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Ultra-Thin Bonded Wearing Course (UTBWC) Winter Maintenance

Prepared by Braun Intertec Corporation

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Image downloaded from www.dot.state.mn.us

Through project development in Phase 1, the Technical Advisory Panel (TAP) has identified that additional data and cost collection (without any field instrumentation and/or laboratory testing) would be beneficial to the research which was the objective of this TRS. The field instrumentation and/or laboratory testing was suggested to be performed under Phase 3 of this study.

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The purpose of this TRS is to serve as a synthesis of pertinent completed research to be used for further study and evaluation by MnDOT. This TRS does not represent the conclusions of either the authors or MnDOT.

Introduction

From the work that has been performed in Phase 1 of the Ultra-Thin Bonded Wearing Course (UTBWC) Snow, Ice, and Wind Effects TRS, we understand that UTBWC pavement occasionally experiences negative pavement performance attributes in cold weather, requiring additional maintenance (beyond typical treatments) to remedy. Observations indicate a phenomenon of ice build-up, potentially due to the accumulation of wind-blown snow, melting and freezing of that wind-blown snow, and bonding of that frozen ice/slush to the underlying pavement. To maintain safe driving conditions and keep the road surface bare and dry, increased plow time and deicing/anti-icing chemicals (relative to non-UTBWC surfaces) are required; however, the various deicing/anti-icing methods currently employed have not yet provided consistent solutions. In addition, the added costs to address these winter issues have not been quantified and compared within various MnDOT Districts.

During Phase 1 of the project, the literature review and interviews with knowledgeable parties yielded commonalities that illustrate general conditions and patterns of the cold weather UTBWC phenomenon, and somewhat effective maintenance methods to prevent and/or mitigate the issue. However, the exact science and nature of the phenomenon, as well as the optimal maintenance program to prevent and/or mitigate it, still remains unknown. In Phase 1 of the project, it was suggested that additional field instrumentation and/or lab testing be performed to better understand the nature of this phenomenon.

Through project development in Phase 1, the TAP has identified that additional data and cost collection (without any field instrumentation and/or laboratory testing) would be beneficial to the research which was done under Phase 2 of this study. The field instrumentation and/or laboratory testing was suggested to be performed under Phase 3.

In a study carried out by the Western Transportation Institute on winter maintenance on permeable friction surfaces (including UTBWC), the following advantages and disadvantages of Porous and Permeable Pavements (PPP) during winter conditions were noted [1]:

Advantages:

- Good drainage and macrotexture limit ice formation on wet surfaces.
- Ice formation within wheel paths covered in snow is reduced due to the macrotexture permeability.
- Friction values are generally the same or better than Dense Graded Pavements (DGP).
- Improved surface drainage reduces glare and spray during wet conditions.

Disadvantages:

- Freeze sooner and for a longer period of time than DGPs.
- Surface dries slower due to moisture trapped in the voids that is “pumped” to the surface by traffic, which can lead to icing when adjacent DGPs are dry.
- Sanding is not recommended to improve friction because of the potential to clog PPPs.
- May require higher application rates of deicers or more frequent application of deicing chemicals.
- May required more frequent application of deicers and for a longer duration than DGPs.
- Snow and ice tend to stick to PPPs sooner because the surface is generally cooler, and snow and ice remain longer because salts have dissipated from the pavement surface.
- Preventative salting (anti-icing) is not as beneficial because the salt penetrates into the void structure; however, this is less problematic in highly trafficked areas or if larger salt grains are used.
- Icing problems can occur in the transition zones between PPPs and DGPs due to a lack of deicers being carried over by traffic.

Winter Maintenance Methods

According to Minnesota Snow and Ice Control manual, typical winter maintenance methods are as follows [2]:

- Anti-icing: the application of chemical freeze-point-depressant materials before a winter storm which prevents ice from bonding to the pavement. Table 1 shows the typical anti-icing materials and their application rates.
- De-icing: the application of chemicals to the top of the accumulation of snow, ice, or frost that is already bonded to the pavement surface. De-icing improves the ability for plows to clear ice and snow from the road by loosening compacted snow and ice without damaging the equipment and pavement. Table 2 presents typical de-icing materials and their application rates.
- Prewetting: the addition of brine or other liquids to granular materials to increase salt's effectiveness by jump-starting the melting process. It also prevents the dry materials to bounce or blow off the road. Table 3 shows typical prewet material application rates.
- Snow Plowing: the removal of snow and ice from the roadway by mechanical means. Plowing removes snow and loses ice before de-icing application. When temperatures are too cold for de-icing materials to be effective, it may be necessary to plow the roadway while adding sand or other abrasives.

Table 1. Typical Anti-Icing Application Rates [2]

Condition	Gallons/Lane Mile			Other Products
	$CaCl_2$	$MgCl_2$	Salt Brine	
Regularly scheduled applications	15 – 25	15 – 25	20 – 40	Follow manufacturers' recommendations
Prior to frost or black ice event	15 – 25	15 – 25	20 – 40	
Prior to light or moderate snow	15 – 25	15 – 25	20 – 50	

Table 2. Typical De-Icing Application Rates [2]

Pavement Temp. (˚F) and Trend	Weather Condition	Maintenance Actions	Lbs./ two-lane mile			
			Salt Prewetted/ Pretreated with Salt Brine	Salt Prewetted/ Pretreated with Other Blends	Dry Salt*	Winter Sand (abrasives)
>30° and increasing	Snow	Plow, treat intersections only	80	70	100	Not recommended
	Freezing Rain	Apply chemical	80-160	70-140	100-200	Not recommended
30° and decreasing	Snow	Plow and apply chemical	80-160	70-140	100-200	Not recommended
	Freezing Rain	Apply chemical	150-200	130-180	180-240	Not recommended
25 to 30° and increasing	Snow	Plow and apply chemical	120-160	100-140	150-200	Not recommended
	Freezing Rain	Apply chemical	150-200	130-180	180-240	Not recommended
25 to 30° and decreasing	Snow	Plow and apply chemical	120-160	100-140	150-200	Not recommended
	Freezing Rain	Apply chemical	160-240	140-210	200-300	400
20 to 25° and increasing	Snow or freezing rain	Plow and apply chemical	160-240	140-210	200-300	400
20 to 25° and decreasing	Snow	Plow and apply chemical	200-280	175-250	250-350	Not recommended
	Freezing Rain	Apply chemical	240-320	210-280	300-400	400
15 to 20° and increasing	Snow	Plow and apply chemical	200-280	175-250	250-350	Not recommended
	Freezing Rain	Apply chemical	240-320	210-280	300-400	400
15 to 20° and decreasing	Snow or freezing rain	Plow and apply chemical	240-320	210-280	300-400	500 for freezing rain
0 to 15°	Snow	Plow, treat with blends, sand hazardous areas	Not recommended	300-400	Not recommended	500-750 spot treat as needed
Below 0°	Snow	Plow, treat with blends, sand hazardous areas	Not recommended	400-600**	Not recommended	500-750 spot treat as needed

*Dry salt is not very effective in general as it is likely to blow off the road before it melts ice, especially at temperatures below 15°F.

**A blend of 6-8 gal/ton MgCl2 or $CaCl_2$ added to NaCl can melt ice as low as -10°F.

Table 3. Prewet Application Rates [2]

Pre-wet Material Chart	Application Rate Recommendation Chart					
	Pavement Temp	Weather Conditions	Pounds Per Two (2) Lane Mile			Actions & Application Recommendation
			100% Salt	50% Salt	Stock Pile	
	Above 30˚	Snow	150-300	Not Recommended	Not Recommended	Plow, treat hazards ONLY
		Freezing Rain	150-300	Not Recommended	Not Recommended	Apply as needed
		Snow	200-400	Not Recommended	Not Recommended	Plow, treat hazards ONLY
		Freezing Rain	200-400	Not Recommended	Not Recommended	Apply as needed
	25 to 30˚	Snow	200-400	Not Recommended	Not Recommended	Plow & apply as needed
		Freezing Rain	200-400	Not Recommended	Not Recommended	Apply as needed
		Snow	300-500	Not Recommended	Not Recommended	Plow & apply as needed
		Freezing Rain	300-500	500-750	Not Recommended	Apply as needed
	20 to 25˚	Snow/Freezing Rain	300-500	500-750	Not Recommended	Plow & apply as needed
		Snow	300-500	Not Recommended	Not Recommended	Plow & apply as needed
		Freezing Rain	400-500	500-750	Not Recommended	Apply as needed
	15 to 20˚	Snow	300-500	Not Recommended	Not Recommended	Plow & apply as needed
		Freezing Rain	400-500	500-750	Not Recommended	Apply as needed
		Snow/Freezing Rain	400-500	500-750	Not Recommended	Plow & apply as needed
	Below 15˚	Snow	Not Recommended	Not Recommended	500-750	Plow, treat hazards w/ stockpile
	Frost: 15˚ & rising: treat by anti-icing (bring 20-40 G/LM) or 15˚ & falling: 100% salt @ 150 #/LM					
	Wind conditions: plow, treat (trouble spots only) with 50/50 @ 300#/LM OR stockpile @ 200-400 #/LM					
	If event/shift temperatures will rise, use salt instead of sand (& vice versa as temps fall)					

A variety of winter maintenance materials are available for local agencies to use to manage snow and ice. Table 4 summarizes the commonly used materials, their uses, attributes and environmental impacts [3].

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Table 4. Winter Maintenance Materials [3]

							
	Abrasives	Solid Rock Salt	Salt Brine	Magnesium Chloride	Calcium Chloride	Acetates	
		(NaCl)		($MgCl_2$)	($CaCl_2$)	Calcium Magnesium Acetate	Potassium Acetate
Usage	Mix with salt to provide traction to slippery roads.	Deicing or anti-icing	Prewetting and anti-icing	Deicing, prewetting, and anti-icing	Deicing	Anti-icing	Anti-icing
Typical Form	Sand (paved roads) or gravel (unpaved roads). Mixed with salt (20% to 33% salt).	Solid granular	Liquid	Liquid or solid	Liquid	Liquid	Liquid
Lowest Practical Melting Temperature	Lowest practical melting temperature	15° F	15° F	-10° F	-20° F	20° F	-15° F
Positive Attributes	- Provides temporary traction - More effective than chemicals at very low temperatures and for spot traction at targeted locations (hills, curves, bridges, intersections, shaded areas, windblown areas) - Useful alternative in environmental sensitive locations (no salt roads)	- Excellent melting capacity - Lower cost compared to other chemicals - Clear roads of snow and ice	- Prevents snow and ice from bonding to pavement (anti-icing) - Lower cost compared to other chemicals - Reduced granular scatter when used for prewetting - Low cost	- Reduced amount of product used, reduced salt and abrasive use over rock salt - Better cold temperature performance than rock salt - Persists on the road surface, aiding in longer black ice prevention than sodium chloride	- Better cold temperature performance than rock salt - Reduced amount of product used	- Non-corrosive	- Non-corrosive - Often used on bridge anti-icing systems
Negative Attributes	- Recovery from storms is slower than chemicals when used alone or in combination with only plowing - More plow passes and applications are required than if chemicals are used - Cannot achieve deicing - Requires clean up after winter season	- Corrosion - Impacts on roadside and waterways - Pavement deterioration - Corrosion to vehicles and infrastructure	- Corrosion - Impacts on roadside and waterways - Corrosion to vehicles and infrastructure	- Pavement deterioration - Corrosion - Material cost is higher than rock salt - More corrosive than sodium chloride	- Pavement deterioration - Corrosion - Material cost is higher than rock salt - More corrosive than sodium chloride	- Expensive	
Environmental Impacts	- Abrasives can enter the waterways and clog streams, clog drains, can impact water quality and aquatic species - Straight abrasive use does not pose corrosion issues, but abrasive-salt mixes can cause this issue	- Entry into waterways - Impact to roadside soil, vegetation	- Entry into waterways - Impact to roadside soil, vegetation	- Entry into waterways - Impact to bridge infrastructure - Leaching/run-off from stockpiles	- Entry into waterways - Impact to roadside - May mobilize heavy metals in soil releasing them into the water	- Their decomposition consumes dissolved oxygen, resulting in lower oxygen levels in water.	

Winter Maintenance Cost

According to Federal Highway Administration (FHWA), approximately, 20% of the state DOT's budget is used to cover winter maintenance costs [4]. Table 5 presents the winter maintenance cost for several state DOTs. As this table shows, the winter maintenance cost is in the range of $2,500 to $3,500 per lane mile. This cost is highly dependent on the winter maintenance "strategy" that is selected by the DOT based on the road and weather conditions. As it was discussed before, plowing, sanding, deicing, pre-wetting and anti-icing and any meaningful combination of them can be utilized.

Table 5. Average Winter Maintenance Costs

State / Region	Winter Maintenance Cost (per lane mile)	Reference
Michigan	$3,100	[5]
Minnesota	$3,503	[6]
Pennsylvania	$3,229	[7]
Wisconsin	$2,537	[8]
Finland	$2,733[1]	[9]

[1]Euro was converted to US dollars using the average annual exchange rate in 2008 [10]. This was then adjusted to 2018 USD using the Consumer Price Index (CPI) inflation calculator [11].

Winter maintenance can be costly; in some cold regions of Europe, winter maintenance can cost up to $5,500 per lane mile for the whole winter season [12]. Winter maintenance costs can be divided into three main categories: material, labor, and equipment. For example, Wisconsin DOT have reported their 2017 winter labor, equipment, and material costs to be $601, $720 and $1,216 per lane mile, respectively [8]. Some other agencies report their winter maintenance costs in terms of the amount of materials that have been applied on their roadways. For example, in 2013, Michigan DOT has spent approximately $55 and $100 per ton of applied salt for the material and the combination of labor and equipment costs, respectively [13].

Table 6 presents the cost of different winter maintenance methods obtained from several available sources. Where available, the cost was divided into the three aforementioned categories of labor, equipment, and material.

Table 6. Winter Maintenance Costs

Winter Maintenance	Region (material type)	Winter maintenance cost (per lane mile)[1]			Reference
		Labor cost	Equipment cost	Material cost	
Plowing	Minnesota	$18.35			[14]
	New York	$41.62 to $42.67			[15]
Sanding	California	$61.98			[16]
	Nevada	$94.19[2]			
	Oregon	$23 to $100			
	Colorado	$1.95 to $3.62	$1.44 to $4.34	$8.38 to $22.27 (per ton)	
	Montana	–	–	$11.14 to $22.27 (per ton)	
Deicing	Washington (salt)	$151.51 to $905.05			[16]
	Michigan (salt)	$2,295[3]	–	$647 to $694	[17]
	Michigan (salt-sand mix)	$2,295[3]	–	$547 to $577	
	Canada (salt)	$562			[18]

[1]All costs are adjusted to 2018 USD using the CPI inflation calculator [11]. Also, where needed, Euro was converted to US dollars using the average annual exchange rate in the same year [10].
[2]Includes the cost of cleaning up the used abrasives.
[3]The high labor costs could be due to the primitive technologies in 1993.

Table 7 presents sodium chloride (salt) application rate and cost based on some state DOTs recommendations. The cost of salt was assumed to be $42 per ton. There are other materials that can be used for deicing and anti-icing purposes including brine, magnesium chloride ($MgCl_2$), calcium chloride ($CaCl_2$), calcium magnesium acetate (CMA), and potassium acetate (KAc). These materials have different melting performance at various temperatures. Melting performance can be defined as the ratio of the melted tons over the deicer tons used. Taking this definition into account, the cost of the required deicer to melt one ton of snow was calculated for different type of deicers and are shown in Table 8. In this table, the concentration is the ratio of the weight of the deicing material to the total weight of the solution. The melting performance and concentration are provided from NCHRP report 577 [20].

