Hydroplaning Mitigation Selection Guide

	PAVEMENT MITIGATION						GEOMETRIC CHANGES							SIGNAGE		
	Pavement Overlays			Surface Treatments			Modifying Roadway Typical		Intercepting Pavement Runoff		Managing Roadway Geometry			Signage Strategies		
Select mitigation topic for more information -->	Open Graded Friction Course[1]	Ultra Thin Bonded Wearing Course	High Surface Friction Treatment[3]	Diamond Grooving[4]	Diamond Grinding	Shotblasting	Slope Shoulder Away	Moving the Crown Point	Gore Valley Gutters	Slotted or Trench Drain	Flatten Longitudinal Slope	Increase Cross Slopes	Adjust SE Transitions	Static Signs	Static Signs with Emphasis	Dynamic Signs
Applicable Project Type (New Pavement[2], Widening, Maintenance)	All	All	Widening or Maintenance	Widening or Maintenance	All	Maintenance	All	All	Widening or Maintenance	Widening or Maintenance	New Pavement	All	All	All	All	New Pavement or Widenings
Spatial Exent[5]	Global	Global	Local	Both	Both	Both	Global	Global	Local	Local	Global	Global	Both	Both	Both	Both
Construction Costs	$$	$$	$$$	$$$	$$$	$$	$	$	$	$$	$	$	$$	$	$	$$
Maintenance Effort	medium	medium	high	medium	medium	high	low	low	low	medium	low	low	low	low	low	medium
Service Life	8-10 years	9-11 years	8-12 years	15 years	15 years	2-5 years	N/A	N/A	N/A	N/A	N/A	N/A	N/A	10 years	10 years	15-20 years
Suitable for the Following Existing Pavement Surfaces[6]	DGAC Concrete UTBWC	DGAC Concrete	DGAC Concrete	Concrete DGAC[4]	Concrete	DGAC Concrete OGFC	All Pavement Surfaces	All Pavement Surfaces	All Pavement Surfaces	All Pavement Surfaces	All Pavement Surfaces	All Pavement Surfaces	All Pavement Surfaces	Applicable for all pavement surfaces including temporary construction conditions.[7]		
Hydroplaning Benefit ★ to ★★★	★★★	★★½	★★★	★★★ *(transverse grooving)*	★½	★★	★	★★½	★★★	★★★	★	★½	★★★	Effectiveness is unknown at this time. Further research is needed.		

Notes:

General Note: Mitigation strategies can be combined for greater hydroplaning potential reduction. Example: geometry, pavement type, or surface treatment.

(1) Open Graded Friction Course is not recommended for regions prone to frequent ice/snow events or longitudinal slopes steeper than 5%. (Divisions 11, 13 and 14)

(2) New pavement consists of new and/or reconstructed pavement.

(3) High Friction Surface Treatment is only applicable for DGAC or Concrete pavement and treatment is vulnerable to maintenance issues in Divisions where sand is used in ice/snow conditions.

(4) Diamond grooving is typically reserved for bridge decks (see NCDOT Specification 420). DGAC grooving can be used for short segments, typically curves, as a spot treatment.

(5) Global treatments are applicable to the entire project limits; Local treatments are considered 'spot treatments' and used in smaller applications.

(6) If hydroplaning potential occurs in OGFC areas, consider geometric solutions.

(7) Variable message boards can be used during construction to warn of temporary hydroplaning concerns.

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Diamond Grinding

Diamond Grinding is a pavement resurfacing technique that corrects a variety of surface irregularities on both concrete and asphalt pavements. Most often used on concrete pavement, diamond grinding removes a thin layer using closely spaced diamond saw blades to improve rideability, increase surface macrotexture and consequent improvement in hydroplaning potential, skid resistance, noise reduction and safety. Diamond grinding has the ability to improve the macrotexture of a concrete surface or simply restore to the originally installed macrotexture. ability to improve the macrotexture of a concrete surface or simply restore to originally installed macrotexture.

Hydroplaning Assessment	HPS increase	0 - 3 mph
	MTD range/target	0.028 - 0.055 in[1]
Design Considerations	Climate	Suitable for all climate conditions
	Pavement	Used on concrete pavement
	Spatial extent	Spot treatment applied in sensitive locations
Costs	Construction cost	$36,819/Lane-Mile
	Life-cycle cost	*Coming soon*
Operations Considerations	Construction	Management and disposal of the concrete slurry is subject to special provision. NCDOT Statewide Permit Guidelines Management Disposal of Concrete Grinding Residuals 5219.pdf
	Service life	15 years
Other Considerations	Secondary Benefits	*See below*

Secondary Benefits

- Restores ride quality of in-service pavement by creating a smoother, uniform travel surface.
- Does not impact the durability of the host pavement.

- Can be used to correct faulting across a joint or crack, polished surfaces, wheel path rutting, and slab warping.
- Diamond grinding can be accomplished during off-peak hours with short lane closures, without having to close adjacent lanes.

Relevant NCDOT Specifications/Design Guidance

SECTION 710 Concrete Pavement

References

1. FHWA Concrete Pavement Texturing, FHWA-HIF-17011, May 2019
2. Journal of Traffic and Transportation Engineering, *Surface texture and friction characteristics of diamond-ground concrete and asphalt pavements*, Indiana DOT 2016
3. Concrete Pavement Rehabilitation – Guide for Diamond Grinding, FHWA 2001

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Diamond Grooving

Diamond Grooving is a technique used to cut small channels within the cured concrete to provide improved pavement surface drainage. Most often used on concrete bridge decks, diamond grooving may be performed longitudinally or transversely to the flow of traffic. NCDOT specifications require transverse concrete grooving for bridge decks, 1/8" wide and 3/16" deep with a center to center spacing of 3/4".

Hydroplaning Assessment	HPS increase	Eliminates hydroplaning potential[1]
	MTD range/target	n/a
Design Considerations	Climate	Suitable for all climate conditions
	Pavement	Used on concrete pavement, mainly bridge decks
	Spatial extent	Spot treatment applied in sensitive locations
Costs	Construction cost	$27,245/Lane-Mile
	Life-cycle cost	*Coming soon*
Operations Considerations	Construction	Management and disposal of the concrete slurry is subject to special provision. NCDOT Statewide Permit Guidelines Management Disposal of Concrete Grinding Residuals 5219.pdf
	Service life	15 years
Other Considerations	Secondary benefits	*See below*

Secondary Benefits

- Longitudinal diamond grooving can be accomplished during off-peak hours without having to close adjacent lanes.

Relevant NCDOT Specifications/Design Guidance

NCDOT Specification SECTION 420

References

1. Ong & Fwa, Transverse Pavement Grooving against Hydroplaning II: Design, 2006

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Dynamic Message Signs

Dynamic message signs (DMS) are changeable message signs which are controlled automatically to be capable of electronically displaying more than one message. Messages for warning situations, such as hydroplaning hazard warnings, are just one of many types of messages that can be relayed to drivers. With DMS, real-time hydroplaning hazard warning messages can be displayed when the hazard is present or is likely to be present.

Figure 1: DMS Real-Time Messages Example

Hydroplaning Assessment	Driver Speed Reduction	Currently under research
Design Considerations	Selection of Location	*See below*
Costs	DMS Cost	$180,000 average for a Type 2C DMS [2]
	Life-cycle cost	*Coming soon*
Operations Considerations	Maintenance needs	*See below*
	Service life	15-20 years
Other Considerations	DMS Types	Type 1, 2, 3 and 4
	DMS Message Color	Amber (A) and Full Color (C)

Design Considerations

- Recommended DMS locations must be provided by NCDOT's Congestion Management Section.
- DMS location must be approximately 2-4 miles in advance of the point of hydroplaning hazard.
- A controller cabinet will be necessary in order for the DMS to operate.
- Phone and power service must be available for the DMS to function.
- Typically, the DMS will have a pedestal-type assembly for 1-2 lanes (each direction), and a full span assembly for 3 or more lanes (each direction).
- The following items may be needed for the DMS to function properly: desktop/laptop, software upgrade, fiber optic communication, dial-up backup system, dial up modems, etc.
- A centralized system for operation is needed to ensure active DMS are always displaying accurate hydroplaning hazard information.

