	0.035	0.9	0.047	1.2	0.039	1.000	0.064	1.62	0.07	1.8	0.07	1.8
Mean Profile Depth ASTM E-2157	0.047	1.2	0.035	0.88	0.047	1.2	0.035	0.900	0.057	1.45	0.07	1.7	0.07	1.8
OBSI (dBA) AASHTO TP 76-08	99.0		99		102.7		104.0		101.0		98.7		98.7	
Ribbed Tire Friction ASTM E-274	Not Feasible		52		68		50		51		52		52	
Smooth Tire Friction ASTME-274	Not Feasible		45		55		30		46		47		47	
Corrugated Landing 1/16” X 1/16”	-		-		-		-		Yes		Yes		Yes	

Grind Improvements (Fall 2008) for Acoustics and Friction

To improve friction in the innovative grind another configuration was performed on another cell in 2008. It was determined that the land width of the configuration needed some macro texture to improve friction. A configuration was then conceived that had approximately the same aspect ratio as the innovative grind but in addition had some corrugations on the land area. This led to the grinding configuration that came to be known as the ultimate grind. A difference between the ultimate grind and the innovative grind was the width of landing (0.375 inch former versus 0.5 inch latter) and corrugated landing. The configurations were ground in cell 9 in fall 2008. It was evident that though cell 9 was not as quiet as cell 7 there was a remarkable improvement in friction. A plan was then made for the next configuration to improve friction and quietness.

At this time some phenomenological models were being developed at the university of Minnesota to optimize the inter grove width and minimize spikiness effect. A texture design based on the phenomenological model developed was applied [12]. Diamond grinding creates grooves and land areas according to the setting of the spacers and blades of the diamond grinding equipment. The next improvement was in a predeploment as part of concrete rehabilitation project on Interstate 94 from Monticello to St. Cloud. The project included surface restoration through diamond grinding.

PREDEPLOYMENT ON MILE POST 175 INTERSTATE 94 NEAR ST. CLOUD

In 2009, a rehabilitaton project performed conventional diamond grinding on 1000-ft of a 4-lane divided hghway that was originally textured with burlap drag in 1980. Over the years, wth a traffic volume of 14000AADTand a ADTT of 1700, most of the texture was worn out. However the texture wear also resulted in some degree of aggregate exposure. The conditon of the joints in the 27-ft dowelled skew jointed panels ranged from good to poor. The joints that were considered fair to poor were repaired before grinding. Some extensively damaged panels were ether partial depth repaired or full depth repaired.

Diamond Surface inc was the contractor for the 5 million Dollar rehab project. In the rehab project a 1000-ft segment was isolated and ground to a different configuration. The

chosen segment had joints in good condition and needed no rehab prior to grinding. The configuration used was an improvement over the 2008 grind of cell 9 MnROAD and obtained from Izevbekhai's (12) phenomenological model. It maintained the same width of groove and the same inter-groove spacing of 2007 cell 7 but utilized the additional corrugation of the 2008 Cell 9 initiative. The actual configuration is elucidated in table 1. The advantage of the predeployment grind in friction was high yet the acoustic property was better than what was observed in cell 9. OBSI and statistical pass by measurements were conducted on the predeploment strip as well as the MnROAD Test cells. Results [12] [13] showed that the innovative grind was quieter in far field as well as in near field than traditional concrete grind. However, the effect of trucks was found to be more pronounced in the far field than the near field measurements. This is attributed to the frequency range reported by SPPB encompassing more of the low frequency noise than OBSI whose lowest frequency is 400Hz. Truck traffic seemed to have a resonant frequency of 100-Hertz arising from the braking system [13].
However, the OBSI difference of 6dBA was observed between the pre existng texture and the texture after grinding. With this result there was confidence in deploying the innovative grind in a major project.

FULL DEPLOYMENT TH 35 DULUTH

The I-35 Duluth "Mega Project" contained two areas of concrete pavement rehabilitation (CPR). Mn/DOT's District 1 – Duluth Office was determined to grind these two areas to enhance the ride and friction, but also sought to implement the new configuration to quieten the existing 1990 vintage transversely tined concrete pavement.