Table 7. Material Cost and Application Rates for Salt [19]

State	Application rate (lb per lane mile)	Material costs ($ per lane mile)
New York	180 to 1400	3.78 to 29.4
Minnesota	80 to 600	1.68 to 12.6
Wisconsin	200 to 600	4.2 to 12.6
Connecticut	300 to 430	6.3 to 9.03
Ontario	280 to 620	5.88 to 13.02
Quebec	350 to 1100	7.35 to 23.1
British Colombia	200 to 620	4.2 to 13.02

Table 8. Melting Performance and Cost Analysis of Various Deicers at -15˚C

Deicer material	Melting performance [20] (concentration)	Unit cost (per ton) [19]	Cost of required deicer to melt one ton of snow
Salt	0.2 (0.23)	$42	$48
Calcium Chloride ($CaCl_2$)	0.9 (0.32)	$140	$50
Magnesium Chloride ($MgCl_2$)	1.1 (0.30)	$111	$37
Calcium Magnesium Acetate (CMA)	0.1 (0.25)	$1,492	$3,730
Potassium Acetate (KAc)	1.2 (0.50)	$1,166	$700

UTBWC Winter Maintenance

Several studies have shown that the temperature and humidity of the porous pavements (including UTBWC) are different from the DGPs mainly due to their higher surface area and permeable voids [1, 21]. Porous pavements are believed to get colder faster and stay frozen longer than the DGPs [1].

The stronger bond between the UTBWC surface and snow and/or ice often requires higher plowing effort [22-23]. On the other hand, the snow plow may induce some damages to the pavement surface. MoDOT has observed some loose aggregates laying on the shoulder after plowing operation which could attribute to the plowing gouge [24]. In another experiment on thin pavements, it was reported that thin pavements are more susceptible to plowing damages [23]. Another study conducted by Iowa Department of Transportation states that inappropriate application of thin pavements, such as applying under humid conditions, could make them significantly more susceptible to degrade while plowing [22].

Several studies have reported that porous pavements require higher amount of salt to be used in snow removal processes [1, 21-23]. As an example, New York state Snow and Ice Control manual suggests that the UTBWC pavements require higher amount of chemicals to prevent bonding due to their open graded structure which cause the brine to drain out quicker [25]. On the contrary, in a study done by Litzka, it was stated that porous pavements require a greater number of passes of winter maintenance service, but smaller quantities of deicer

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could be applied on each pass [23]. A similar recommendation is made by the Oregon DOT [26]. In another study, the same level of skid resistance was obtained from the porous pavement which had received about 70% less salt [27]. Some countries including Japan have utilized porous pavements to provide higher skid resistance and reduce the crash rates on some of their snowy roads [28].

Winter maintenance have two primary elements: Intra-storm and Inter-storm maintenances. Intra-storm maintenance includes operations performed during and closely after the storm event. The Inter-storm maintenance includes all strategies conducted between two storm events. The deicing mechanism within the Intra-storm maintenance is through the creation of salt brine solution above the snow/ice. Melting occurs as the brine solution penetrates into the snow/ice and the additional water from these molten snow/ice leads to the expansion of brine solution and the nearby snow/ice will be exposed. This mechanism cannot thoroughly happen on porous pavements, as the molten water and brine solution may infiltrate into the pavement structure and drain out. This could be one of the reasons for higher salt requirement in these type of pavements for intra-storm maintenances [27]. For the DGPs, additional salting as Inter-storm maintenance is required to prevent the formation of black ice or refreezing of the standing water on the pavement surface. This is not the case for porous pavements due to their enhanced draining capabilities. Also, infiltration of brine solution into the voids of porous pavements can store some amount of salt in their pores. The stored salt can prevent the pavement from formation of ice and/or weaken the snow bond with pavements between the storm events. Therefore, the Inter-storm maintenance of porous pavements requires significantly less salt load [27, 29]. On the contrary, a study conducted in France states that very thin asphalt concretes are susceptible to the cold and can facilitate the production of black ice [21].

The snow removal process of porous pavements has been evaluated via laboratory testing in some studies. In a study, the snow bond of two UTBWC mixtures (New York's Nova Chip Type B with a NMAS of ½ inches and Missouri's UBAS Type C with a NMAS of ¾ inches) was investigated and compared with the OGFC and the DGP pavements under four different strategies:

- No winter maintenance (just traffic)
- Anti-icing using salt brine
- Deicing using dry salt
- Deicing using pre-wet salt

The shear force required to plow the snow from the surface of the pavement was measured and used as an indicator to evaluate the effect of each winter maintenance strategy. The results showed that the average snow bond ranges between 0.5 and 10 psi. The OGFC pavement exhibited the strongest bond with the snow followed by UTBWC and DGP. Also, application of anti-icing could weaken the snow bond significantly while, as expected, applying no winter maintenance resulted in the strongest bond. The effect of using anti-icing on the OGFC and DGP pavements was significant, while it was less significant on Ulta-thin ones. Figure 1 shows the snow bonds in psi for different pavement surfaces in which UTFCmo and UTFCny are the UTBWC pavements from Missouri and New York, respectively [1].

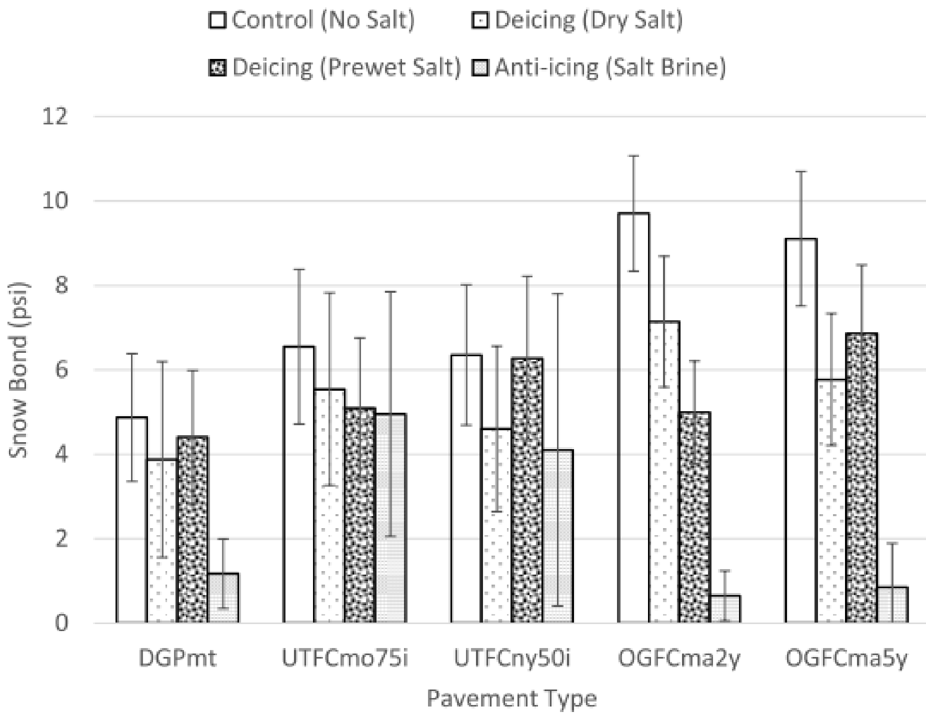

Figure 1. Snow-Pavement Bond Test Results [1].

Minnesota Experience with UTBWC

As part of this research project, Braun Intertec reached out to several MnDOT personnel to gather data and cost information on the existence UTBWC sections. Unfortunately, in many cases little to no information was available. Also, in some cases, the costs associated with UTBWC sections were not collected separately and therefore, could not be used in this report.

Below is a summary of the information that was collected from some Minnesota UTBWC sections.

District 3

District 3 constructed a one-mile section of UTBWC on Highway 169 north bound in Elk River in 2012. The south bound was overlaid with a traditional ½ inches bituminous wearing surface at the same time. This urban segment of Highway 169 carries more than 30,000 vehicles per day. During 2018-2019 winter, plow operators did not notice any significant differences in labor, equipment, and materials between the UTBWC and non-UTBWC segments to maintain them during snow and ice operations. This UTBWC segment is a relatively short segment of a 20-mile plow route which makes it difficult to distinguish and/or track mileage, salt quantities, passes of blades, etc. However, even on a longer route, it would be difficult to measure cost differences because of different topography, roadway geometry, traffic volumes, plow operators, etc.

The maintenance staff reported that any snow and ice cost differences between UTBWC and non-UTBWC segments would be negligible for Highway 169 which may be partly due to the heavy traffic and the relatively high travel speeds on this segment which could help with the effectiveness of the deicing materials (rock salt and salt brine) on this facility, regardless of the surfacing type.

The District has reported that during the first couple of years, it was noticeable that early application of deicing chemicals on UTBWC helped to keep the lanes from accumulating compacted snow and ice. The maintenance staff have reported that the deicing chemicals stay longer in the open and depressed surfacing of UTBWC. During heavy snow fall (i.e. more than half an inch per hour or a total accumulation of more than 3 inches), compaction depths of UTBWC tended to become deeper than traditional paved surfaces and became more difficult to remove. Additional snow and ice compaction typically consumes significant resources including rock salt and plow under-body blades to remove. District 3 encounters an average of 30 snow and ice events per year and estimates that 6 to 10 events may result in some prolonged compaction. Additional depth of compaction that may occur on new UTBWC has not been measured nor have labor, equipment, and material resources been quantified. Plow operators and supervisor have reported that additional snow and ice resources would not exceed 10% for the first two seasons of a UTBWC surfacing.

District 3 has another UTBWC section on Highway 65 north of Mora in Kanabec County which was constructed in 2010. The life performance of this segment has reported to be similar to Highway 169. However, in the open wind-swept areas, any moisture held in open surfacing is more susceptible to blown snow. Thus, newly surfaced UTBWCs in open rural areas need to be monitored closely during the first couple of years during snow and ice operations. It should be noted that the open wind-swept areas on Highway 65 are isolated and issues that may be arising that need additional snow and ice resources are sporadic. The additional snow and ice costs for isolated/spot treatments is in the range of 10 to 15% for this type of rural highway. In general, the areas which experience more wind events would cause more concerns with the use of UTBWC.

Another observation by the District is that the UTBWC section are holding up way better compared to the traditionally surfaced tie-in between the mainline and the City streets. In general, the District seems to be pleased with cost, performance and life-cycle benefits of UTBWC surfaces.

District 4

District 4 has two UTBWC sections summarized in Table 9. Figures 2 and 3 show I-94 and US 10 UTBWC sections, respectively.

Table 9. UTBWC Sections in District 4

Route	County	Direction	Year	R.P.		Length (miles)	Pavement Type
				Begin	End		
I-94	Douglas	WB	2012	102+0.688	109+0.001	6.313	Bituminous over concrete
US 10	Becker	EB	2012	47+0.263	56+0.144	8.881	Bituminous pavement

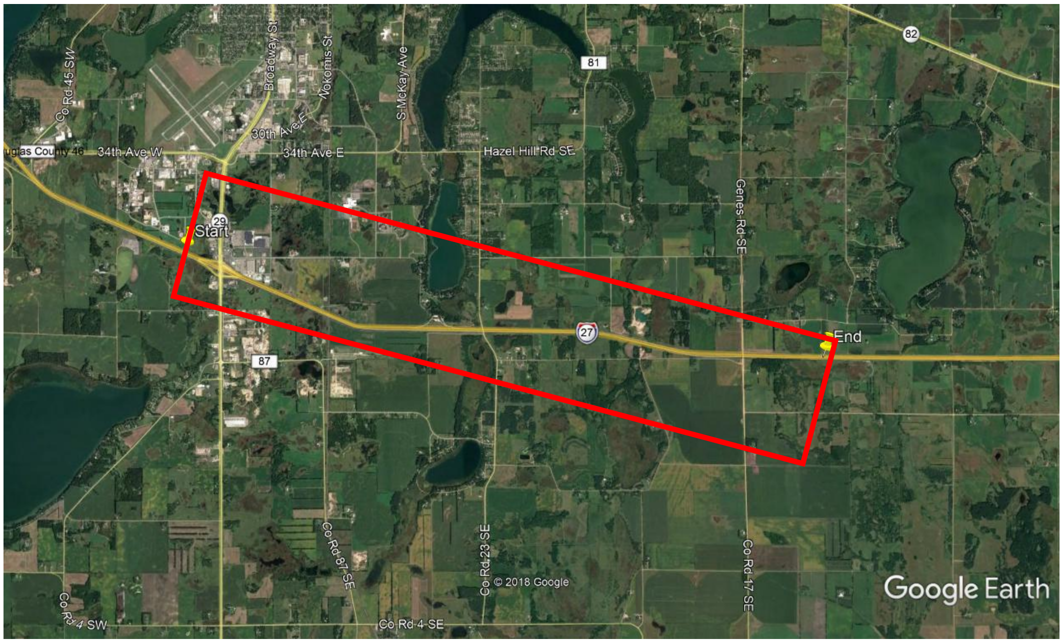

Figure 2. I-94 in Douglas County

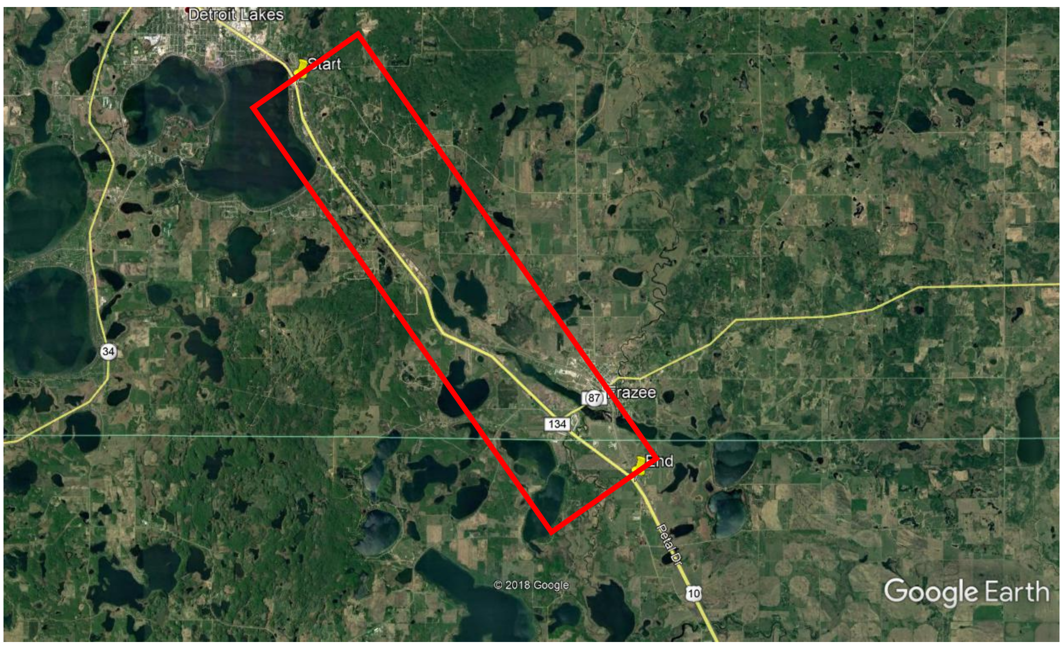

Figure 3. US 10 in Becker County

For both I-94 and US 10 sections, MnDOT currently treats UTBWC sections the same way as other non-UTBWC sections with the same equipment and materials. They reported some issues with snow and ice during the first winter where they had to use some additional chemical and under body blade work, but would have no way of estimating the additional cost. It did not sound like it was a significant amount anyway.