- DMS messages should adhere to format and wording guidelines provided by NCDOT and be limited to no more than three lines, with no more than 20 characters per line.
- DMS are more expensive than other types of signs.
- Increased design coordination is needed for proposed DMS in terms of available right of way, underground/overhead utilities, geotechnical and structural designs, etc.

Expected Maintenance Needs

- DMS need to be constantly monitored for proper function from the main operations center. All the components must be functioning at all times and replaced or fixed whenever they are damaged.
- Any power/connectivity issue can make the DMS not operate properly by not showing real-time hydroplaning hazard warning information to drivers.

Secondary Benefits

- Customizable, with ability to provide any textual messages or images.
- Most effective, relevant message only displayed when triggered by real-time conditions.

NCDOT Specification

SPECIAL PROVISIONS: NCDOT SIGNALS AND INTELLIGENT TRANSPORTATION SYSTEMS PROJECT – 27. DYNAMIC MESSAGE SIGNS (DMS)

References

1. FHWA, Manual on Uniform Traffic Control Devices (2009 Edition). Part 2. SIGNS
2. NCDOT, Bidding & Letting- Let Central. 2021 BID AVERAGES. Webpage: https://connect.ncdot.gov/letting/letcentral/forms/allitems.aspx
3. NCDOT, Design Manual - Signal Design Section Part 3. Dynamic Message Signs – Site Selection & Design Process (Std. No. 7.0). Webpage: https://connect.ncdot.gov/resources/safety/ITS%20and%20Signals%20Resources/ITS%20and%20Signals%20Unit%20Design%20Manual%20Part%203%20-%20ITS.pdf

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High Friction Surface Treatment (HFST)

HFST is a surface treatment added to the top of a road surface to increase macrotexture and microtexture depth on the pavement, and resultant increased hydroplaning speed (HPS) and skid resistance, respectively. The treatment consists of high quality, polish-resistant aggregates (most commonly used is calcined bauxite) distributed over a polymer resin binder that is applied to the road.

HFST photos, FHWA Everyday Counts

Hydroplaning Assessment	HPS	Dependent on the proprietary product
	MPD range/target	0.050 in
Design Considerations	Climate	Suitable for all climate conditions
	Pavement	Used on DGAC, PCC, but not recommended for use over OGFC
	Spatial extent	Global treatment applied to entire cross section
Costs	Construction cost	$175,155/Lane-Mile *(Costs taken from limited NCDOT site data)*
	Life-cycle cost	*Coming soon*
Operations Considerations	Construction	HFSTs are installed quickly with minimal traffic impact. Expect one lane of traffic to be shut down for 2-3 hours during application and curing. [2]
	Maintenance needs	For a few months after installation, weekly sweeping is recommended to remove any loose aggregate.
	Service life	8-12 years[2]
Other Considerations	Secondary benefits	*See below*

Design Considerations

- HFST must be applied to an existing road surface in good condition with few to no cracks, minor rutting, and no structural damage.
- Certain types of epoxy-resins used in HFST application cannot be applied at temperatures below 60°F. However, polyester and polyurethane resins may be applied at lower temperatures.
- Without adequate surface preparation, HFST is liable to debond and delaminate, especially on concrete. This issue is often caused by changes in temperature. HFST will expand and contract much more than asphalt or concrete and will "pop-off" under thermal stress if the bond is insufficient.[1]
- Crash reduction has proven most effective on horizontal curves and tight-radius loop ramps. HFST is also used at locations with high crash rates related to friction deficiency, at downhill signal approaches, and on concrete pavements and bridge decks, to help with preservation.
- HFST uses aggregates that are both polish-resistant and wear-resistant and develops channels to prevent water buildup on wet surfaces. The bonding materials, such as epoxy and other available blends, are designed to set quickly.

Secondary Benefits

- Effective in improving pavement skid resistance.
- Reduces splash and spray from surrounding vehicles.

Relevant NCDOT Specifications/Design Guidance

Revised High Friction Surface Treatment Provision

References

1. FDOT High Friction Surface Treatment Guidelines: Project Selection, Materials and Construction
   FDOT: High Friction Surface Treatment Guidelines
2. FHWA Everyday Counts, HFST FAQs
3. Indiana Department of Transportation (INDOT) 2021

   Determination of Friction Performance of High Friction Surface Treatment Based on Alternative Macrotexture Metric - PMC (nih.gov)
4. Auburn University Research

   Microsoft Word - 15-04.docx (auburn.edu)

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Intercepting Pavement Runoff

The following two techniques can be used to mitigate hydroplaning by intercepting pavement runoff:

(1) Grading a shallow gore gutter to direct runoff to an adjacent grassed area or to an inlet within the gore area; or

(2) The placement of a collection system, such as a slotted drain or trench drain, within the gore area to intercept the water film thickness before it flows onto down cross slope lanes. Trench drains, though more expensive, are preferable due to greater flow acceptance capacity and superior maintenance access afforded by their removable grates. Slotted drains are essentially pipes with a throated slot opening that are cast into concrete for stability.

Figure 1: Informal Gore Gutter

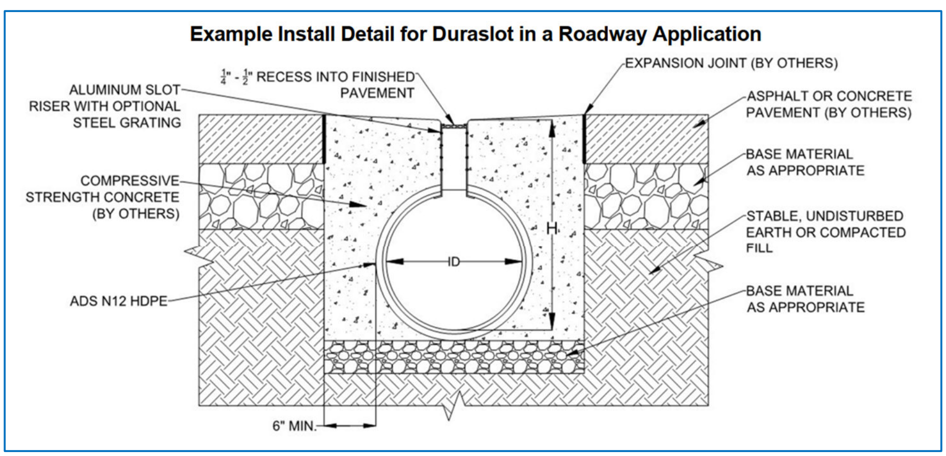

Figure 2: Typical Slotted Drain Installation (ADS Duraslot)

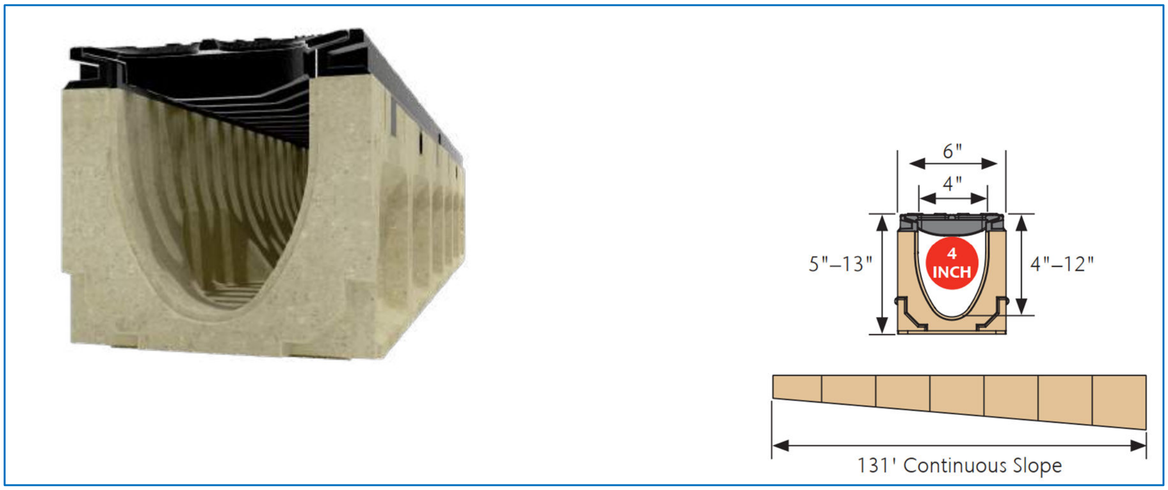

Figure 3: 4" Trench Drain with Removable Grates and Continuous Slope (ACO PowerDrain S100K)

