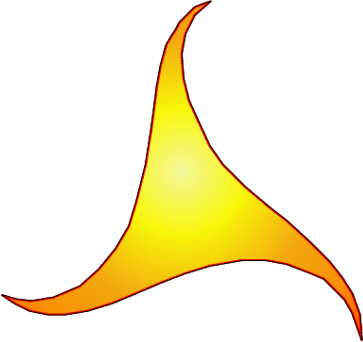
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**Use of Full Depth Shoulders  
on Wisconsin Highways**

**Final Report**



**July 2012**

Use of Full Depth Shoulders  
on Wisconsin Highways  
Research Study # WI-10-01

**Final Report**

Report # WI-03-11

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Executive Summary

In the State of Wisconsin, paved shoulders are typically constructed with less than half the thickness of the mainline pavement, consequently providing for a lower structural capacity for traffic loading. In some construction projects, this situation is recognized and addressed during design by improving, or in some cases even reconstructing, the shoulders prior to use as temporary travel lane. Unfortunately, during several recent Wisconsin highway construction projects this was not accounted for; and deterioration and early failure occurred when existing paved shoulders were used as temporary travel lanes.

These failures, as well as the additional effort and expense of pre-project shoulder improvement/reconstruction have brought construction of full depth shoulders (FDS) into consideration. With a thickness equal to mainline pavement, FDS have adequate structure to carry temporary traffic during highway construction projects. The additional structure also allows shoulders to be reliably used during unplanned events, such as emergency evacuations and other incident management applications. As is typically the case, increased performance reliability comes as a trade-off. In this instance, construction costs. The construction cost of FDS is higher than that of conventionally designed shoulders.

Other state agencies were queried regarding their shoulder construction practices. Over 60 percent of responding states noted that FDS were used in some or all roadway designs, typically on Interstate and other high volume roadways. Sometimes FDS were constructed with the specific intent for use as temporary travel lanes in the future.

This study analyzed the construction, life cycle, and benefits cost of FDS and investigated future use of these thicker shoulders in temporary traffic applications. Shoulder construction costs for ten Wisconsin Interstate and freeway reconstruction projects were evaluated. It was determined that the cost of full depth HMA shoulders next to concrete mainline pavement was approximately twice the cost of conventionally designed HMA shoulders. The cost of full depth HMA shoulders next to HMA mainline pavement was approximately 1.5 times the cost of conventionally designed shoulders. The impact on total project cost was variable: the increased FDS cost ranged from 1.5 to almost 13 percent of the total as-bid construction cost.

Life cycle cost analyses (LCCA) and benefit-cost analyses (BCA) were performed to contrast FDS and conventionally designed shoulders. The LCCA investigated and quantified the more tangible lifetime maintenance costs of the shoulder types. The BCA further expanded this investigation by valuing the user delay each shoulder type is estimated to produce or save. Decreased user delay was a major benefit of the former option, as FDS can provide additional travel lanes during construction activities, emergency evacuations, and events requiring lane closures. Another major benefit of FDS can be realized during future reconstruction projects. Temporary pavement widening is often constructed to maintain multiple lanes of traffic during construction. Existing shoulders, which lack adequate structure, are often removed and replaced. Existing FDS can remain in place, resulting in time and cost savings. Including these factors in the BCA example resulted in a lower net present value for FDS compared to conventional shoulders.

FDS can provide a reliable travel lane in emergency situations. For example, the shoulder can provide congestion relief during a mass evacuation. Traffic can also be routed onto the shoulder if a mainline travel lane is closed due to an accident or severe weather incident. The increased thickness with FDS ensures that shoulders can safely support temporary traffic loading during unplanned events.

It is recommended that FDS be constructed on Interstates and other high volume highways where it is important to maintain traffic capacity during lane closures and future construction projects. On these roadways, FDS can be utilized as a reliable temporary travel lane. This type of shoulder use maximizes the initial FDS investment and reduces user delay costs. Interstates and high volume roadways are also most likely to be part of evacuation routes, where it is beneficial to use the outside FDS as an additional travel lane.