It is also interesting to note that after the first winter, they have experienced no differences between the UTBWC and non-UTBWC sections in terms of ice and snow.

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Metro District

County Road (CR) 11, between 134th St. and 122nd St., is 1.5 mile stretch of UTBWC in Burnsville, Minnesota and is illustrated in Figure 4.

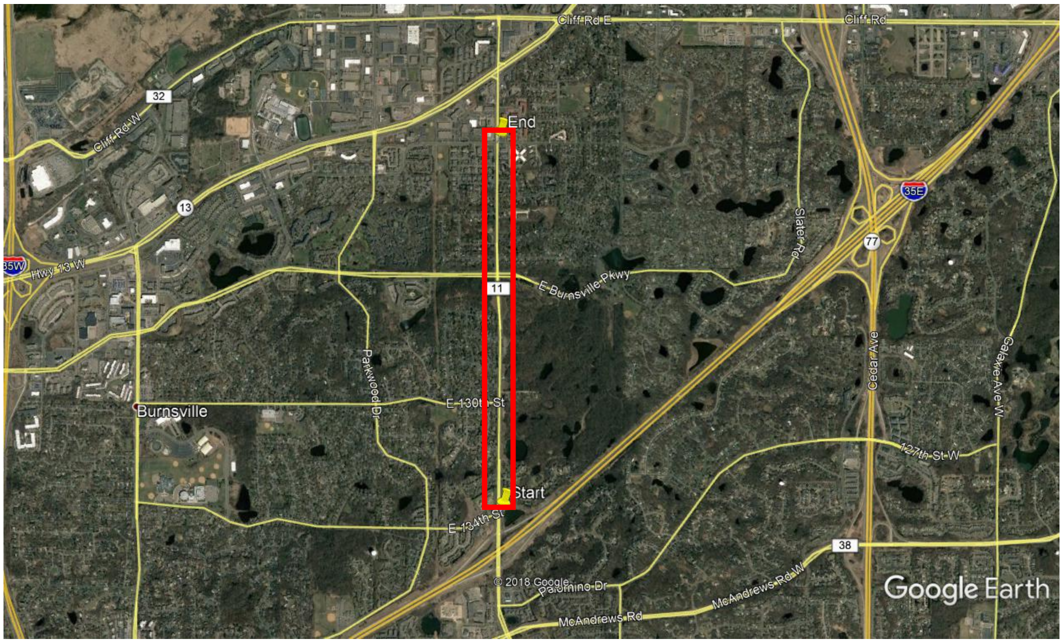

Figure 4. CR 11 in Dakota County

CR 11 is a north-south running roadway that was paved in the Fall of 2016. During the 2016-2017 snow and ice season, Burnsville officers had to close the road twice due to slippery conditions. After this occurred, maintenance personnel started putting more salt down. The extra salt was approximately 200 lbs per lane-mile. They had about 10 snow and ice events during that season. Assuming $65 per ton of salt, the extra cost associated with the UTBWC section was only about $200 for the whole season.

It is interesting to note that the County has not had any incidents with this roadway since that first snow and ice season and they are not placing any more deicer on this segment than any other non-UTBWC roadway. One explanation to this observation is that the open voids in UTBWC can plug up over time, thus eliminating the need for additional salt usage.

County State Aid Highway (CSAH) 80, between Dodd and Cedar is another 2.5 mile stretch of UTBWC in Dakota County, Minnesota. Figure 5 shows this section.

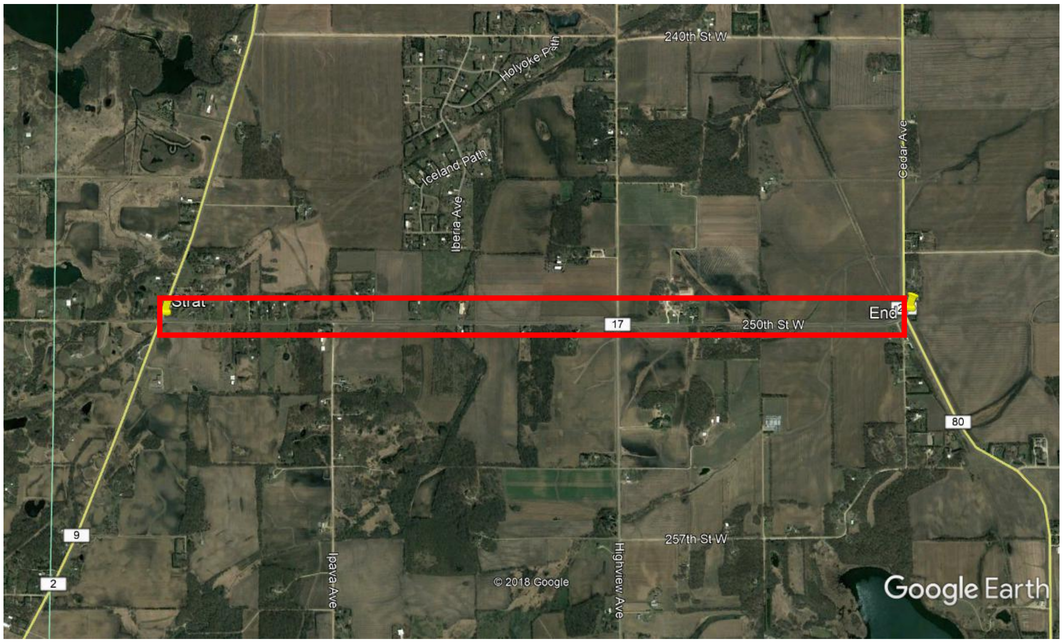

Figure 5. CSAH 80 in Dakota County

CSAH 80 is an east-west running rural roadway that was paved in 2017. This section has had no snow and ice issues to differentiate it from any other rural non-UTBWC segment in Dakota county.

Asset Management in Metro Maintenance collects costs per segment. Each segment may or may not include UTBWC sections, so unfortunately, the cost associated with UTBWC sections could not be separated and summarized.

District 8

MnDOT has constructed two UTBWC test sections in District 8. The test sections are located on Trunk Highway (TH) 23 north of Marshall, Minnesota. Both Type A and Type B UTBWC's were placed on these test sections. Figure 6 shows the limits of Type A and Type B.

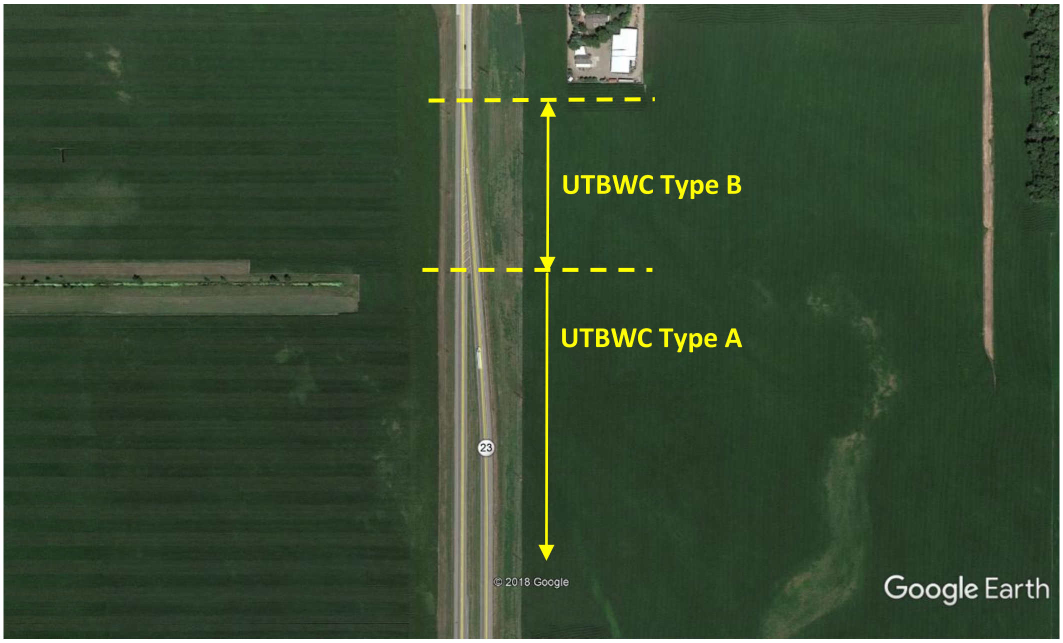

Figure 6. TH 23 UTBWC Type A and Type B

Table 10 shows Type A and Type B Job Mix Formula (JMF) gradation limits. As this table shows, the JMF limits for Type A and Type B are different for 1/2-inch through #4 sieves and are the same for #8 through #200 sieves and therefore, Type A is designed to be finer than Type B.

Table 10. UTBWC Type A and Type B JMF Limits

Sieve Size mm (inches)	Type A JMF Limits	Type B JMF Limits
12.5 (1/2)	100 – 100	100 – 100
9.5 (3/8)	100 – 100	85 – 100
4.75 (#4)	40 – 55	28 – 42
2.36 (#8)	21 – 33	21 – 33
1.18 (#16)	14 – 24	14 – 24
0.600 (#30)	9 – 20	9 – 20
0.300 (#50)	6 – 15	6 – 15
0.150 (#100)	5 – 11	5 – 11
0.075 (#200)	3 – 7	3 – 7

Figures 7 and 8 show the UTBWC gradations used on the test sections along with the JMF upper and lower limits for Type A and Type B, respectively. Figure 9 presents both gradations on the same graph. As expected, Type A is slightly finer than Type B.

It is worth mentioning that Type A gradation is very close to the upper JMF limits for type B and Type B gradation is very close to the lower JMF limits for Type A.

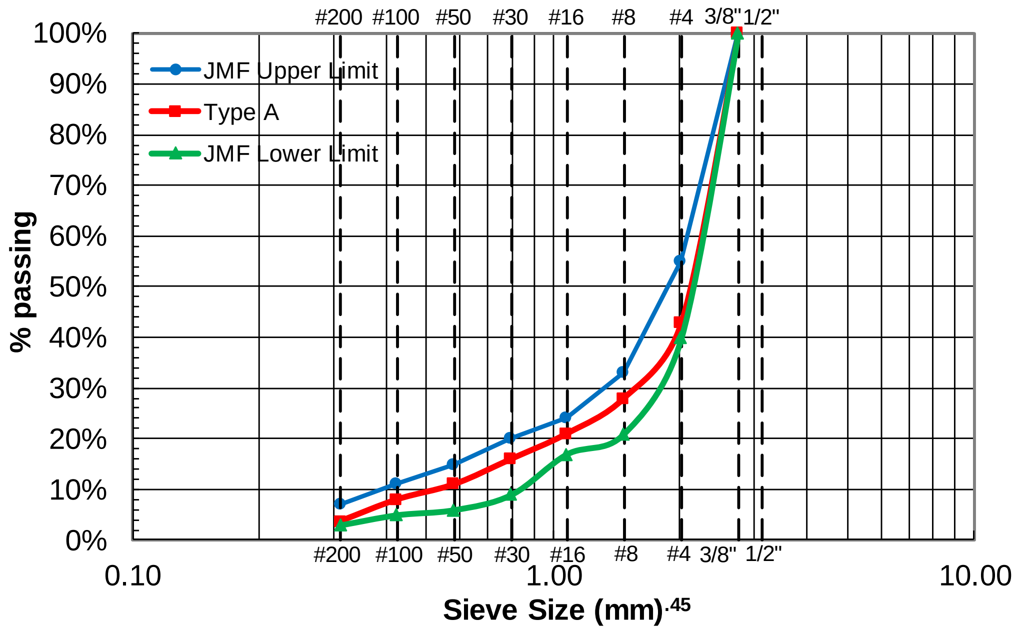

Figure 7. UTBWC Type A gradation used on TH 23

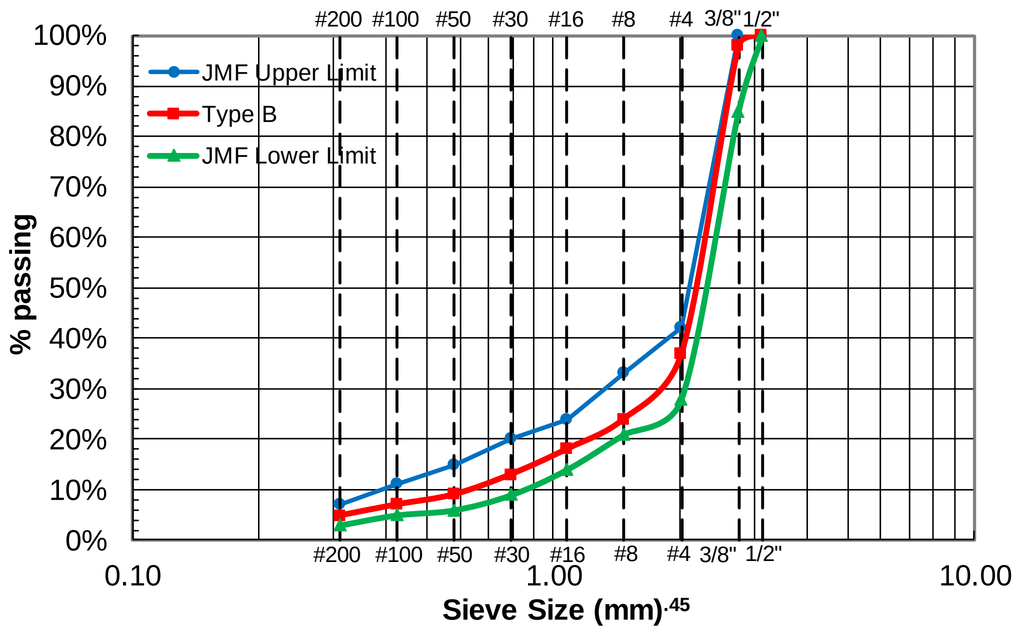

Figure 8. UTBWC Type B gradation used on TH 23

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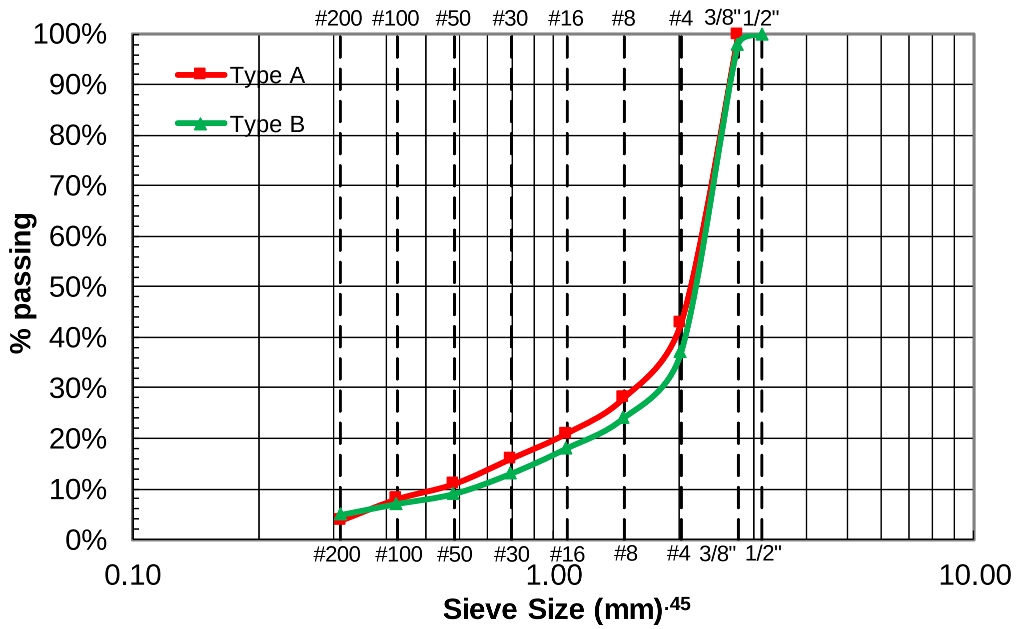

Figure 9. UTBWC Type A and Type B gradation used on TH 23

There were some reports regarding snow and ice issues with UTBWC Type B. In response to this issue, MnDOT decided to change the gradation to finer Type A a few years ago and since then they have had little if any snow and ice problems.