Table 1: Characteristics of Intercepting Flow Approaches

Hydroplaning Assessment	HPS increase	Varies depending on the size of the area intercepted
Design Considerations	Drainage	Requires a place to outfall the intercepted runoff
	Spatial extent	Localized interception, typically within a gore area
Additional Costs	Construction cost	4" slotted drain: $150/LF 6" slotted drain: $175/LF 4" trench drain: $215/LF
Operations Considerations	Construction	Minimal effort to install slotted or trench drain
	Maintenance	Periodic cleanout of sediment from slotted or trench drain

Design Approach and Limitations of Slotted and Trench Drains

The design approach for slotted and trench drains is divided into two scenarios: (1) where the longitudinal slope of the gore pavement is sloped in the same direction of intercepted flow; or (2) where the longitudinal slope of the gore pavement is adverse to the direction of the intercepted flow.

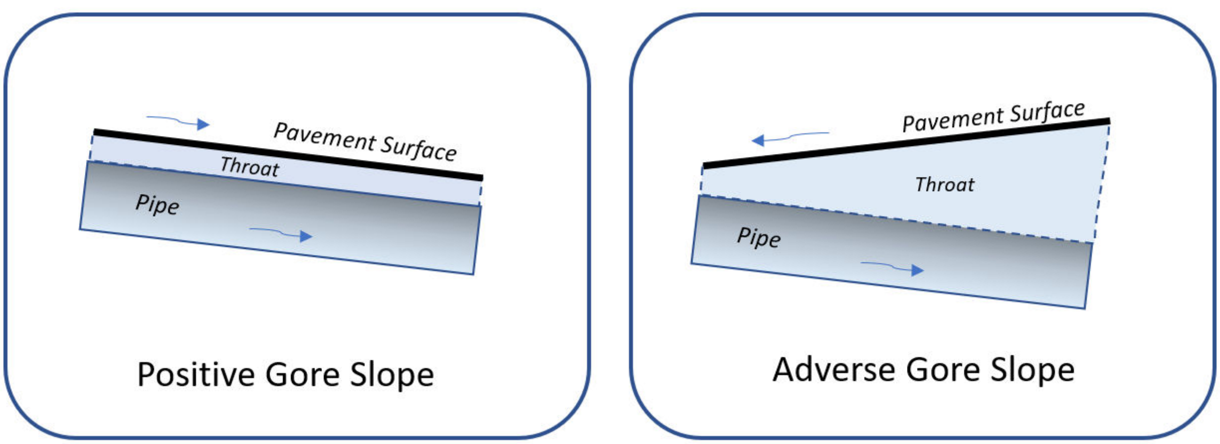

Figure 4a and 4b: Gore Slope Definitions with Respect to Slotted Drains

To determine where to begin intercepting the water film thickness flowing across the gore, use the Hydroplaning Analysis Tool to determine the point at which the gore pavement becomes too wide and presents unacceptable hydroplaning risk in down cross slope lanes. An example is shown in **Figure 5** below, in which the maximum allowable contributing gore width was determined to be 8 ft.

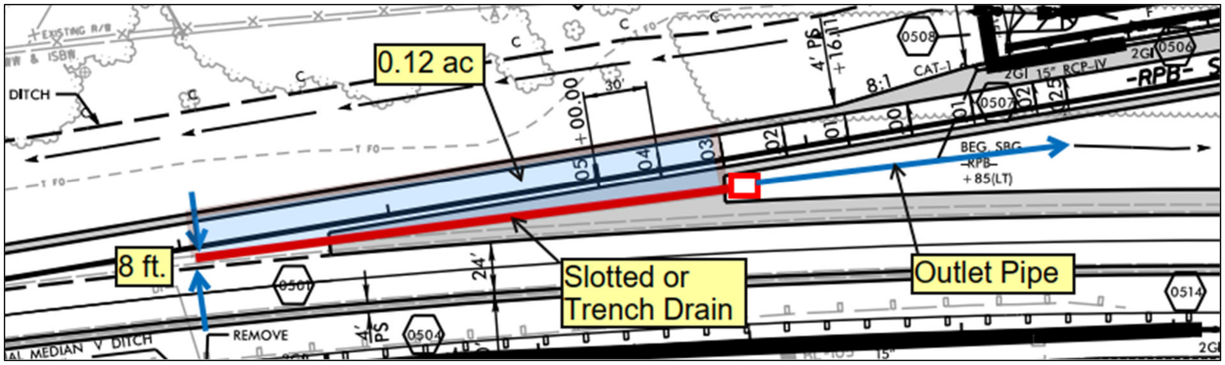

Figure 5: Slotted/Trench Drain Layout within a Gore Area

Favorable Gore Longitudinal Slope

When the longitudinal slope of the gore is in the same direction as that of the outfall for the intercepted flow, the gore surface may be shaped as a shallow gutter to channel runoff into a grassed area at the downstream end of the gore, or to an inlet as shown in Figure 5 above. Collaborate with a roadway designer to ensure that the slopes involved in developing the gore gutter are safely traversable.

If the geometry of the gore does not allow for the development of an adequate, traversable gutter, then a slotted drain or trench drain may be installed to intercept the water flowing across the gore. Both drains are available with an internal slope parallel to the pavement surface for when the longitudinal slope of the gore is in the same direction as the proposed outfall for the intercepted flow. Slotted drains should maintain a minimum internal slope of 0.5% when maintenance access is provided on both ends, and 1% when access is from only one end. If sloping the internal pipe parallel to the surface does not result in sufficient pipe slope, the slotted or trench drains may be specified with an internal slope as shown in **Figure 3** above and **Figure 6** below.

Both slotted drains and trench drains require an outlet pipe; head losses should be checked for a 2”/hr rainfall which is typically the critical intensity for assessing hydroplaning risk.

Adverse Gore Longitudinal Slopes

When the longitudinal slope of the gore is adverse to the direction of flow of the collection system, slotted drains and trench drains must have a continuous internal slope as shown in Figure 5 above and **Figure 6** below. As a practical limit, trying to counter an adverse longitudinal gore slope greater than 0.3 % is difficult to overcome due to length limitations of the drains that decrease with increasingly adverse gore slopes. The nuances of these drain length and gore slope limitations are discussed below for both slotted drains and trench drains.