Mn/DOT measured tire pavement noise and finding noise levels of 106-dBA recommended the pavement should be diamond ground. After determining that an additional macro texture was required on the landing to improve fraction, a replication of the pre-deployment configuration was used in on Mn/DOT's I-35 Mega Project in Duluth, Minnesota in 2010. The contractor selection was based on lowest bid at an award price of $66,876,987.25. The funding was made up of Federal ($38.3 million) and

State Bonds ($26.4 million). The Federal fund required a state grant of $2.1 million. The prime contractor for the Duluth Mega Project is Arrowhead Constructors – with project specific partnership with Lunda Construction (bridges) and PCI (pavements). Highway 35 is the only interstate highway servicing Duluth. It carries large summer peak traffic volumes of tourists to various resorts at the shores of Lake Superior and feeds traffic on to highway 61 northwards towards the Canadian border.

The Mega project was divided into three areas for the purpose of staging. Areas 1 and 3 were considered rehabilitation areas and Area 2 was complete reconstruction. Innovative grinding occurred after concrete pavement rehabilitation in areas 1 and 3. Area 1 includes the Thompson Hill area and Cody street ramp. Area 2 includes the area from Central Avenue to Garfield Avenue. Area 3 includes Mesaba Avenue to London Road/ 34th Avenue east. This segment included pavement rehabilitation, intersection improvement and culvert replacement.

Initial attempt to achieve an IRI of 60 inches/ mile were not realized. Subsequently the 2 stage grinding provided the solution and facilitated IRI of less than 60 inches per mile. Friction and OBSI measurements as well as MPD were measured and results summarized in table 1 shows that the 2010 Duluth grind was not only quiet but met the requirements for sufficient friction comparable to common network values as well as significant IRI improvement.The total length ground in this project was 20 lane miles.

FIGURE 4: Project Area in Three Segments

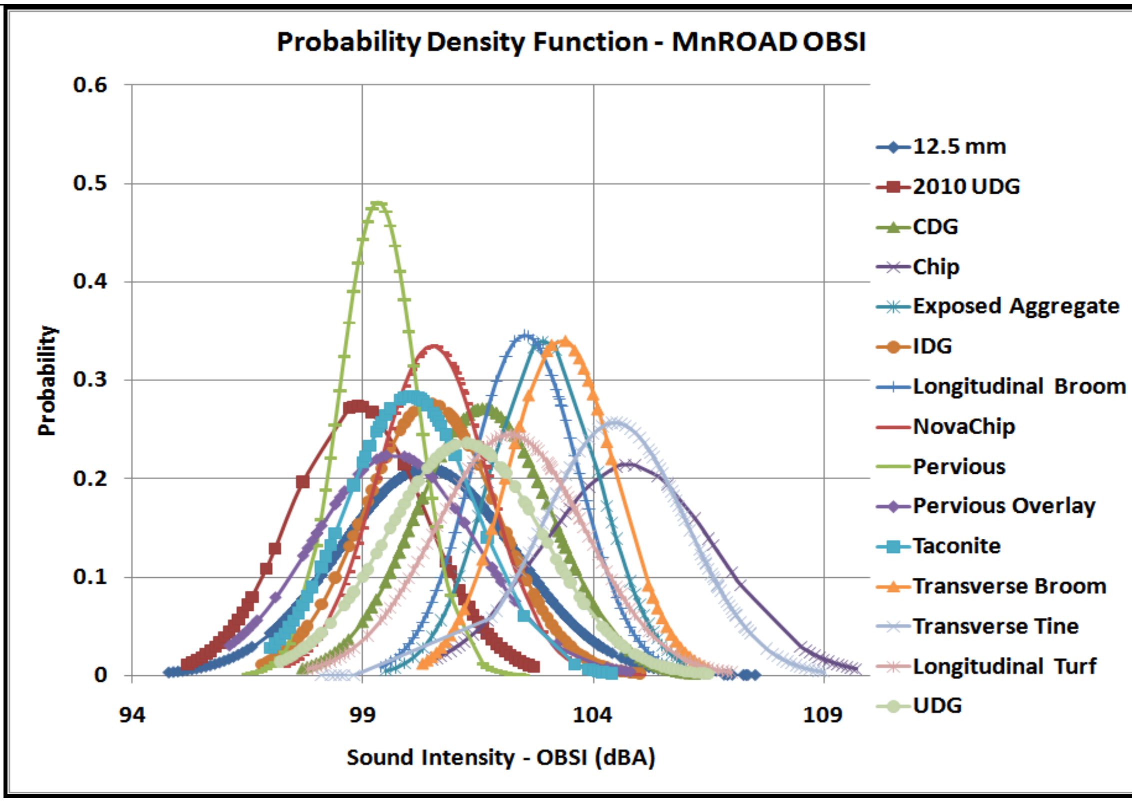
The first stage grinding included the conventional grind utilized to remove bumps and dips. The corrugations of the conventional grind formed the macro texture on the landing and in a second stage the innovative configuration was grooved in to the surface. This process provided the same effect as the 3 stage grinding that included a flush grind, an innovative grind and a third corrugation of 1/16th to 1/12th of an inch deep on the land area. Unforeseen problems included the manufacturers' disclaimer on the use of adhesive striping on the ground surface. When used there was sufficient adhesion in spite of the corrugation on the landing. After the 2010 grinding, tire pavement noise of 98.7 was measured in the vicinity of Edgewater Hotel.