MnDOT (D8) does not pretreat any of their roads and applies salt at the same application rate for all pavements (including UTBWC). On UTBWC sections they occasionally have runoff dam up at the edge which would require additional salt, but it is not frequent.

Instead of one application of salt at the middle of the road, MnDOT has recently switched to applying 1/2 of the application rate in each direction. According to MnDOT staff, there were minimal if any additional costs with this change.

Other States Experience with UTBWC

In a study conducted by the Western Transportation Institute on winter maintenance on permeable friction surfaces, several interviews were conducted with DOT personnel to determine the types of porous and permeable pavements, problems with them during winter conditions, and successful treatment strategies for dealing with snow and ice [1]. Below is a summary of those states that have utilized UTBWC on their pavements.

Kansas

In Kansas, UTBWC is called UBAS (Ultra-thin Bonded Asphalt Surface). This type of pavement was used for more than 10 years in three different gradation types of A, B, and C. All the gradation types have Nominal Maximum Aggregate Size (NMAS) of 5/8 inches, with Type B being the most common. Plowing, anti-icing and deicing using salt, salt brine, pre-wetted sand, and sand-salt mixtures are common UBAS winter maintenance practices in the state. In general, the same treatment is applied on all type of pavement surfaces, but may be modified on the

UBASs. This modification could include higher application rates on UBAS surfaces using flood nozzles to get more brine down into the pavement and provide more surface coverage, while stream nozzles are used on DGPs.

The stronger bonds between the UBAS pavement surface and snow/ice in addition to the infiltration of the deicing liquids cause the field staff to spend more time and effort for snow/ice removal purposes. However, they have noticed that residual chemicals in the pavement pores help weaken ice-pavement bonds for subsequent storms.

Kansas DOT is generally pleased with the overall structural performance and life cycle cost of UBAS's, but they are not happy with their winter performance with respect to snow and ice removal.

Missouri

In Missouri, UTBWC is known as UBAWS (Ultrathin Bonded Asphalt Wearing Surface). It is used as a preventive maintenance treatment to help extend the life of pavements less than 10 years old in good condition but are beginning to crack. There are three aggregate gradations available: Type A, Type B, and Type C where the gradation gets coarser by going from A to C. Type C is most commonly used.

Some problems have been reported with UBAWS winter maintenance. Snow and ice tend to melt quickly but it can also refreeze quickly. Also, water gets trapped in the surface voids and tend to dilute the salt. UBAWS surfaces increase plow blade wear compared to non-UBAWS pavements. Also, more accidents have been reported at the transition zones (between UBAWS and non-UBAWS pavements).

Generally, Missouri DOT pretreats the pavement before storms using a sand/gravel/salt/cinders mixture with a salt concentration of less than 50 percent. Missouri DOT personnel have reported that increased application rates and more frequent applications are required on UBAWS, especially for new pavement and high speed roads. It is interesting to note that after three to five years or on low speed roads application rates and numbers of applications are comparable to non-UBWS pavements.

New York

In New York, UTBWC is known as PPST (Paver Placed Surface Treatment). There are three aggregate gradations available: Type A, Type B, and Type C where the gradation gets coarser by going from A to C. Types B and C are most commonly used.

NYDOT does not have specific guidelines for winter maintenance. They typically anti-ice with salt brine and follow up with applications of road salt. Sanding and deicing with liquids are generally avoided. It has been reported that PPST tends to require a greater amount of salt than non-PPST pavements during its first year.

Higher accidents rates on PPST sections were reported during dry, cool humid days on areas with salt residue. Even with the large amount of salt residue, moisture was freezing on the surface and decreasing surface friction.

Washington

Washington State DOT have a very limited amount of UTBWC pavements. A 10-year old section of UTBWC has performed well with no extra snow and ice control requirements.

Wyoming

Wyoming DOT has a few sections of UTBWC. Winter maintenance on the UTBWC pavements is similar to non-UTBWC pavements and generally consists of plowing, sanding, and deicer applications. Anti-icing at 35 gal/LM

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with salt brine or 60 percent salt brine/40 percent Geomelt during cold months is performed to delay snow accumulation and allow for better snow removal after the storm. During and post storm, sand applications contain 10 percent salt and may be prewet at 4–6 gal/ton with salt brine or salt brine/Geomelt.

Other States

In a study conducted by the Iowa Department of Transportation, a series of anecdotal information about the winter maintenance of thin maintenance pavement were collected. The following discussions were obtained from about 600 responses: some responders report that thin surfaces wore plow blades more quickly than other surfaces. Stronger and more effective bond between the pavement surface and ice/snow was also reported which could also form more rapidly. Using finer gradations was found to alleviate this effect [22].

Summary

UTBWC pavements have been utilized as a preventive maintenance across the United States. Almost all the state DOTs classify UTBWCs into three different categories based on their gradation. Regarding the winter maintenance, almost the same treatments are being applied on the UTBWCs in comparison with non-UTBWC pavements with the exception of higher application rates and/or higher frequencies for the UTBWC pavements due to the stronger bond of ice/snow with their surface. It is interesting to note that several states have reported that after the first winter, they have experienced little to no differences between the UTBWC and non-UTBWC sections in terms of ice and snow.

TH 15 Investigations

District 7 has constructed a 5/8-inch thick UTBWC section on TH 15 in 2012 which is summarized in Table 11. Figure 11 illustrates this section.

Table 11. TH 15 in District 7

Route	County	Direction	Year	R.P.		Length (miles)	Pavement Type
				Begin	End		
TH 15	Watonwan	NB/SB	2012	32+0.392	38+0.584	6.192	Bituminous over concrete

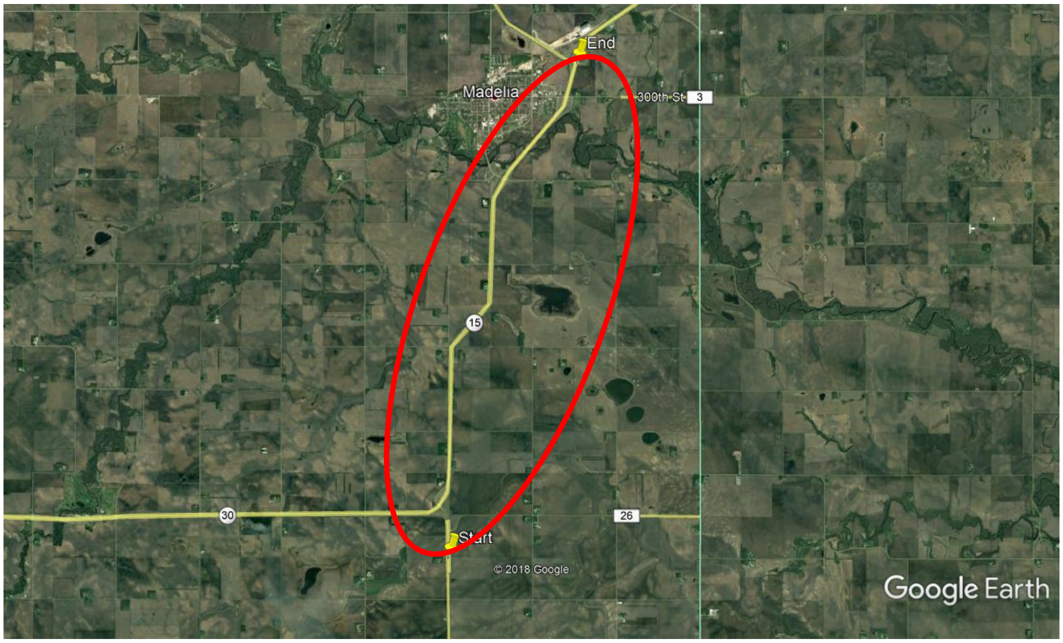

Figure 11. TH 15 UTBWC section in Watonwan County

A 3/8 inches (9.5 mm) gap graded gradation was utilized in the mixture. Tables 12 and 13 present the coarse and fine (passing the No. 4 sieve) aggregate testing requirements, respectively. Table 14 also summarizes the UTBWC mix requirements.

Table 12. Coarse Aggregate Testing Requirements

Test	Limit
Flat and Elongated Ratio @ 3:1 (%)	25 max
Los Angeles Rattler (LAR)	40 max
Soundness (Magnesium Sulfate)	No more than 18% loss for the composite loss
Bulk Specific Gravity	NA*

*with UTBWC density tests are not run as roller passes are used to seat the aggregate in place, not to compact the mix to a specified density.

Table 13. Fine Aggregate Testing Requirements

Test	Limit
Uncompacted Void Content	40 min
Sand Equivalent	45 min
Bulk Specific Gravity	NA

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Table 14. TH 15 UTBWC Mix Requirements

Sieve Size mm (inches)	Gradation Broadband Limits (% Passing)
12.5 (1/2)	100
9.5 (3/8)	85 – 100
4.75 (#4)	28 – 42
2.36 (#8)	22 – 32
1.18 (#16)	15 – 23
0.600 (#30)	10 – 18
0.300 (#50)	8 – 13
0.150 (#100)	6 – 10
0.075 (#200)	4 – 5.5
Asphalt content: 4.8 to 6.0%	
Adjusted Asphalt Film Thickness (AFT): 10.5 µm, minimum	
Draindown Test (AASHTO T 305): 0.10%, maximum	
Lottman (TSR) Test: 80%, minimum	

According to District 7, UTBWC and non-UTBWC sections are treated with the same material including rock salt blended with calcium chloride at 3 to 5 gallons per ton. The salt is also pre-wetted with a 90% salt brine and 10% calcium chloride mixture. The same equipment is used on the adjacent routes during winter maintenance. The equipment typically is a plow truck with the salt and brine mixtures loaded onto it. The treatment frequency can vary from one storm to another, but all the routes receive the same level of service in general. The UTBWC may require an additional treatment at times due to its rough texture. A typical application rate ranges from 100-400 pounds of salt per lane-mile.

In order to compare UTBWC vs. non-UTBWC winter maintenance cost, the cost information from 2009 to 2018 was gathered for three adjacent sections of TH 60 including UTBWC and non-UTBWC sections:

- Section A: Non-UTBWC section – from Butterfield to South Junction of TH 15
- Section B: UTBWC section – from South Junction of TH 15 to Madelia (same as TH 15)
- Section C: Non-UTBWC section – from Madelia to US 169

TH 60 and TH 15 run together throughout section B and Sections A and C are adjacent routs of TH 15 UTBWC section. Figure 12 illustrates these three sections on a map.

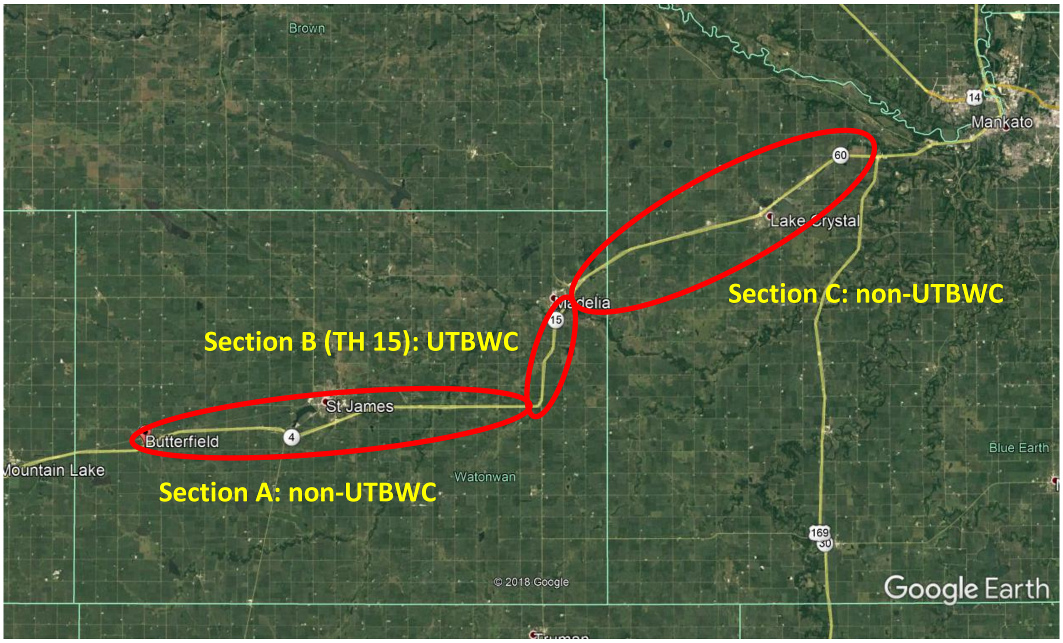

Figure 12. TH 15 UTBWC and adjacent non-UTBWC sections

Winter maintenance cost was broken down into three sub-categories:

- Labor cost
- Equipment cost
- Material cost

Total lane-miles services on different sections are as follows:

- Section A: 68 miles
- Section B: 26 miles
- Section C: 75 miles

In order to better compare the maintenance cost of different sections, all the costs were converted to cost per lane-mile serviced. Tables 15 through 17 present the winter maintenance cost of Section A, Section B, and Section C, respectively.