Slotted Drains within Adversely Sloped Gore Areas

Slotted drains are manufactured with minimum and maximum throat depths as shown below in Figure 6 and **Table 2**, below:

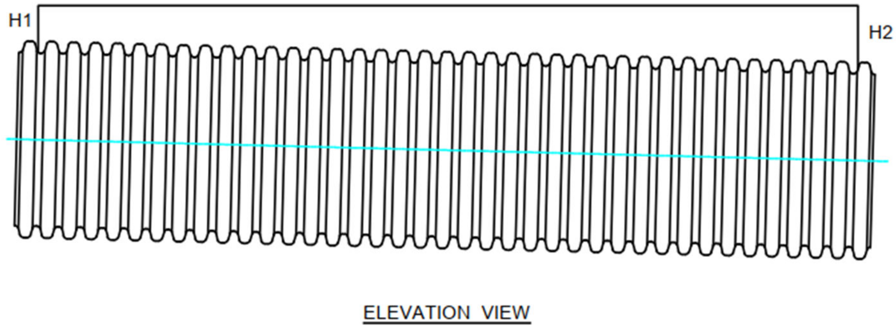

Figure 6: Diagram of Typical Slotted Drain with Internal Slope (ADS Duraslot)

Table 2: Minimum and Maximum Slotted Drain Invert Depths (ADS Duraslot)

Table 1

Minimum Invert Depth below Finish Grade by Pipe Size and Loading Condition

Inside Diameter of Pipe, in. (mm)		4 (100)	6 (150)	8 (200)	10 (250)	12 (300)	15 (375)	18 (450)	24 (600)	30 (750)	36 (900)
Minimum Invert Depth, in. (mm)	*Pedestrian Only:*	7.00 (178)	9.25 (235)	11.25 (286)	13.25 (337)	16.00 (407)	19.00 (483)	22.25 (566)	29.00 (737)	35.25 (896)	41.50 (1055)
	Roadway Projects:	10.75 (274)	13.00 (331)	15.00 (381)	17.00 (432)	19.50 (496)	22.50 (572)	25.50 (648)	31.75 (807)	38.75 (985)	44.75 (1137)
	Airport Projects:	13.75 (350)	16.00 (407)	18.00 (458)	20.00 (508)	22.50 (572)	25.50 (648)	28.50 (724)	34.75 (883)	41.75 (1061)	47.75 (1213)

Duraslot can also be made to order with a custom or variable slot height. **Table 2** provides the maximum invert depth by pipe diameter. Invert depths are calculated by adding the inside diameter of the pipe, maximum actual slot height and the recess into the pavement.

Table 2

Maximum Invert Depth below Finish Grade by Pipe Size

Inside Diameter of Pipe, in. (mm)		4 (100)	6 (150)	8 (200)	10 (250)	12 (300)	15 (375)	18 (450)	24 (600)	30 (750)	36 (900)
Maximum Invert Depth, in. (mm)	*Pedestrian Only:*	28.25 (718)	30.25 (762)	32.25 (820)	34.25 (870)	48.25 (1226)	51.25 (1302)	54.25 (1378)	60.25 (1531)	66.25 (1683)	72.25 (1836)
	Roadway Projects:	28.50 (724)	30.50 (775)	32.50 (826)	34.50 (877)	48.50 (1232)	51.50 (1309)	54.50 (1385)	60.50 (1537)	66.50 (1690)	72.50 (1842)
	Airport Projects:	28.50 (724)	30.50 (775)	32.50 (826)	34.50 (877)	48.50 (1232)	51.50 (1309)	54.50 (1385)	60.50 (1537)	66.50 (1690)	72.50 (1842)

Designers should use the smallest pipe size (4”), if head losses allow, and the maximum available change in invert depth (28.50” – 10.75”, per **Table 2**) to maximize internal cleanout velocities. Maximum 4” slotted drain lengths between intermediate inlets, using an internal slope of 0.5% or 1%, are tabulated in **Table 3** below. The length of the slotted drain may be extended beyond the lengths in **Table 3** using intermediate inlets to “step up” the drain’s invert depth.

Table 3: Maximum 4" Slotted Drain Lengths (ft), between Intermediate Inlets, Using Net 1.0% and 0.5% Internal Pipe Slopes

Adverse Gore Surface Longitudinal Slope	Pipe Invert Slope	
	1.0%	0.5%
0.2%	123	211
0.3%	114	185
0.4%	106	164
0.5%	99	148
0.6%	92	134
0.7%	87	123
0.8%	82	114
0.9%	78	106
1.0%	74	99

Trench Drains within Adverse Gore Slopes

As shown in **Figure 3** above, trench drain sections with internally cast slopes of 0.5% are readily available, but also present a very flat net pipe slope within a gore area whose adverse longitudinal slope (see **Figure 4b**) is greater than 0.3%. The length of the trench drain may be extended with intermediate, manufacturer-made inlets approximately every 130 ft. which are used to "step up" the drain's invert depth.

References

1. ACO Brochure, 2023, PowerDrain Heavy Duty Trench Drain
2. ADS Brochure, 2023, Duraslot

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Managing Roadway Geometry

The roadway cross slope, longitudinal slope, and superelevation transition may be adjusted to reduce the water film thickness (WFT) and thereby increase hydroplaning speed (HPS).

Roadway Longitudinal Slope

A steeper longitudinal slope causes the runoff to move in a longer travel path with a greater residence time on the roadway, resulting in an increase in WFT, as shown below in Figure 1. **Therefore, to reduce the WFT, flatten the roadway longitudinal slope as much as feasible.** Flatter grades make sheet flow more perpendicular to the road, which reduces the runoff flow path length and resultant water film thickness.

$$L = W\sqrt{1+\left(\frac{S_G}{S_C}\right)^2}$$

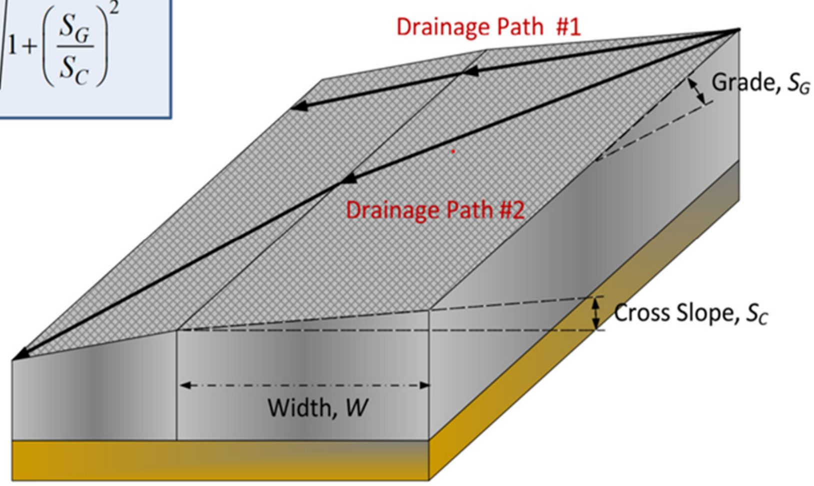

Figure 1: Effect of Longitudinal Roadway Slope on Runoff Travel Length (FDOT Research Project BE570, 2020)

Roadway Cross Slope

Increase the cross slope steepness, on tangent sections, to provide faster and more efficient removal of water from the pavement. The AASHTO Greenbook recommends breaking the cross slope every two lanes and specifies that, "where three or more lanes are provided in each direction, the maximum cross slope should be limited to 4 percent" (Chapter 4.2.2.2). **Therefore, to reduce the maximum WFT, break the roadway cross slopes every two lanes within allowable Greenbook standards.** An example of a multilane cross section with increasing cross slopes is shown in Figure 2, below:

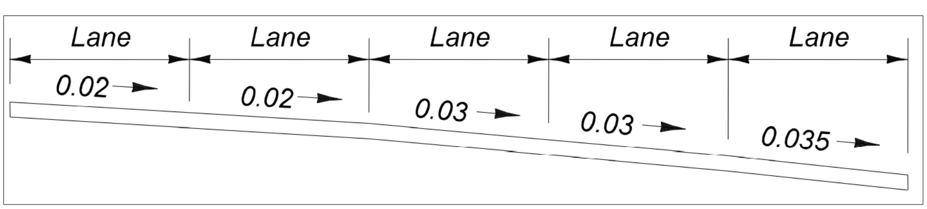

Figure 2: 5-Lane Roadway Section with Increasing Cross Slopes

Adjusting Superelevation (SE) Transitions

The SE transition adjustment should only be used, for now, on 4-lane divided highways (2-lanes in each direction) and must be a collaborative effort between the roadway engineer and the hydraulic engineer, with roadway design geometric safety issues being primary. The goal is to lower the WFT, on the outside of the curve, by reducing the contributing pavement to lower lanes when the cross section is too flat during an SE rollover. This involves rolling over one lane at a time so that the lower lane achieves a safe cross slope before receiving additional runoff from the upper lane(s). This approach increases the length of SE transitions; be careful, however, to not extend an SE transition to vary the cross slope on a bridge deck. The steps to designing this adjustment to the outside roadway of the curve are discussed below:

Step 1. Determine the minimum cross slope, with all travel lanes sloped in one direction, which yields a safe hydroplaning WFT.