To facilitate monitoring of the Duluth grind, the configuration was replicated in the MnROAD test cells. In 2010, a fifth strip was ground on cell 37 and the driving lane of cell 71 was ground with the Duluth configuration (FIGURE 5 inset). The passing lane of cell 71 was ground with the conventional grinding configuration. For an acoustic evaluation of the various grinding configurations in comparison to the other surface textures, a statistical analysis using a quasi probability-density-function (fitted normal distribution) was chosen and used.

ACOUSTIC EVALUATION

On Board sound intensity test data abounds in MnROAD where seasonal measurements have been taken since 2007. A data base therefore exists for all the surface types. The surface type used in Duluth was the 2010 Ultimate grind. To compare acoustic properties of various textures can be cumbersome unless such data is expressed as a probability density function. In the probability density function, the area under a data set plot for each texture type is unity. Additionally, the range of OBSI is clearly evident on the x-axis and the probability that the data is less than a particular value is the area split by that value to the left hand side.

FIGURE 5 shows a representation of OBSI data since 2007 for all MNROAD textures. Evidently, the 2010 ultimate grind has the lowest mean and is therefore by that definition the quietest surface in the MnROAD facility. It is also evident that the probability that this surface is louder than 100dBA is only 20 % with a mean OBSI of 98.7dBA. To compare this with transverse tining in the same figure, the mean is 105 dBA and the probability of being quieter than 100dBA is zero. The innovative grind shows a 50%



Statistical Representation of UDG Configuration in Prespective

Original Transverse Tine Texture

Final Grind (UDG)

FIGURE 5: PDF of All Pavement Types at MnROAD.

likelihood of being quieter than 100dBA. The pervious concrete surfaces exhibit a mean of 99.5 but the full depth pervious cells are much less tailed than the pervious overlay cell. It is also evident that the traditional grind shows a mean of102.5 dBA and a 25% likelihood of being quieter than 100dBA. The quietest asphalt surface at MnROAD is the 4.75 mm taconite cell as shown in the fitted normal distribution. It exhibits a mean of 100dBA,

The 2010 ultimate grinding (2010 UDG) is not only therefore fulfilling the requirement of a quiet pavement but appears to be the quietest surface at MnROAD.

CONCLUSION

This study examined the acoustic and frictional implication of performing a transverse drag instead of a longitudinal drag. It also chronicled the stepwise field improvement of noise and friction of the conventional grind, through the 2007 innovative grind, 2008 Ultimate grind, the 2009 pre-deployment and the 2010 (Duluth) Ultimate grind.

The frictional benefits derived from transverse brooming appear to supersede the noise demerits obtained.

Both frictional and acoustic benefits have been derived from the diamond grinding improvements at MnROAD. The final configuration is the quietest pavement at MnROAD facility based on a probability density function representation of entire database and maintains high friction properties comparable to surfaces in the network with acceptable friction numbers.

The initiative to improve diamond grinding configuration for quietness without a forfeiture of frictional resistance has been successfully achieved.

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