Table 15. Section A (non-UTBWC) Winter Maintenance Costs

Year	Labor Cost Per Lane-Mile	Equipment Cost Per Lane-Mile	Material Cost Per Lane-Mile	Total Cost Per Lane-Mile
2009	$490	$692	$651	$1,833
2010	$598	$846	$431	$1,875
2011	$664	$841	$546	$2,051
2012	$292	$380	$508	$1,180
2013	$547	$748	$868	$2,163
2014	$784	$1,177	$565	$2,526
2015	$553	$1,179	$738	$2,470
2016	$699	$1,465	$687	$2,851
2017	$695	$968	$518	$2,181
2018	$945	$1,160	$518	$2,623
Average	**$627**	**$946**	**$603**	**$2,175**
Minimum (year with the minimum cost)	**$292 (2012)**	**$380 (2012)**	**$431 (2010)**	**$1,180 (2012)**
Maximum (year with the maximum cost)	**$945 (2018)**	**$1,465 (2016)**	**$868 (2013)**	**$2,851 (2016)**

Table 16. Section B (UTBWC) Winter Maintenance Cost

Year	Labor Cost Per Lane-Mile	Equipment Cost Per Lane-Mile	Material Cost Per Lane-Mile	Total Cost Per Lane-Mile
2009	$862	$1,390	$1,314	$3,566
2010	$1,107	$1,580	$828	$3,515
2011	$1,448	$1,724	$1,063	$4,235
2012	$496	$648	$1,224	$2,369
2013	$1,161	$1,525	$1,600	$4,286
2014	$1,641	$2,292	$1,037	$4,970
2015	$1,141	$1,774	$893	$3,808
2016	$1,196	$2,129	$814	$4,139
2017	$1,478	$2,096	$1,059	$4,633
2018	$2,098	$2,444	$1,188	$5,731
Average	**$1,263**	**$1,760**	**$1,102**	**$4,125**
Minimum (year with the minimum cost)	**$496 (2012)**	**$648 (2012)**	**$814 (2016)**	**$2,369 (2012)**
Maximum (year with the maximum cost)	**$2,098 (2018)**	**$2,444 (2018)**	**$1,600 (2013)**	**$5,731 (2018)**

Table 17. Section C (non-UTBWC) Winter Maintenance Cost

Year	Labor Cost Per Lane-Mile	Equipment Cost Per Lane-Mile	Material Cost Per Lane-Mile	Total Cost Per Lane-Mile
2009	$435	$769	$479	$1,683
2010	$592	$1,132	$466	$2,190
2011	$541	$862	$606	$2,010
2012	$210	$389	$415	$1,015
2013	$488	$795	$905	$2,188
2014	$915	$1,413	$1,656	$3,985
2015	$394	$1,041	$529	$1,963
2016	$446	$1,156	$814	$2,416
2017	$403	$885	$709	$1,998
2018	$590	$1,029	$1,076	$2,695
Average	**$502**	**$947**	**$766**	**$2,214**
Minimum (year with the minimum cost)	**$210 (2012)**	**$389 (2012)**	**$415 (2012)**	**$1,015 (2012)**
Maximum (year with the maximum cost)	**$915 (2014)**	**$1,413 (2014)**	**$1,656 (2014)**	**$3,985 (2014)**

Since the UTBWC is constructed in 2012, the cost data from 2008 to 2011 (before UTBWC application) should be looked at separately from the cost data from 2012 to 2018 (after UTBWC application). It should also be noted that during the analysis period, some segments of Sections A and C have also received resurfacing and/or surface treatments which may have affected their winter maintenance cost. These treatments include:

Section A:

- Approximately 5.5 miles of bituminous overlay in 2008
- Approximately 6 miles of bituminous overlay in 2009
- Approximately 5 miles of seal coat in 2013
- Approximately 5.5 miles of concrete surfacing in 2014

Section C:

- Approximately 2.5 miles of bituminous mill and overlay in 2012
- Approximately 1.5 miles of concrete pavement repair in 2012

Figure 13 compares the labor cost of different sections. As this graph suggests, all the sections have about the same trend. The UTBWC section has the highest labor cost compared to the non-UTBWC sections both before and after UTBWC construction. Figure 14 shows the same comparison for equipment cost; similar to labor cost, all the sections generally have the same trend with the UTBWC section having the highest cost among all the sections, again for both before and after the construction of the UTBWC. Figure 15 compares the material cost among different sections. Again, the UTBWC section has the highest cost (before and after 2012) except in 2014 where Section C material cost shows a sudden jump.

Figure 16 presents the total cost of different sections from 2009 to 2018. The UTBWC has the highest cost, while the non-UTBWC sections have about the same total costs except in 2014, where Section C total maintenance cost has notably gone beyond Section A total maintenance cost.

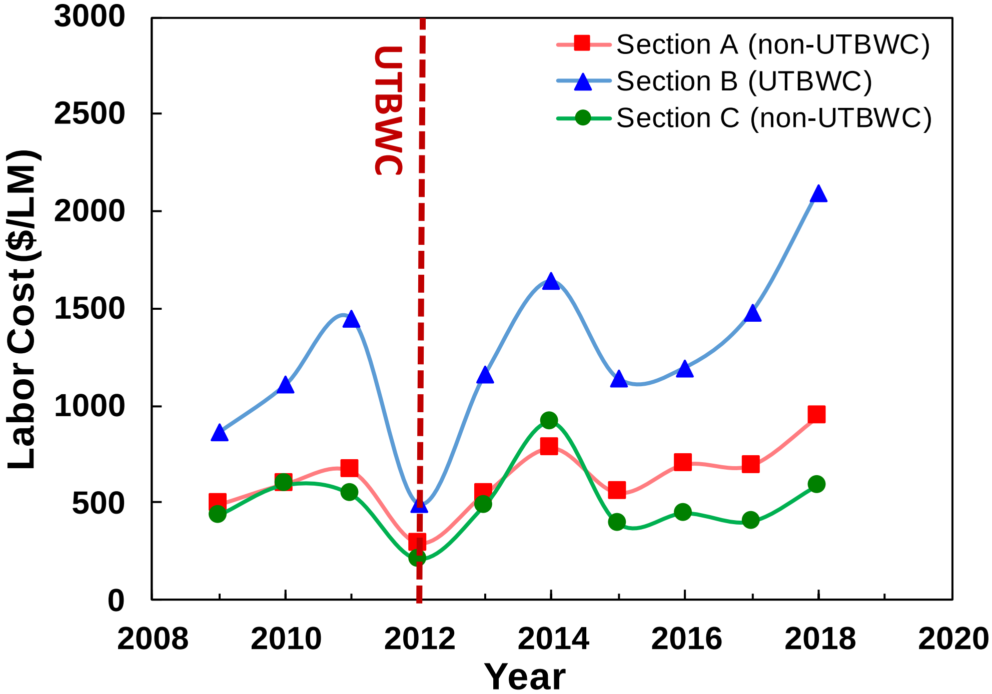

Figure 13. Labor Cost ($/LM) Comparison Among Different Sections

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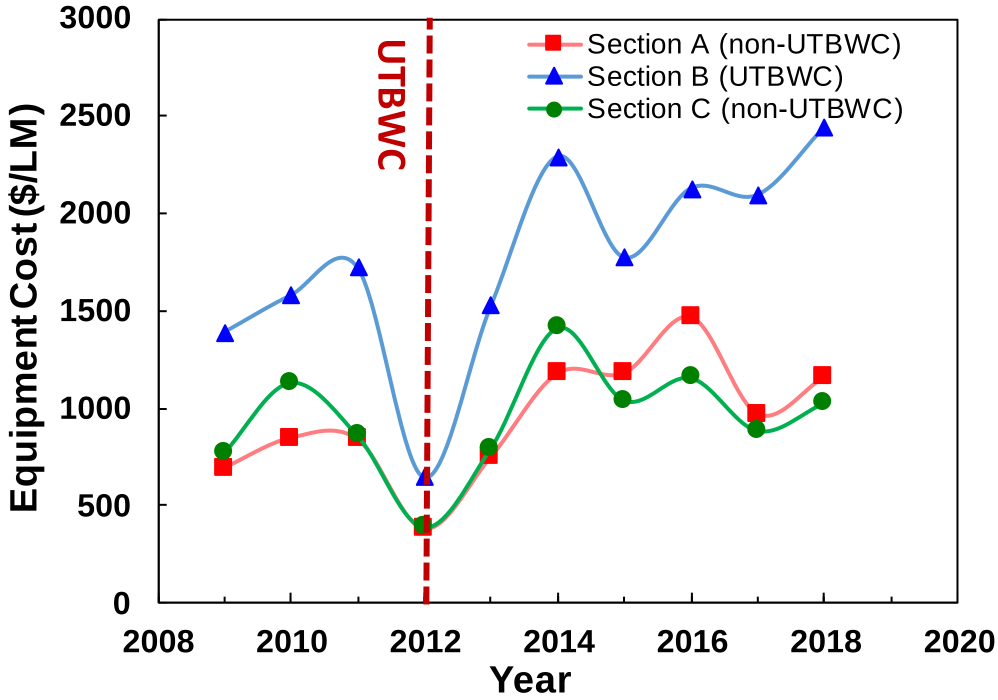

Figure 14. Equipment Cost ($/LM) Comparison Among Different Sections

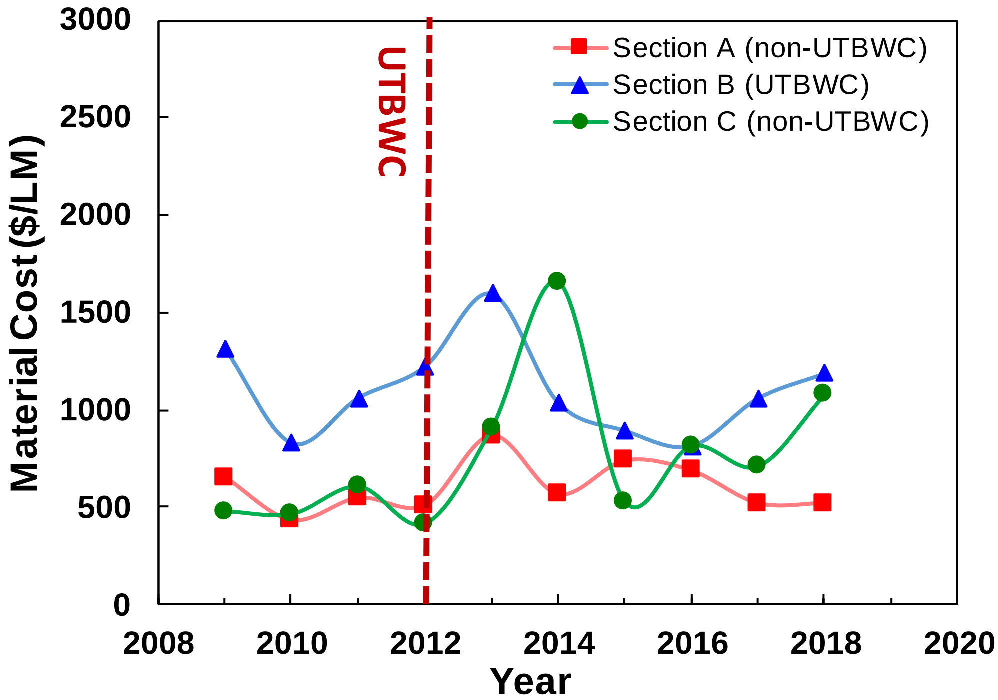

Figure 15. Material Cost ($/LM) Comparison Among Different Sections

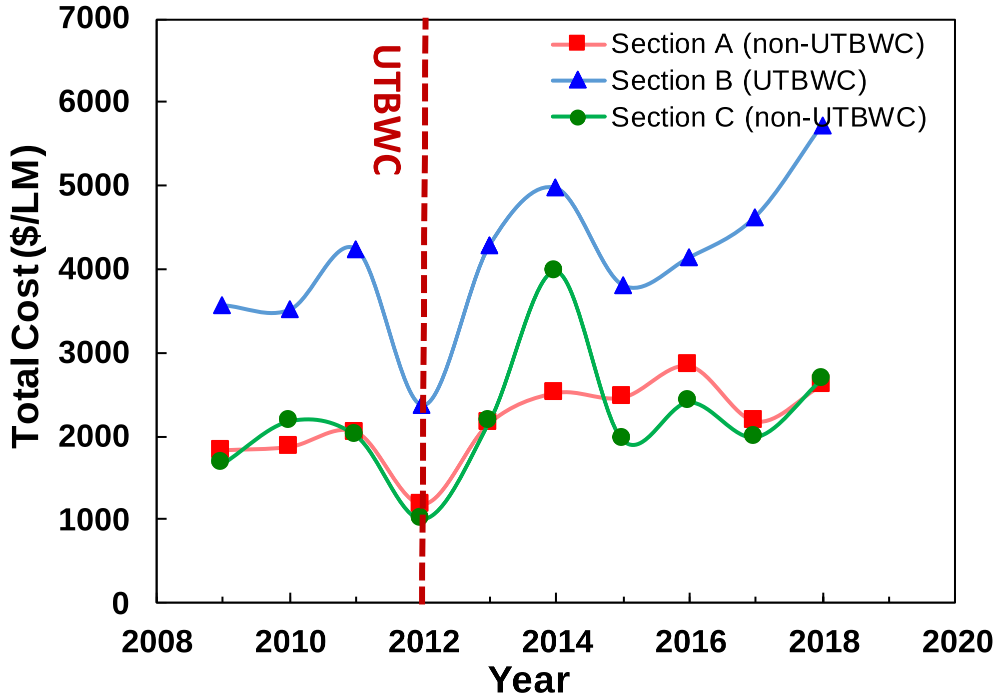

Figure 16. Total Cost ($/LM) Comparison Among Different Sections

It is interesting to note that the UTBWC section has the highest cost even before the construction of the UTBWC which could be partly due to difference in the surface types. Another possible reason for the higher winter maintenance cost of Section B could be its different orientation which is generally North-South compared to Sections A and C which are generally East-West.

As it was discussed in Phase 1 of this study, blowing snow, which is the snow lifted from the surface by the wind, can stick to the pavement surface in between winter events requiring more frequent winter maintenance efforts. The wind direction that has the greatest snow transport is of importance in determining the areas with high potential of blowing snow. Wind directions of greatest snow transport were identified for several stations in Minnesota as a part of the snowfall and snowdrift study [30] which Figure 17 summarizes the results. Figure 18 presents degrees versus cardinal direction table. As Figure 17 suggests, the wind direction of the greatest snow transport in Watonwan County is equal to 300 degrees. From Figure 18, the wind direction would be equal to west-northwest (WNW) which is almost perpendicular to Section B and therefore, the wind is expected to have the highest adverse effect on this section compared to Sections A and C.