Step 2. In the areas where the SE transition results in a lower cross slope than determined in Step 1 above, first transition only the innermost lane, before or after the curve, depending on whether the roadway is going into or coming out of an SE.

Step 3. Begin transitioning the adjacent lane when needed to stay within the AASHTO maximum allowable slope change for slopes on adjacent travel lanes.

Step 4. If the section has more than 2 lanes in one direction, continue to transition the additional lanes following Steps 2 and 3 above.

Considerations

Considerations in using these geometric mitigation strategies are summarized below:

Category	**Issue**	**Geometric Mitigation Strategies**		
		Flatten Longitudinal Slope	**Break Cross Slope**	**Adjust SE Transition**
Hydroplaning Assessment	HPS increase	App. 0.5 mph for a 1% slope change	1 – 3 mph	Up to 10 mph
Design Considerations	Design Effort	No change	No change	Increases
	Plans Preparation Effort	No change	No change	Increases
	Pavement	None	Avoid bridge decks*	Avoid bridge decks*
Costs	Construction cost	Possible additional earthwork	Possible additional earthwork	Possible additional earthwork
Operations Considerations	Construction	None	Possibly new to some contractors	New to contractors

* Transverse grooving on bridge decks, required per NCDOT specifications, will acceptably mitigate hydroplaning potential without breaking the bridge deck cross slope.

References

1. Florida Department of Transportation, 2020, Research Project BE570, Enhanced Hydroplaning Prediction Tool
2. AASHTO, 2018, A Policy on Geometric Highway Design (AASHTO Greenbook)

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Moving Crown Point

Moving the crown point is when the designer amends a roadway section by sloping (1) the high-side shoulder or (2) the high-side shoulder and inside lane(s) toward the median and away from the travel lanes. This reduces the contributing area flowing to the outside lanes, reducing the resulting water film thickness, and thereby increasing the hydroplaning speed (HPS).

The figure below illustrates an example of the original typical section, on the bottom, with all lanes sloping toward the outside, and the improved section, on the top, with the innermost lane sloped toward the median:

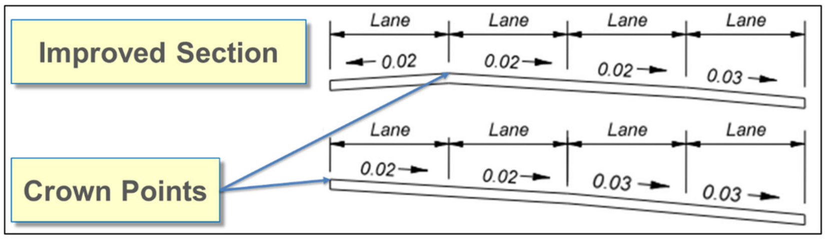

Figure 1: Moving the Crown Point

On resurfacing projects, when using wedging to reverse the cross slope of the innermost lane, coordinate with the roadway designer to re-establish an appropriate roadway profile if the grade point is being lowered.

Hydroplaning Assessment	HPS increase	3 - 5 mph
	Superelevations	*See below*
Design Considerations	Drainage	Requires a median drainage system
	Pavement	Applicable for all pavement types No additional pavement strength added
	Spatial extent	Applied to entire cross section
Costs	Construction cost	Median drainage system and, if using wedging, additional asphalt
Operations Considerations	Construction	Additional MOT for crossing drainage pipes
	Maintenance needs	Snow removal, if used for snow storage
Other Considerations	Secondary benefits	Allows for storage of accumulated snow

Superelevations

When the crown point is moved toward the outside and one lane is now sloping toward the median, analyze the location where all lanes are now sloping toward the inside during the superelevation transition to ensure a hydroplaning risk has not been inadvertently created.

In the illustration below, note that the water film thickness (WFT) in the lowest lane of the superelevated section will be greater than the maximum WFT in the original section. Therefore, if the original section requires mitigation, resulting in the improved section, the superelevated section will also require mitigation <u>unless</u> the -0.02 ft/ft cross slope is transient on the way to a steeper superelevation rate, *e*. To mitigate for this condition, consider breaking the inner lanes to a steeper cross slope (-0.03 ft/ft in the case below) before the outer lanes contribute to the inner lane(s).

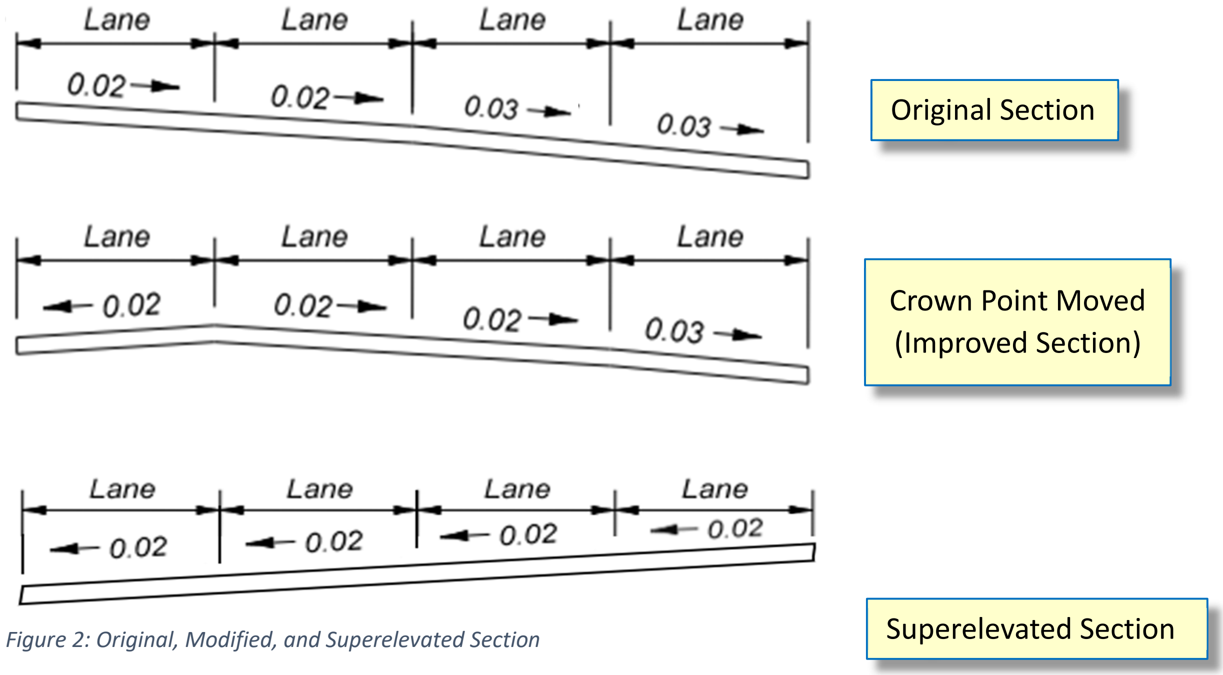

Figure 2: Original, Modified, and Superelevated Section

References

1. AASHTO, 2018, *A Policy on Geometric Design* (AASHTO Greenbook)

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Open Graded Friction Course (OGFC)

OGFC is defined as a thin, permeable layer of asphalt with a uniform aggregate size and a minimum number of fines. This creates an asphalt mixture with an 'open-gradation' containing a high percentage of air voids (e.g., usually 15% - 22%) and a high macrotexture that the reduces water film thickness.

Figure 1: Open Graded Friction Course paving process.

Hydroplaning Assessment	HPS increase	5 – 7 mph
	MTD range/target	0.067 in
Design Considerations	Climate	Not recommended for snow/ice conditions
	Pavement	*See below*
	Spatial extent	Global treatment applied to entire cross section
Costs	Construction cost	$37,331/Lane-Mile
	Life-cycle cost	*Coming soon*
	Maintenance needs	*See below*
	Service life	8 - 10 years
Other Considerations	Secondary benefits	*See below*

Design Considerations

- Typically used over a structural course of DGAC.
- OGFC performs best on high-volume, high-speed roadways, where the suctioning action of the tires on the pavement helps to remove material residue from the porous layer.