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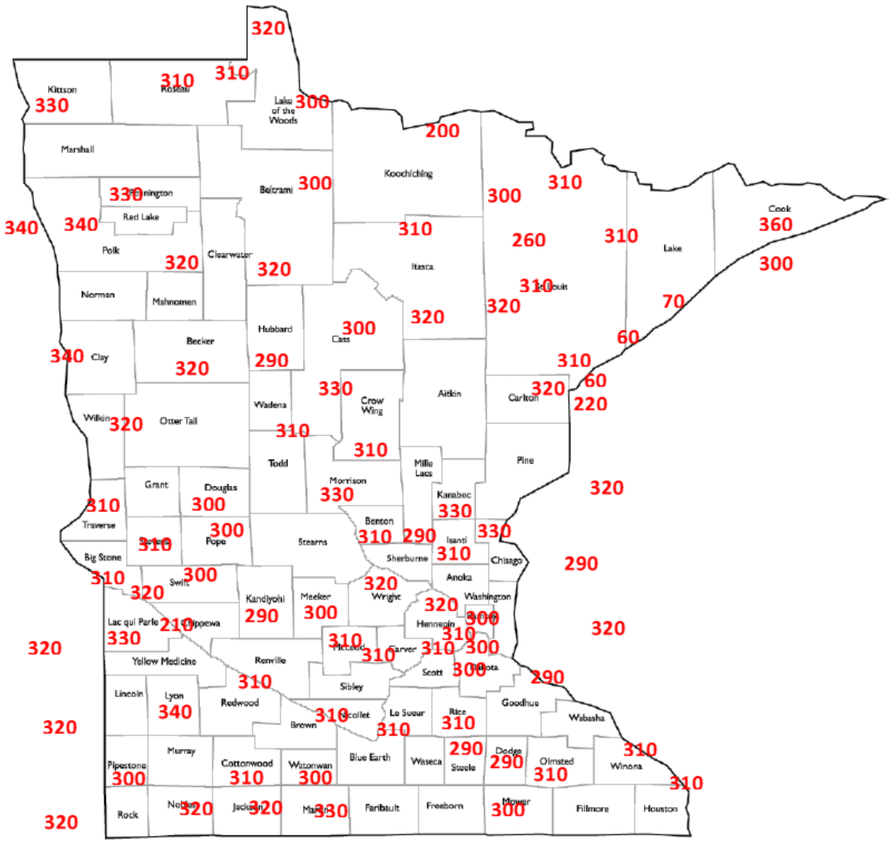

Figure 17. Wind Direction of Greatest Snow Transport [12]

Cardinal Direction	Degree Direction
N	348.75 - 11.25
NNE	11.25 - 33.75
NE	33.75 - 56.25
ENE	56.25 - 78.75
E	78.75 - 101.25
ESE	101.25 - 123.75
SE	123.75 - 146.25
SSE	146.25 - 168.75
S	168.75 - 191.25
SSW	191.25 - 213.75
SW	213.75 - 236.25
WSW	236.25 - 258.75
W	258.75 - 281.25
WNW	281.25 - 303.75
NW	303.75 - 326.25
NNW	326.25 - 348.75

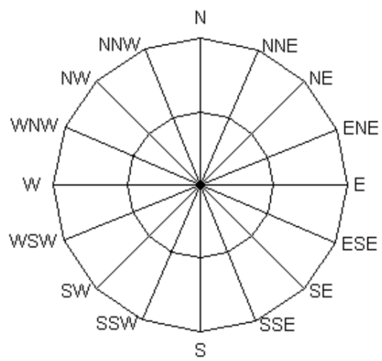

Figure 18. Wind Directions and Degrees [12]

It may be interesting to compare the winter maintenance cost of Section B before and after application of the UTBWC. For this, the average maintenance cost from 2009 to 2011 is compared with the average maintenance cost from 2012 to 2018 which Figure 19 shows the results. As this graph shows, there is a slight increase in the labor and equipment costs, the material cost remains about the same. The average total cost per lane-mile shows about 13% of increase.

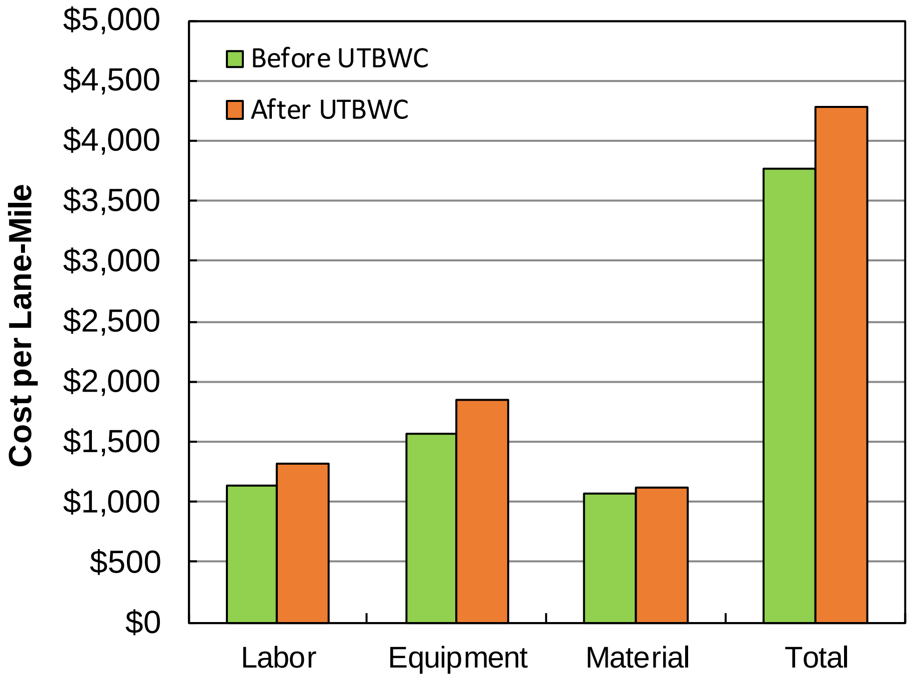

Figure 19. Average cost per lane-mile before and after application of UTBWC

It should be noted that the winter maintenance cost increase that is observed after UTBWC application may not be solely due to the application of UTBWC, as the change in the severity of the winter seasons can also affect the winter maintenance efforts required. One way to separate out the effect of winter severities is to compare the winter maintenance cost of Section B in relation to the adjacent non-UTBWC sections. For this, since the two non-UTBWC sections had similar overall trends, their data was combined together and the averaged labor, equipment, and material costs were calculated which Table 18 shows the results.

Table 18. The Non-UTBWC Winter Maintenance Cost

Year	Labor Cost Per Lane-Mile	Equipment Cost Per Lane-Mile	Material Cost Per Lane-Mile	Total Cost Per Lane-Mile
2009	$463	$730	$565	$1,758
2010	$595	$989	$448	$2,033
2011	$603	$851	$576	$2,030
2012	$251	$385	$461	$1,098
2013	$518	$772	$886	$2,176
2014	$850	$1,295	$1,111	$3,255
2015	$473	$1,110	$633	$2,216
2016	$573	$1,311	$750	$2,634
2017	$549	$926	$614	$2,089
2018	$767	$1,094	$797	$2,659
Average	**$564**	**$946**	**$684**	**$2,195**
Minimum (year with the minimum cost)	**$251 (2012)**	**$385 (2012)**	**$448 (2010)**	**$1,098 (2012)**
Maximum (year with the maximum cost)	**$850 (2014)**	**$1,311 (2016)**	**$1,111 (2014)**	**$3,255 (2014)**

Table 19 shows the UTBWC cost ratios which are calculated by dividing the UTBWC costs presented in Table 16, by the corresponding non-UTBWC costs from Table 18. This was done both for before and after application of UTBWC on Section B in 2012. As Table 19 suggests, except for the material cost in 2014, all other cost ratios are above 1.0 suggesting a higher winter maintenance cost for Section B from labor, equipment, and material points of view from 2009 to 2018 (for both before and after application of the UTBWC). Also, comparing the cost ratios before and after application of the UTBWC shows that the labor and equipment costs have slightly increased, while the material cost has slightly decreased, resulting in the same total cost ratio of 1.9. This suggests that the application of UTBWC had almost no effect on the winter maintenance cost.

Table 19. UTBWC Cost Ratio

Status	Year	Labor Cost Per Lane-Mile	Equipment Cost Per Lane-Mile	Material Cost Per Lane-Mile	Total Cost Per Lane-Mile
Before UTBWC Application	2009	1.9	1.9	2.3	2.0
	2010	1.9	1.6	1.8	1.7
	2011	2.4	2.0	1.8	2.1
	Average	**2.0**	**1.8**	**2.0**	**1.9**
	Minimum	**1.9**	**1.6**	**1.8**	**1.7**
	Maximum	**2.4**	**2.0**	**2.3**	**2.1**
After UTBWC Application	2012	2.0	1.7	2.7	2.2
	2013	2.2	2.0	1.8	2.0
	2014	1.9	1.8	0.9	1.5
	2015	2.4	1.6	1.4	1.7
	2016	2.1	1.6	1.1	1.6
	2017	2.7	2.3	1.7	2.2
	2018	2.7	2.2	1.5	2.2
	Average	**2.3**	**1.9**	**1.6**	**1.9**
	Minimum	**1.9**	**1.6**	**0.9**	**1.5**
	Maximum	**2.7**	**2.3**	**2.7**	**2.2**

Figures 20 to 23 show the graphical representation of the UTBWC cost ratios. Figure 20 shows UTBWC to non-UTBWC labor cost ratios. As this graph suggest, the labor cost ratio is in the range of 1.9 to 2.7. Also, labor cost appears to have a slight increasing trend after the UTBWC is constructed in 2012.

Figure 21 presents the UTBWC to non-UTBWC equipment cost ratios which are mainly in the range of 1.6 to 2.3. The equipment cost ratio appears to remain the same before and after application of the UTBWC, but shows a slight increase in the last two years.

Figure 22 shows the UTBWC to non-UTBWC material cost ratio. As this graph suggests, the material cost ratio is in the range of 0.9 to 2.7. Also, there seems to be a reduction in the material cost ratio starting right after the UTBWC is constructed in 2012. The average material cost ratio before the UTBWC construction is 2.0 while it drops to 1.6 after the UTBWC is constructed.

Figure 23 illustrates the UTBWC to non-UTBWC total cost ratio. The total cost ratio is in the range of 1.5 to 2.2 with an average of 1.9. As this figure suggests, application of the UTBWC has not affected the total cost ratio

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trend. Section B has incurred an average of 90% more cost per lane-mile compared to Sections A and B in a 10-year period from 2009 to 2018. This is regardless of the application of the UTBWC in 2012.