- Susceptible to raveling and should be avoided in snow/ice areas. The use of snowplows, studded tires, and chains are known to accelerate raveling. Additionally, sand, salt and other snow removal materials may clog pavement pores.
- Can require special patching and rehabilitation techniques.
- Does not add structural value to the pavement (performance is governed by the condition of underlying pavement).
- May ravel when used at intersections, locations with heavy turning movements, ramp terminals, curbed sections, and other adverse geometric locations.

Expected Maintenance Needs

Maintenance of OGFC can include sealing or patching localized areas of distress, such as cracks or potholes, with a dense graded asphalt mix. Larger areas of distress may be patched with an open graded mix, or in cases of complete failure/raveling, a mill and overlay would be needed. Any surface treatment repair should depend on the size and severity of the failure.

Secondary Benefits

- Reduces splash and spray from surrounding vehicles.
- Reduces glare from on-coming headlights during rainy conditions and enhances the visibility of pavement markings.
- Reduces the tire/pavement noise, often providing a 3 to 5 decibel reduction.
- Improves the water runoff quality.

NCDOT Specification

NCDOT SECTION 650 2 OPEN-GRADED ASPHALT FRICTION COURSE, 3 TYPES FC-1, FC-1 MODIFIED AND FC-2 MODIFIED

References

1. FHWA, Technical Advisory, Open Graded Friction Courses, T 5040.31, 1990 Open Graded Friction Courses (T 5040.31) (multiscreensite.com)
2. Open-Graded Friction Courses-R1.pdf (cedengineering.com)
3. Life Cycle Cost Analysis | Caltrans

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Shotblasting

Shotblasting is a rejuvenating technique used to remove debris and irregularities from pavement, restoring the micro and macrotexture by systematically impacting steel beads onto the existing surface at high velocity. As shown in Figure 3, the system consists of a shot propeller to blast the steel balls, a vacuum unit to recover the abraded material from road surface, a magnetic separator to collect the steel shots for reuse, and a residue container followed by a power broom to pick up dust particles (Gransberg 2009)[1]. Used on both concrete and asphalt pavements, including OGFC, the shotblasting procedure should be used to temporarily extend the life of the pavement.

Figure 1: I-26 in Buncombe County, NC [2]

Figure 2: Close-up schematic of shotblasting process [2]

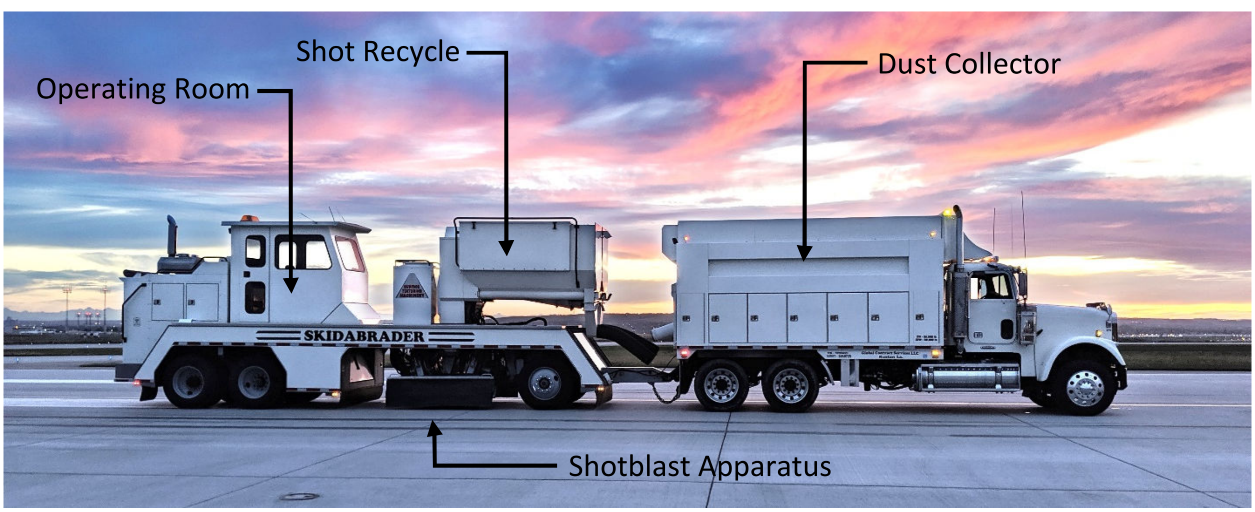

Figure 3: Shotblasting Treatment at National Center for Asphalt Technology (NCAT) Pavement Test Track [3]

Shotblasting is an efficient means of rejuvenating road surfaces. The process uniformly treats all areas of the road surface without excessively damaging surface integrity, and effectively improves both macro and microtexture. It is environmentally friendly in that it is a dust-free process and recycles all materials used and generated by the process (Bennett 2007)[4].

Rehabilitation of Asphalt and Concrete Pavements

Design guidance for appropriate target MPD values is currently being studied by NCDOT. The designer should discuss target MPD values with the shotblasting vendor.

Hydroplaning Assessment	MTD increase	Site-specific: discuss target MPD requirements with vendor. Rejuvenated MPD values should not exceed that of the original pavement.
Design Considerations	Climate	Suitable for all climate conditions
	Pavement	Used on concrete and asphalt, except for UTBWC and HFST
	Spatial extent	Spot or global treatment
Costs	Construction cost	$24,076/Lane-Mile[3]
Operations Considerations	Construction	Treated pavement may be immediately opened to traffic after process
		Using a 6 ft. treatment swath, approximately 1.9 Lane-Miles may be treated per night using rolling lane closures
	Service life	Vendor estimation: 3 – 5 years[3], but further experience is needed to more confidently target expected service life. Service life is highly dependent on pavement type.
Other Considerations	Secondary benefits	Improves microtexture for improved skid resistance Mild rounding of PCC grooving helps reduce glare

NCDOT Specifications/Design Guidance

SPT 6-25, dated 11/16/2021, from TIP No. HS-2014E, Division 14, is included in the Appendix to this document.

References

1. Gransberg, D.D, 2009. Life cycle cost analysis of surface retexturing with shotblasting as a pavement preservation tool. Transportation research record. *Journal of the Transportation Research Board*, 2108, 46–52. Transportation Research Board of the National Academies

2. Md Tanvir Ahmed Sarkar, Fan Gu, Michael Heitzman and Buzz Powell, 2021, National Center for Asphalt Technology, Auburn University, Auburn, AL, USA, *Influence of Shotblasting Treatment on Asphalt Pavement Performance,* International Journal of Pavement Engineering, https://doi.org/10.1080/10298436.2021.1959581

3. Sheldon Spears, Skidabrader, *Discussion (2-7-2023) and Correspondence (2-8-2023) with NCDOT*

4. Bennett, R. *Blastrac Shotblasting Trial and Technical Assessment*, Geotest Civil Services, Bendigo Victoria, June 2007, 23pp

5. Paul Rogers, PE, KPR Engineering, PLLC, *Pavement Friction and Texture Testing - I-26 Buncombe County, NC - Draft Report Update*, 11-21-2021, to Joseph Barbour, Data Collection Engineer, NCDOT

Appendix

Example Technical Specification

SPT 6-25, dated 11/16/2021, from TIP No. HS-2014E, Division 14

PAVEMENT TEXTURING:

(11/16/2021) SPI 6-25

Description

This work consists of pavement texturing of existing asphaltic concrete pavement and/or Portland cement concrete pavement and the texturing of bridge deck surfaces at the locations shown on the plans or as directed by the Engineer and in accordance with the requirements herein.

Equipment & Materials

The texturing shall be done by a machine designed and built for high production pavement texturing. Each machine must have a minimum average production rate of 1,200 sq. yd. per hour for concrete surfaces and 1,800 sq. yd. per hour for asphalt surfaces. The machine must employ the High Velocity Impact Method (HVIM) by hurling steel abrasive media at high velocity to abrade and texture the pavement surface. The machine must be capable of varying the velocity of the steel abrasive as well as the speed of the machine to produce the desired pavement surface texture. Utilization of radial blades in multiple centrifugal wheels must produce a continuous, minimum 6 ft. wide swath. This is synchronous to the recycling of abrasive and vacuuming of surface materials into a self-contained vacuum unit of 6 cu. yd. or more, meeting or exceeding all environmental air quality standards. No objectionable dust shall be emitted during the work. The machinery must direct the velocity of abrasion in a bi-directional fashion, giving uniform abrasion to the pavement surface. When transverse grooves are present, the abrasion shall be at an angle transverse to the grooves to give equal texture to the groove edges.

On-board controls capable of providing and monitoring uniform velocity and direction will be required. Self-contained lighting for night operations will be required.

Provide additional equipment to electro-magnetically remove any remaining steel abrasive at the same width and production rate of the texturing equipment.

Construction Requirements

For pavement texturing treatment processes, the Contractor and any Subcontractor shall demonstrate that all equipment has been calibrated in the presence of the Engineer with a minimum 100-foot test section. The test section shall be incorporated into the production section. A minimum of 2 tests utilizing an Outflow Meter shall be performed in accordance with the latest version of ASTM E-2380 in the presence of the Engineer at locations designated by the Engineer within the test section. An average of 10 seconds or less will be required before full production can commence.

Texture only areas indicated on the plans. Texturing shall be performed in a continuous operation of consecutive passes up to 6 ft. in width (if necessary), parallel to the centerline, so that one 12 ft. lane can be completed in a maximum of 2 passes. The textured pavement surface must have a uniform surface appearance and be devoid of machine produced streaks, ruts, or over-lap grooves which shall inhibit the free flow of water. It must have a non-directional texture. Following the texturing operation, the electromagnet must pass over the entire pavement surface.

Ensure pavement texturing process does not obliterate or remove pavement striping or markings and without causing damage to the raised and/or inlaid pavement markers unless approved by the Engineer. The distance from the edge of traffic markings to the texture must be a maximum of 3 in.

All pavement surface materials removed during the texturing process must be collected and stored in the vacuum unit until it can be removed from the project and disposed of by the Contractor. No on-site transfer of, or storage of, the materials will be permitted. No loose material shall be left on the roadway or swept off to the side of the roadway. Haul and dispose removed material in accordance with applicable federal, state, and local regulations. Obtain approval for the sequence of work and the estimated daily production.

The Contractor and any Subcontractor shall attend a preconstruction meeting prior to the construction or the first day of application of the pavement texturing as scheduled by the Engineer.

Acceptance Testing

The Contractor shall provide appropriate Outflow Meter test equipment and perform Texture Drainage testing in accordance with the latest version of ASTM E-2380 in the presence of the Engineer. Within the first lane mile, 5 outflow meter tests shall be conducted at randomly selected wheel path locations as determined by the Engineer. An average of 10 seconds or less will be required of all 1 lane mile sections. After the first lane mile, test frequency can be reduced at the discretion of the Engineer. Sections not meeting this criterion shall be retextured at the Contractor's expense.

Measurement and Payment

Payment for the accepted quantity for *Pavement Texturing* will be measured and paid in square yards of pavement surface area where pavement abrasion was completed and accepted. Square yard calculations will be based on the neat dimensions shown on the plans or as adjusted by the Engineer. Material placed outside of the designated treatment area is disregarded in computing the quantity. Asphaltic concrete pavements, Portland cement concrete pavements, including bridge decks will be paid at the singular contracted unit bid price for the pay item.

This unit bid price will be full compensation for texturing the pavement surface as well as vacuuming, hauling, unloading, and disposing of the material, for all labor, equipment, supplies, and incidentals, including labor and additional equipment to electro-magnetically remove any remaining steel abrasive.

Payment will be made under:

Pay Item	Pay Unit
Pavement Texturing	Square Yard

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Sign with Emphasis

A series of options are available to increase driver attention to static signs and warn of real-time hydroplaning hazard conditions. Some of the available emphasis systems are warning beacons and light emitting diode (LED) units within the symbol, legend, or border of sign. Warning beacons and LED units within the sign are activated to indicate specific periods when a hydroplaning hazard is present or is likely to be present.

LED Enhanced Sign.

Hydroplaning Assessment	Driver Speed Reduction	Currently under research
Costs	Sign with Beacon Cost	$10,000 per Type E sign with beacon
	Life-cycle cost	unknown
Design Considerations		*See below*
Operations Considerations	Construction	Available ROW, adequate perception-reaction time
	Maintenance needs	*See below*
	Service life	10 years for sign
Other Considerations		*See below*

Design Considerations

- A “WHEN FLASHING” (W16-13P) plaque shall be included when beacons or LED units are present for emphasis on the real-time hydroplaning hazard.
- When considering the location of warning signs with flashing beacons or LEDs, the signs need to be placed with enough distance to the potential hydroplaning hazard location to give the driver enough perception-response time (PRT) after reading the sign message. Additional signs should be placed at appropriate intervals along the road where the hydroplaning hazard exists.

Warning signs too far in advance, however, tend to make drivers forget about the warning due to other distractions while driving.

- For multi-lane divided roadways with medians, dual ground mounted signs with warning beacons or LEDs should be installed.
- Signs with warning beacons or LEDs will need additional infrastructure when compared to the static warning sign by itself. A communication source will be needed to be able to activate the systems when the hydroplaning hazard is present or may be present.

Expected Maintenance Needs

- Current NCDOT Routine Maintenance Improvement Plan (RMIP) states that the service life of signs is 10 years. Damaged or deteriorated (including retroreflectiveness not meeting NCDOT standards) signs need to be replaced. Weeds, trees, and/or shrubbery blocking a sign should be removed.
- Flashing beacons and LED components must be maintained and replaced if faulty or damaged.
- To keep the warning beacons and LEDs reliable, these must be activated only when the hydroplaning hazard will most likely happen or is already existing. Activating the devices when no hazard takes place will make drivers lose respect for the warnings. The same principle applies when activation does not occur while the hazard is happening or about to happen.

Secondary Benefits

- Increased driver attention to static sign messaging triggered by real-time conditions.
- Flexible, multiple deployment options (e.g., solar-powered, flashing beacons, LED borders).
- Moderate cost.
- Moderate level maintenance.

Other Considerations

- Warning signs with beacons or LED shall be diamond-shaped with a black legend and border on a yellow background. Plaques shall be rectangular with black legend and border on a yellow background.
- When used, plaques shall be placed immediately adjacent to a sign to supplement the message on the sign. Plaques shall always accompany a warning sign and cannot be used by itself.
- If using two warning beacons, these shall flash alternately.
- LEDs shall have a maximum diameter of ¼ inch.
- LED lights shall be white or yellow for warning signs, and these shall flash simultaneously.
- Warning signs with beacons or LED are required to be retroreflective and need to comply with NCDOT's Grade of Retroreflective Sheeting.
- Warning beacons shall consist of one or two signal sections (beacon) of a standard traffic signal face with a flashing circular yellow signal indication. If using just one beacon, it shall be located on top of the sign. If using two beacons, these shall be one on top and one at the bottom of the sign.
- When appropriate, solar panels can be used as a power source for the flashing beacons or LED assembly.