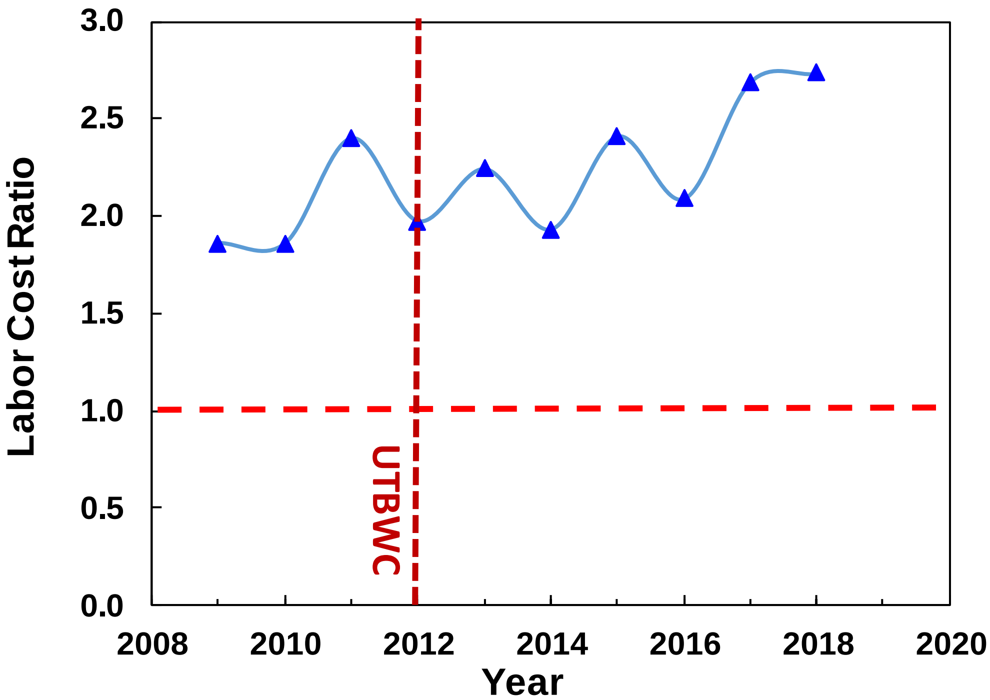

Figure 20. UTBWC to non-UTBWC Labor Cost Ratio

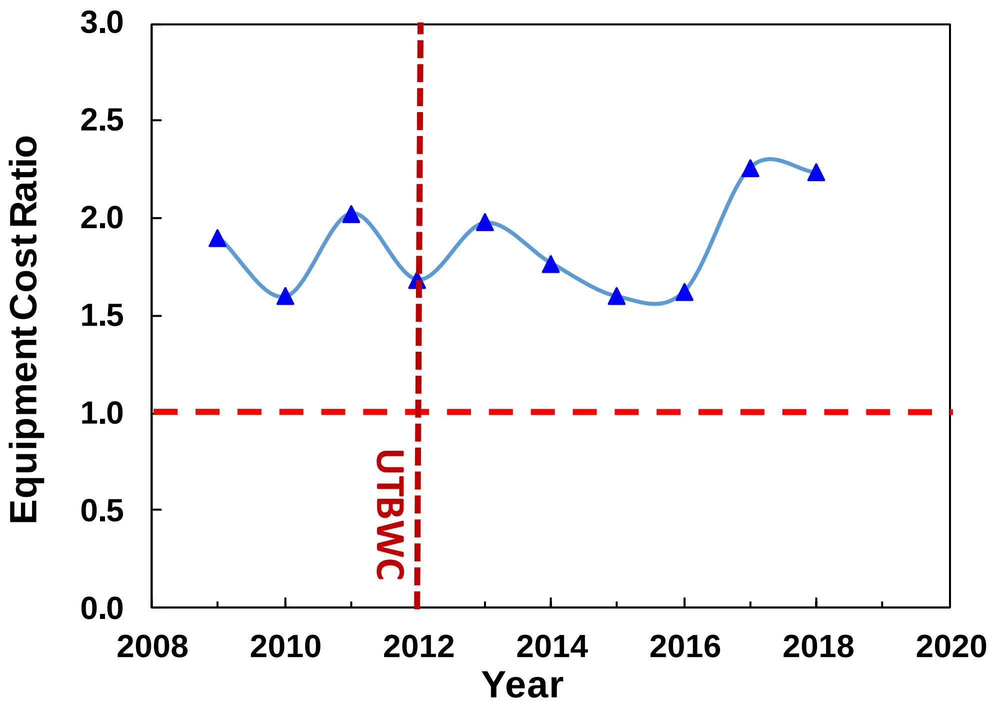

Figure 21. UTBWC to non-UTBWC Equipment Cost Ratio

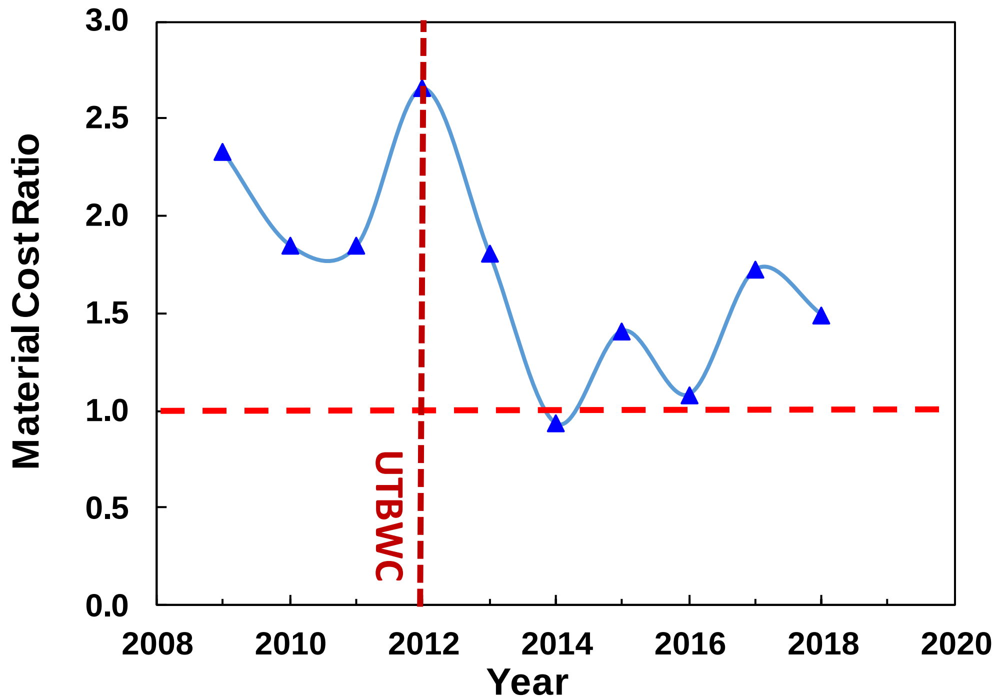

Figure 22. UTBWC to non-UTBWC Material Cost Ratio

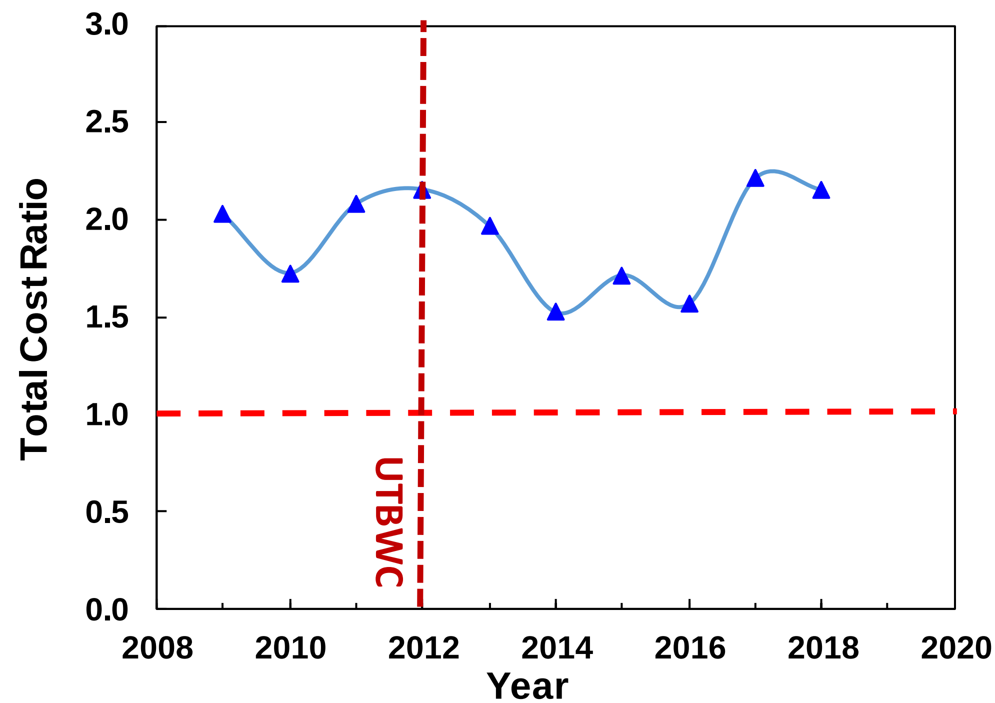

Figure 23. UTBWC to non-UTBWC Total Cost Ratio

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Summary

From the work that has been performed in Phase 1 of the Ultra-Thin Bonded Wearing Course (UTBWC) Snow, Ice, and Wind Effects TRS, we understand that UTBWC pavement occasionally experiences negative pavement performance attributes in cold weather, requiring additional maintenance (beyond typical treatments) to remedy. Observations indicate a phenomenon of ice build-up, potentially due to the accumulation of wind-blown snow, melting and freezing of the wind-blown snow, and bonding of the frozen ice/slush to the underlying pavement.

In Phase 1 of the project, it was suggested that additional field instrumentation and/or lab testing be performed to better understand the nature of this phenomenon. Through project development, the Technical Advisory Panel (TAP) has identified that additional data and cost collection would be beneficial to the research which was the objective of this TRS. The field instrumentation and/or laboratory testing was suggested to be performed under Phase 3 of this study.

A summary of the findings that can be concluded from this study are as follows.

- Several studies have shown that the temperature and humidity of porous pavements (including UTBWC) are different from the Dense Graded Pavements (DGP) mainly due to their higher surface area and permeable voids. Porous pavements are believed to get colder faster and stay frozen longer than the DGPs.

- The stronger bond between the UTBWC surface and snow and/or ice often requires higher plowing effort. The snow plow may induce some damages to the pavement surface.

- Several studies have reported that porous pavements require higher amount of salt to be used in snow removal processes.

- The deicing mechanism within the Intra-storm maintenance is through the creation of salt brine solution above the snow/ice. Melting occurs as the brine solution penetrates into the snow/ice and the additional water from these molten snow/ice leads to the expansion of brine solution and the nearby snow/ice will be exposed. This mechanism cannot effectively take place on porous pavements, as the molten water and brine solution may infiltrate into the pavement structure and drain out. This could be one of the reasons for higher salt requirement in these pavements during intra-storm maintenances.

- The infiltration of brine solution into the voids of porous pavements can store some amount of salt in their pores. The stored salt can prevent the pavement from formation of ice and/or weaken the snow bond with pavements between the storm events.

- UTBWC pavements have been utilized as a preventive maintenance across the United States. Almost all the state DOTs classify UTBWCs into three different categories based on their gradation. Regarding the winter maintenance, almost the same treatments are being applied on the UTBWCs in comparison with non-UTBWC pavements with the exception of higher application rates and/or higher frequencies for the UTBWC pavements due to the stronger bond of ice/snow with their surface. It is interesting to note that several states have reported that after the first winter, they have experienced little to no differences between the UTBWC and non-UTBWC sections in terms of ice and snow.

- According to Minnesota District 3 maintenance staff, any snow and ice cost differences between UTBWC and non-UTBWC segments is negligible for Highway 169 which may be partly due to the heavy traffic and the relatively high travel speeds on this segment. Heavy traffic could help with the effectiveness of the deicing materials (rock salt and salt brine) on this facility, regardless of the surfacing type. The staff also noticed that during the first couple of years, early application of deicing chemicals on UTBWC have helped to keep the lanes from accumulating compacted snow and ice. The deicing chemicals stayed longer in the open and depressed surfacing of UTBWC.

- District 3 plow operators and supervisor have reported that additional snow and ice resources would not exceed 10% for the first two seasons of a UTBWC surfacing.

- In general, the areas which experience more wind events cause more concerns with the application of UTBWC, as they are more susceptible to blown snow. It is recommended that newly surfaced UTBWCs in open rural areas be monitored closely during the first couple of years during snow and ice operations.

- District 4 treats UTBWC sections the same way as other non-UTBWC sections with the same equipment and materials. They had some issues with UTBWC snow and ice during the first winter where they had to use some additional chemical and under body blade work, but the additional cost did not seem to be significant. After the first winter, they have experienced no differences between the UTBWC and non-UTBWC sections in terms of ice and snow.

- Metro District CR 11 was closed twice during the 2016-2017 snow and ice season due to slippery conditions which led the maintenance personnel to put more salt down. The district has not had any incidents with this roadway since the first snow and ice season and they are not placing any more deicer on this segment than any other non-UTBWC roadway. This might be due to plugging up of the open voids of the UTBWC over time.

- District 8 first started utilizing UTBWC Type B. As there were some reports regarding snow and ice issues with this type of UTBWC, the district decided to change the gradation to finer Type A and since then they had little if any snow and ice problems. District 8 does not pretreat any of their roads and applies salt at the same application rate for all the pavements (including UTBWC). On UTBWC sections, they occasionally have runoff dam up at the edge which would require additional salt, but it is not frequent.

- According to District 7, UTBWC and non-UTBWC sections are treated with the same material including rock salt blended with calcium chloride at 3 to 5 gallons per ton. The salt is also pre-wetted with a 90% salt brine and 10% calcium chloride mixture. The same equipment (plow truck) is used on the adjacent routes during winter maintenance. The treatment frequency can vary from one storm to another, but all the routes receive the same level of service in general. The UTBWC may require an additional treatment at times due to its rough texture. A typical application rate ranges from 100-400 pounds of salt per lane-mile.

- In order to compare UTBWC vs. non-UTBWC winter maintenance cost, the cost information from 2009 to 2018 was gathered for a section of TH 15 (UTBWC) and two sections of TH 60 (non-UTBWCs) in District 7. TH 15 (UTBWC) was found to have the highest labor, equipment, material, and total cost both before and after the UTBWC construction in 2012. One identified reason for this was the direction of TH 15 (north-south) which was found to be almost perpendicular to the wind direction of the greatest snow (west-northwest). As such, TH 15 would be more susceptible to blowing snow compared with the adjacent TH 60 roadway segments which are generally in the east-west direction.

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- The comparison of the winter maintenance cost of TH 15 before and after application of UTBWC showed that there was a slight increase in the labor and equipment costs after the UTBWC is constructed in 2012, while the material cost has remained about the same. The average total cost per lane-mile showed about 13% of increase. This may not be solely due to the application of UTBWC, as the change in the severity of the winter seasons can also affect the winter maintenance efforts required.

- To separate out the effect of winter severities, TH 15 winter maintenance cost was looked at in relation to the adjacent TH 60 non-UTBWC sections. Comparing the cost ratios before and after application of the UTBWC showed that the labor and equipment costs have slightly increased, while the material cost has slightly decreased, resulting in the same total cost ratio of 1.9 before and after UTBWC application. This suggests that the application of UTBWC had almost no effect on the winter maintenance cost.

References

[1] Akin M., Cuelho E, Fay L. and Muthumani A. (2018, April) "Winter Maintenance, Friction and Snow-Pavement Bond on Permeable Friction Surfaces," Bozeman: Western Transportation Institute.

From the abstract: Porous and Permeable Pavements (PPs) have been successfully used by many transportation agencies as a wearing surface to help reduce water splash and spray, increase friction, reduce potential for hydroplaning, and reduce noise. Despite their inherent advantages, when used in colder climates PPPs tend to freeze more rapidly, appear whiter and "snowier" longer, and need greater and more frequent application of deicers than traditional Dense Graded Pavements (DGPs). Laboratory tests were conducted on DGP pavement samples, new and old open graded friction course pavements, and ultrathin friction course samples in walk-in cold lab at 28°F with snow, compaction equipment, and trafficking device. Snow-pavement bond strength and static friction were measured to determine the effectiveness of anti-icing with salt brine and deicing with dry and prewet solid salt. Compacted snow bonds more strongly to PPPs, yet friction of PPPs was significantly greater than DGPs after snow removal, even without the use of salt. The PPPs appear more white and snowy, and this appearance may be contributing to unnecessarily high application rates of salt. Even when snow is trapped in PPPs, friction tends to be higher than DGPs treated for snow and ice control, owing to the overall greater frictional properties of open graded, ultrathin and permeable friction courses. Field testing is recommended to better understand the frictional behavior of PPPs during a variety of winter storm conditions and deicer application strategies.

[2] Fortin C. and Dindorf C. (2012, October) "Minnesota Snow and Ice Control: Field Handbook for Snowplow Operators," St. Paul: Minnesota Local Road Research Board (LRRB), Accessed February 27, 2019.

Link: http://www.mnltap.umn.edu/publications/handbooks/documents/snowice.pdf.

[3] (2016, June) "Snow & Ice Control Guidebook," St. Paul: Minnesota Local Road Research Board (LRRB), Accessed February 27, 2019. http://www.dot.state.mn.us/research/TS/2016/2016RIC11.pdf.

[4] Federal Highway Administration (FHWA). "How Do Weather Events Impact Roads," US Department of Transportation, last modified September 17, 2018.

Link: https://ops.fhwa.dot.gov/weather/q1_roadimpact.htm.

Weather Impact on Productivity:

- Adverse weather can increase operating and maintenance costs of winter road maintenance agencies, traffic management agencies, emergency management agencies, law enforcement agencies, and commercial vehicle operators (CVOs).
- Winter road maintenance accounts for roughly 20 percent of state DOT maintenance budgets. Each year, state and local agencies spend more than 2.3 billion dollars on snow and ice control operations. (Sources: *"Highway Statistics Publications, Highway Finance Tables SF-4C and LGF-2," 1997 to 2005, https://www.fhwa.dot.gov/policy/ohpi/hss/hsspubs.cfm*)
- Each year trucking companies or CVOs lose an estimated 32.6 billion vehicle hours due to weather-related congestion in 281 of the nation's metropolitan areas. Nearly 12 percent of total estimated truck delay is due to weather in the 20 cities with the greatest volume of truck traffic. The estimated cost of weather-related delay to trucking companies ranges from 2.2 billion dollars to 3.5 billion dollars annually. (Source: " *Analysis of Weather Incident Effects on Commercial Vehicle Mobility in Large U.S. Cities," Mitretek Systems*).

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[5] Michigan Department of Transportation (MDOT). "How much does MDOT spend per lane mile on winter maintenance," Accessed February 27, 2019.

Link: https://www.michigan.gov/mdot/0,4616,7-151-52374-228674--,00.html.

[6] Hill D., Collins P., Cheney C. and Petrowske B. (2018) "2017-2018 Winter Maintenance Fact Sheet," Duluth: Minnesota Department of Transportation (MnDOT), Accessed February 27, 2019.

Link: https://www.dot.state.mn.us/d1/images/SnowIceFactSheet.pdf.

From the body text: The quantities of deicing materials used during the winter of 2016–17 (rounded figures) in MnDOT District 1 were:

- Road salt – 35,529 tons (current average price is approximately $57 per ton)
- Sand – 18,509 tons (current average price is approximately $7 per ton)
- Liquid magnesium chloride – 20,857 gallons (current price is approximately $1.20 per gallon)
- Salt brine – 319,366 gallons (D1 makes salt brine in-house by mixing water and salt)
- Liquid calcium chloride – 14,270 gallons
- Salt brine additive (beet juice) – 1,873 gallons
- Potassium acetate – 4,139 gallons
- The average cost per-lane-mile for snow and ice maintenance was $3,503.

MnDOT District 1 maintains 1,600 miles (3,710 lane miles) of state highways and 589 bridges.
During the winter of 2016-17, an average of 80.1 inches of snow fell in Northeastern Minnesota.

[7] (2019) "Winter Service Guide," Pennsylvania Department of Transportation (PennDOT), Accessed February 27, 2019.

Link: http://www.dot.state.pa.us/public/pubsforms/publications/pub%20628.pdf.

[8] Hughes J., Sproul M., Johnson A, Adams M., Meinholz C., Meinholz L., Lyden D. and Rahman A. (2017, December) "Annual Winter Maintenance Report 2016-2017," Wisconsin Department of Transportation (WisDOT), Accessed February 27, 2019.

Link: https://wisconsindot.gov/Documents/doing-bus/local-gov/hwy-mnt/winter-maintenance/workers/2016-2017annualreport.pdf.

From the introduction: Every year, WisDOT gathers a multitude of data on winter weather and the state's response to it. Tracking and analyzing this data helps us become more efficient by identifying good performance as well as areas that need improvement. In this way we use our limited resources to achieve the greatest benefit.

Through this report, WisDOT's Bureau of Highway Maintenance shares data with the department's regional maintenance staff and with our partners in the county highway departments. This allows regional and county staff to compare resource use with that of their peers across the state. The report has also been shared with the WisDOT Secretary's Office, the state legislature, national organizations such as Clear Roads, and the general public.

[9] Nokkala M., LeviaKangas P. and Ovia K. (2012) "The Costs Of Extreme Weather For The European Transport Systems," Espoo: VTT Technology, Accessed February 27, 2019.

Link: https://www.vtt.fi/inf/pdf/technology/2012/T36.pdf.

From the conclusion: European Union's 27 member states face each year at least 15 billion € cost resulted by extreme weather. This cautious estimate is about 0.1% of the EU-27 GDP, and about 30 € annual extra cost to each EU-27 citizen. However, we did not find any significant signals that these costs would significantly increase in the future, except for the time costs. But the figures are yet so profound that actions are needed. In some parts of Europe, they are probably needed more in some other parts, somewhat less. The figure we estimated could well be twice as high.