NCDOT Specification

NCDOT SECTION 900 GENERAL REQUIREMENTS FOR SIGNING

NCDOT SECTION 901 SIGN FABRICATION

NCDOT SECTION 902 FOUNDATIONS FOR GROUND MOUNTED SIGNS

NCDOT SECTION 903 GROUND MOUNTED SIGN SUPPORTS

NCDOT 904 SIGN ERECTION

NCDOT 1098-17 BEACON CONTROLLER ASSEMBLIES

References

1. FHWA, Manual on Uniform Traffic Control Devices (2009 Edition). Part 2. SIGNS
2. NC STATE UNIVERSITY, Operation Staff Meeting, Sign Service Life. Webpage: https://connect.ncdot.gov/resources/safety/Signing%20and%20Delineation%20Library/Sign%20Service%20Life.pdf
3. NCDOT, Signing and Delineation Unit (SDU) Procedures Manual. Webpage: https://connect.ncdot.gov/resources/safety/Pages/Signing-and-Delineation-Unit-Procedures-Manual.aspx
4. NCDOT, Bidding & Letting- Let Central. 2021 BID AVERAGES. Webpage: https://connect.ncdot.gov/letting/letcentral/forms/allitems.aspx
5. NCDOT, 2018 Roadway Standard Drawings. Division 09 – Signing.
6. NCDOT, Design Manual - Signal Design Section Part 1. Warning Beacons (Std. No. 7.1). Webpage: https://connect.ncdot.gov/resources/safety/ITS%20and%20Signals%20Resources/ITS%20and%20Signals%20Unit%20Design%20Manual%20Part%201%20-%20Signal%20Design.pdf

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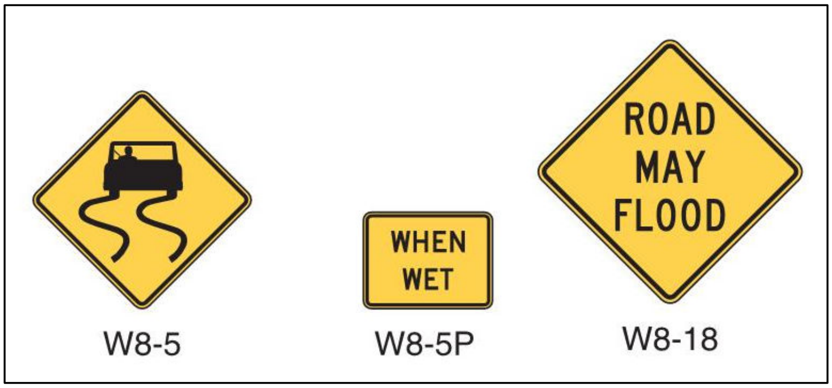
Static Signs

A static sign can be defined as a sign which conveys to the motorist one message only and is installed in a fixed location. These signs can be complemented by a plaque. Surface and weather condition signs are part of the "Warning" sign category. Surface and weather condition warning static signs/plaques provide the driver with advance notice of flooding or a slippery situation that might not be readily apparent.



Static Warning Signs for surface and weather conditions.

Hydroplaning Assessment	Driver Speed Reduction	Currently under research
Costs	Sign Construction/Installation Cost	$230 per Type E sign[4]
	Life-cycle cost	unknown
Operations Considerations	Construction	Available ROW, adequate perception-reaction time
	Maintenance needs	*See below*
	Service life	10 years
Other Considerations		*See below*

Design Considerations

- When used, plaques shall be placed immediately adjacent to a sign to supplement the message on the sign. Plaques shall always accompany a warning sign and cannot be used by itself.
- Static warning signs should be placed with enough distance to the potential hydroplaning hazard location to provide the driver enough perception-response time (PRT) after reading the sign message. Additional signs should be placed at appropriate intervals along the road where the hydroplaning hazard exists. Warning signs too far in advance tend to make drivers forget about the warning due to other distractions while driving.
- In order to enhance sign conspicuity, red or orange flags can be added above the sign.
- Since static warning signs have a constant message even if hydroplaning hazard is not present, and drivers may begin to disregard the potential for the hydroplaning hazard.

Expected Maintenance Needs

Current NCDOT Routine Maintenance Improvement Plan (RMIP) states that the service life of signs is 10 years. Damaged or deteriorated (including retroreflectiveness not meeting NCDOT standards) signs need to be replaced. Weeds, trees and/or shrubbery blocking a sign need to be removed.

Secondary Benefits

- Lowest cost for hydroplaning advance warning
- Low level of maintenance
- Ability to deploy immediately (e.g., minimum Right of Way, no power/communications needed)

Other Considerations

- Static warning signs shall be installed on 3-lb U channel or square tube posts in accordance with the NCDOT Roadway Standard Drawings. Wood supports may be installed on a case-by-case scenario if approved by the management unit.
- Static warning signs are required to be retroreflective and need to comply with NCDOT's Grade of Retroreflective Sheeting.
- Static warning signs shall be diamond-shaped with a black legend and border on a yellow background. Plaques shall be rectangular with a black legend and border on a yellow background.

NCDOT Specification

NCDOT SECTION 900 GENERAL REQUIREMENTS FOR SIGNING

NCDOT SECTION 901 SIGN FABRICATION

NCDOT SECTION 902 FOUNDATIONS FOR GROUND MOUNTED SIGNS

NCDOT SECTION 903 GROUND MOUNTED SIGN SUPPORTS

NCDOT 904 SIGN ERECTION

References

1. FHWA, Manual on Uniform Traffic Control Devices (2009 Edition). Part 2. SIGNS
2. NC STATE UNIVERSITY, Operation Staff Meeting, Sign Service Life. Webpage: https://connect.ncdot.gov/resources/safety/Signing%20and%20Delineation%20Library/Sign%20Service%20Life.pdf
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5. NCDOT, 2018 Roadway Standard Drawings. Division 09 – Signing.

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Ultra-Thin Bonded Wearing Course (UTBWC)

UTBWC is defined as a final layer of asphalt, approximately 0.58" thick (70#/SY), that increases the hydroplaning speed by increasing the pavement macrotexture. The wearing course is laid as a heavy spray application of polymer modified asphalt emulsion followed immediately by an ultra-thin gap-graded hot mix asphalt[1].

Figure 1: Ultra-Thin Bonded Wearing Course being laid[1]

Hydroplaning Assessment	HPS increase	1 – 5 mph
	MTD range/target	0.039 in
Design Considerations	Climate	Suitable for snow/ice removal
	Pavement	• Used over both PCC and DGAC • No additional strength added • Preferred for steeper grades
	Spatial extent	Applied to entire cross section
Costs	Construction cost	$33,500/Lane Mile
	Life-cycle cost	*Coming soon*
Operations Considerations	Construction	Heavy paving train load on bridges
	Maintenance needs	*See below*
	Service life	9 - 11 years[2]
Other Considerations	Secondary benefits	*See below*

Maintenance Needs

MnDOT District Maintenance staff have recently observed that in-service UTBWC surfaces can increase time demands and/or the amount of deicing material needed to achieve a clear and dry pavement surface[3]. These observations are summarized as follows:

- There have been observations that UTBWC is causing ice build-up in the wheel paths on some sections.
- The rough (popcorn like) texture of UTBWC surfaces has a tendency to accumulate wind-blown snow.
- The rough texture and open-graded characteristics of UTBWC surfaces may require additional deicing material compared to conventional hot mix asphalt surfaces, thus allowing accumulated snow to melt at the surface and form a bond with the underlying pavement.
- Once a bond of ice/frozen slush has formed, achieving a bare pavement surface requires increased plow time and deicing chemicals as compared to conventional mixes or seal coated surfaces.
- Various deicing methods such as prewetting and early application have been tested to address this situation, but do not consistently address the phenomenon in all MnDOT Districts.

Secondary Benefits

The overall advantages of UTBWC are as follows[3]:

- Slows down deterioration caused by traffic, weathering, raveling, and oxidation
- Seals small cracks
- Speedy application during construction
- Immediate opening to traffic
- Tire noise reduction
- High skid resistance
- Reduces splash and back spray
- Thinner lift equipment reduces applied weights and is appropriate for areas with overhead clearance, curb reveal, and drainage profiles limitations
- [5]Provides a chloride barrier and some waterproofing capability at low cost

References

1. Sunland Asphalt, ULTRA THIN BONDED WEARING COURSE | Sunland Asphalt
2. NCDOT, District 13 Operations, informal testimony
3. MnDOT, Ultra-Thin Bonded Wearing Course Snow, Ice, and Wind Effects, TRS1804.pdf (state.mn.us)
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5. MnDOT, Bridge Office, Innovation AGrzybowski 2021 BDW-13185140-v1.PDF, Grzybowski, Ashley 2021