[10] "Euro (EUR) to U.S. dollar (USD) annual average exchange rate from 1999 to 2018," The Statista Portal, Accessed February 27, 2019. https://www.statista.com/statistics/412794/euro-to-u-s-dollar-annual-average-exchange-rate/.

[11]"CPI Inflation Calculator," Accessed February 27, 2019. http://www.in2013dollars.com/1999-dollars-in-2014?amount=100.

[12] Norem H., Jaasko J., Bergdahl L., Hegseth A., Arnason D., Gillies N., and Dyce I. (2014) "Winter Maintenance Practice in the Northern Periphery," Northern Periphery, ROADEX sub project B phase I, Accessed February 27, 2019.

Link: https://www.roadex.org/wp-content/uploads/2014/01/roadexspbsummary0111.pdf.

From the introduction: The information assembled is based on written answers of questionnaires for specific topics, interviews of supervisors, field trips in each partner district and literature review. The results of the project are presented in the State-of-the–art reports for both project A and B as well as a multimedia presentation on CD-ROM was made. Other publications concerning presentation of sub-project B and related issues are listed in the appendix at the end of this summary.

[13] Fortin C. and Mulhern N. (2013, February) "Michigan Winter Maintenance Manual: Promoting Safe Roads and Clean Water," Michigan State University,

Link: http://miwintermaintenance.weebly.com/uploads/1/7/1/6/17161926/mi_winter_maintenance_manual_2013.pdf.

[14] (2017, December) "Major Highway Projects, Trunk Highway Fund Expenditures and Efficiencies Report," St. Paul: Minnesota Department of Transportation (MnDOT), accessed February 27, 2019.

Link: https://www.dot.state.mn.us/govrel/reports/2017/mhpr-report.pdf.

[15] (2011) "Regional and Statewide Weighted Average Awarded Prices," New York Department of Transportation (NYDOT), Accessed February 27, 2019.

Link: https://www.dot.ny.gov/divisions/engineering/design/dqab/dqab-repository/USC_RSWAIP0710_0611.pdf.

From the introduction: The Regional and Statewide Weighted Average Price Report is produced using information from NYSDOT's Trns*Port BAMS/DSS. It is a numerical listing of all items used in Department contracts that have been let within the time period indicated on the report. The report shows statistics for each item in each Region as well as overall averages and totals for each item. Included in the report are the number of contract occurrences, total quantity and the weighted average awarded price.

[16] Fay L., Veneziano D., Muthumani A., Shi X., Kroon A., Falero C., Jason M. and Petersen S. (2015, September) "Benefit-Cost of Various Winter Maintenance Strategies," Bozeman: Western Transportation Institute, Accessed February 27, 2019.

From the abstract: Various costs and benefits are incurred while performing winter maintenance operations. However, a summary of these costs and benefits for different maintenance scenarios has not been compiled to date. This report summarizes past work that documented the quantified and non-quantified costs and benefits of three different winter maintenance strategies of interest; use of abrasives, salts and other chemicals in solid and liquid forms, and snow plows. Basic strategies were defined as plowing and use of abrasives, intermediate strategies were defined as the use of rock salt and salt brine (NaCl), and advanced strategies were defined as the use of corrosion inhibitors, inhibited salt brine, magnesium chloride, calcium chloride, and blended products. These approaches employ different components, both in terms of equipment as well as materials. Some components of the various strategies have better cost and benefit information available than others. This is particularly true of sanding/abrasives and salting. Other, more recently developed and employed approaches and materials have more limited cost and benefit information published. There are also a number of different environmental impacts associated with different components of each maintenance strategy. Using information gained from the literature review, surveys, and interviews summary benefit-cost matrices were developed for various winter maintenance strategies. Information and data gap analysis has aided in identification of areas for recommended research. This document is intended for use by transportation agencies, such as by maintenance supervisors, to aid in the decision making process in terms of the selection of winter maintenance strategies used to achieve a prescribed LOS.

Link: http://clearroads.org/wp-content/uploads/dlm_uploads/FR_CR.13-03_Final.pdf.

[17] (1993, December) "The Use of Selected Deicing Materials on Michigan Roads: Environmental and Economic Impacts," Michigan Department of Transportation (MDOT), Accessed February 27, 2019.

Link: https://www.michigan.gov/documents/mdot/RR736CON_14_542480_7.pdf.

[18] Veneziano D., Fay L., Williams D. Shi X., Ballard L. and Solutions C. T. (2010, November) "Development of a toolkit for cost-benefit analysis of specific winter maintenance practice, equipment and operations," Bozeman: Western Transportation Institute. Accessed February 27, 2019.

Link: https://wisconsindot.gov/documents2/research/09-08costbenefitanalysis-f.pdf.

From the abstract: The operators and maintainers of highway networks are facing increasing demands and customer expectations regarding mobility and transportation safety during inclement weather, while confronting budget and staffing constraints and environmental challenges related to chemical and material usage. It is desirable to use the most recent advances and best practices to improve the effectiveness and efficiency of winter operations, optimize material usage, and reduce annual spending, corrosion and environmental impacts. Determining the benefits and costs of various winter maintenance practices, equipment and operations is a difficult and time consuming proposal for winter maintenance managers. This project developed a toolkit which would facilitate such a benefit-cost analysis to address this need.

[19] Kelting D. L. and Laxon C. L. (2010) “Review of effects and costs of road de-icing with recommendations for winter road management in the Adirondack Park,” Paul Smiths: Adirondack Watershed Institute, Accessed February 27, 2019.

Link: http://www.protectadks.org/wp-content/uploads/2010/12/Road_Deicing-1.pdf.

From the abstract: This document provides a comprehensive evaluation of road salt and recommendations for managing snow and ice on winter roads to minimize environmental impacts and increase management effectiveness. It argues that the use of best management practices can reduce the negative impacts of road salt on the environment, while simultaneously improving road safety and saving money.
Sodium chloride (road salt) is used throughout the winter months in the Adirondacks to maintain clear roads.

Road salt can be an effective and economical choice for de-icing when applied correctly as part of a comprehensive highway de-icing management system; however, numerous studies have documented the negative effects of road salt on forest and aquatic ecosystems, drinking water, vehicles, and infrastructure. When considering these negative effects, the effectiveness and economical arguments for road salt are called into question, as these often hidden, chronic, and cumulative costs may outweigh the short term benefits.

[20] Levelton Consultants (2007) “Guidelines for selection of snow and Ice control materials to mitigate environmental impacts,” Washington: National Cooperative Highway Research Program, NCHRP report 577.

From the introduction: Studies of the most common chemical alternatives—sodium chloride (salt), magnesium chloride, calcium chloride, calcium magnesium acetate, potassium acetate, and urea—have focused on performance and cost under various weather conditions without evaluating their relative impacts on the environment. Several new chemical preparations, including some that are trademarked, have entered the market as snow and ice control chemicals for use by transportation agencies, but there is limited information about their environmental impacts. There is a need for rational decision-making guidelines to assist DOT maintenance managers in selecting the most appropriate snow and ice control materials for the conditions that exist in their jurisdictions.

[21] Gibbs D., Iwasaki R., Bernhard R., Bledsoe J., Carlson D., Corbisier C., Fults K. et al. (2005, May) “Quiet Pavement Systems in Europe,” Alexandria: Federal Highway Administration (FHWA), Accessed February 27, 2019.

Link: https://international.fhwa.dot.gov/pubs/quiet_pav/pl05011.pdf.

From the body text: In France, porous pavements are obtaining a service life of greater than 10 years. The French indicated that clogging is more of a problem in porous pavement than in very thin asphalt concrete. The French do not try to clean clogged porous pavements because they have not found cleaning to be effective. Instead, the mix design is optimized to eliminate or reduce clogging. When it is necessary to rehabilitate the pavement surface, milling is employed. If the worn surface is completely plugged, it is permissible to overlay the existing pavement. Porous pavement is no longer used in built-up areas because of fast clogging.
Although porous mixes can be used on any type of pavement, France has experienced some problems with the mixes freezing during the winter. As a rule of thumb, porous mixes are not used in France east of Paris’ meridian and at altitudes above 600 m. Thin mixes are typically used east of Paris’ meridian and porous mixes are used west of the meridian. Porous pavements and, to a lesser degree, very thin asphalt concrete are susceptible to the cold and can facilitate the production of black ice.

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[22] Jahren C. T., Nixon W. and Bergeson K. L. (2003, January) "Thin Maintenance Surfaces: Phase Two Report with Guideline for Winter Maintenance on Thin Maintenance Surfaces," Ames: Iowa Department of Transportation (IowaDOT), Accessed February 27, 2019.

Link: http://publications.iowa.gov/16487/1/IADOT_tr435phase2_Thin_Maintenance_Surfaces_2003.pdf.

From the conclusion: This study has collected information on the performance of thin maintenance surfaces under winter maintenance conditions. The study included a review of the literature, which is very sparse in this area, the collection of anecdotal information from maintainers about the performance of such treatments, and site visits to four locations in eastern Iowa where such treatments have been used. On the basis of the information gathered in the study, some simple recommendations have been made on the use of three types of treatments in conditions where winter maintenance is regularly conducted.

[23] Litzka J. (2002, August) "Austrian Experience with Winter Maintenance on Porous Asphalt," In 9th International Conference on Asphalt Pavement, Copenhagen, Denmark.

From the abstract: The paper deals with the specific requirements for winter maintenance on sections with porous asphalt and the experiences in Austria with some additional information from neighboring countries. After extensive use of porous asphalt on motorways in Austria in the early nineties the application of this type of surface course has been reduced significantly. Additional problems such as clogging, durability and difficulties with local repairs, the main reason for this change is the difficulty of winter maintenance on porous asphalt connected with increased risk for the highway operators. This is of special importance for the Austrian climatic situation with rather cold winters and a large number of freeze-thaw cycles.

[24] (1999, December) "Nova Chip," Jefferson: Missouri Department of Transportation (MoDOT), Accessed February 27, 2019.

Link: https://library.modot.mo.gov/RDT/reports/Pd98055/brief.htm.

[25] (2012, January) "Highway Maintenance Guideline: Snow and Ice Control," New York State Department of Transportation (NyDOT), Accessed February 27, 2019.

Link: https://www.dot.ny.gov/divisions/operating/oom/transportation-aintenance/repository/NYS_SI_Manual_Apr2006_RevJan2012.pdf.

[26] Rogge, D. (2002, March) "Development of Maintenance Practices for Oregon F-Mix" Oregon Department of Transportation (ODOT). Accessed February 27, 2019.

Link: https://www.oregon.gov/ODOT/Programs/ResearchDocuments/DevMaintPractORFMix.pdf.

From the conclusion: Conclusions regarding winter maintenance are as follows:

- F-mix and other porous pavements freeze sooner as air temperatures fall below freezing, and stay frozen longer because of the reduced thermal conductivity of porous pavements.
- F-mix and other porous pavements generally require larger amounts of de-icing chemicals than dense-graded asphalt pavements. The porous nature of the pavement means that the deicers flow down into the pavement rather than staying at the surface.

[27] Roseen R. M., Ballestero T. P., Houle K. M., Heath D. and Houle J. J. (2013) "Assessment of winter maintenance of porous asphalt and its function for chloride source control," Journal of Transportation Engineering, 140(2), 04013007.

<u>From the conclusion</u>: Winter maintenance of porous asphalt pavements is different than standard pavements. There are two primary elements of winter maintenance: intra-storm and inter-storm maintenance. Intra-storm maintenance is typically not as effective as on standard pavement surfaces. The deicing mechanism on a standard pavement is through the creation of a brine solution as the salt rests on the surface, melts the ice below it, and this brine then expands to melt nearby ice on the surface. On porous pavements, once the salt melts the ice below it, that liquid infiltrates into the porous pavement system. For this reason, intra-storm maintenance may require more salt on PA. However, the need for inter-storm maintenance is considerably diminished in the days or weeks between storms. When snow stockpiles melt, pool, and refreeze on a standard pavement between storms, black ice forms, requiring additional application of salt or chemical deicer. On porous pavements, no standing water occurs, and thus in some instances with good solar exposure, plowing at the time of snowfall is sufficient for winter maintenance resulting in a virtual elimination of the use of deicer. Although porous pavement surfaces do freeze during the winter in cold climates, it is a frozen porous media that maintains high infiltration capacities. Much of the salt applied to a porous pavement remains on the pavement days after it is applied. It should be recognized that the porous pavements are one of the very few salt reduction strategies for cold climates.

[28] Ichihara K., Sakagami Y. and Tanifuji S. (1977, May) "Standard Bituminous Mixtures for Skid-Resistant Pavements in Japan" In Proceeding of International Symposium on Porous Asphalt, Amsterdam, Netherlands.

<u>From the abstract</u>: In Japan, open graded dense asphaltic concrete is used in general areas, while gap graded dense asphaltic concrete which has high filler/asphalt ratio is used in snowy areas. Gap grading is recommended for the mixture, thus ensuring durability, abrasion resistance, and comparatively high skid resistance.

[29] Takahashi N., Tanaka S., Tokunaga R. A., Tayu F., Takeichi K., Kami S. and Sakakibara H. (2015) "Ice formation and the effectiveness of deicing agent on porous asphalt and stone mastic asphalt," Transportation Research Record, 2482(1), 57-66.

<u>From the abstract</u>: Porous asphalt (PA) and stone mastic asphalt (SMA) are widely used by many transportation agencies and public works officials. However, the best winter maintenance practices for PA and SMA are unclear and generally unquantified. In this study, laboratory tests under controlled, artificial wintry conditions were conducted to evaluate the winter performance of PA and SMA. The test results are summarized as follows: (a) PA was effective at reducing the amount of water that formed an ice layer on the pavement surface and the thickness of the ice layer. SMA had intermediate effects between those of dense-graded asphalt (DGA) and PA. (b) The rate of decrease in ice layer thickness was found to be the largest for PA; that for SMA was intermediate between those for DGA and PA. (c) The features described above were dependent on the temperature and the amount of water applied.

[30] Shulski M. and Seeley M. "Climatological Characterization of Snowfall and Snow Drift in Minnesota (for the Design of Living Snow Fences)," MnDOT Agreement No. 74708.
Link: http://snowcontroltools.umn.edu/background/research/climatology/project/index.html

<u>From the abstract:</u> Research conducted in the 1960's and 70's by the U.S. Forest Service has shown that snow fences cause blowing snow to deposit on the landscape such that it is stored over the winter season. In the early 1970's, construction for Interstate 80 was completed in eastern Wyoming, however, the highway was subject to numerous drifting problems. Ronald Tabler and others utilized this as an opportunity to apply research results and deploy structural snow fences at problem locations along the interstate and test their effectiveness as snow control measures. It is estimated that these snow fences prevented 35 accidental injuries and cut winter

maintenance costs in half for one season. Through these research efforts, detailed guidelines were established by Tabler (1994) outlining the steps necessary for the deployment of snow fences, both structural and living.

The Minnesota Department of Transportation chose to utilize the technique for site specific snow control and one study estimated that there are 4,000 sites, encompassing 1,000 miles, where blowing and drifting snow is problematic (Gullickson 1999). When comparing the cost of snow removal with living snow fences, an average cost/benefit ratio of 17:1 exemplifies the efficiency of this method validating widespread use in Minnesota.