1. Introduction

The majority of roadways on the Wisconsin State Trunk Network (STN) are constructed with shoulders that are paved thinner than the mainline travel lanes. It has been demonstrated in several cases that the thinner shoulder pavement does not reliably provide adequate structure when used as a temporary travel lane. Premature deterioration or failure of paved shoulders results in increased costs, future problems with construction staging, detrimental effects on highway maintenance operations, and increased user delays and inconveniences.

One solution for improved paved shoulder performance is to construct full depth shoulders (FDS): paved shoulders with a thickness equal to that of the mainline pavement. With the FDS scenario, traffic can be confidently routed onto shoulders when a temporary travel lane is required. Such temporary travel capacity may be necessary during construction or rehabilitation projects, during repair and maintenance activities, and when traffic accidents or catastrophic acts of nature occur. FDS could also be used as temporary additional capacity during emergency evacuations. The added material cost of increased shoulder thickness is the greatest drawback to routine use of FDS.

The primary objective of this study was to determine whether construction of FDS is a cost effective practice for Wisconsin highways. Using actual project plans and bid data, construction, maintenance, and user cost differences were calculated to compare FDS and conventional shoulder designs. Life cycle and benefit-cost analyses were performed to compare these costs over the lifetime of a theoretical project. Construction geometrics were analyzed to determine when shoulders could be used as temporary travel lanes. This information was used to determine if and when FDS is an effective design and construction practice.

2. Literature Review

2.1 Shoulder Structure

Unlike mainline pavement design, there are no standard procedures for the structural design of paved shoulders. Few research studies have addressed the design of shoulders. Design has typically been based on experience and previous performance. [*1, 2*]

A technical advisory released in 1990 by the Federal Highway Administration (FHWA) provided several recommendations regarding shoulder design. It was noted that consideration should be given to the possibility of future use of the shoulder as a temporary or permanent travel lane. The advisory also stated that the following factors cause most shoulder damage: truck encroachment, water infiltration, poor material quality, and inadequate thickness. Furthermore, shoulder distress is typically found within two feet of the longitudinal joint between the mainline and shoulder pavements. [*1*] This has motivated many state agencies, including Wisconsin, to widen concrete mainline pavement by two feet. In this design scenario, two feet of the right paved shoulder are integral with the mainline pavement (see Section 3.2).

Regarding shoulder thickness, the advisory contains the following statements: [*1*]

"Shoulders should be structurally capable of withstanding wheel loadings from encroaching truck traffic. On urban freeways or expressways, the shoulders should be constructed to the same structural section as the mainline pavement to ensure adequate load capacity at the interface between the mainline and shoulder, to provide for ease and economy of construction, and to prevent a 'bathtub' condition under the pavement. This will also allow the shoulder to be used as a temporary detour lane during rehabilitation or reconstruction.

"For other than urban freeways and expressways, a structural section less than that of the mainline may be warranted. It is recommended that the thickness be based on an evaluation of life-cycle costs and past performance under similar conditions. The use of widened lanes should be considered in the life-cycle cost analysis."

A study published in 2003 through the Wisconsin Highway Research Program (WHRP) reported on paved shoulders for concrete mainline pavements. A survey regarding shoulder design and performance was conducted among six Midwestern states. A portion of the survey results are summarized in Table 1. Shoulder thickness design practices are shown in Table 1, along with responses to the question "was inadequate shoulder thickness the cause of premature failures or poor performance?" Inadequate thickness was "sometimes" or "always" an issue 40 percent and 90 percent of the time for concrete and HMA shoulders, respectively. [*2*]

Table . Shoulder Thickness and Performance Survey Results, Concrete Mainline (Adapted from [*2*])

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Shoulder Type** | **Shoulder Thickness Range** | **Was inadequate thickness a cause of shoulder failure?** | | |
| **Never** | **Sometimes** | **Always** |
| Concrete | 6 inch to equal to mainline thickness | 60% | 33% | 7% |
| HMA | 2 inch to equal to mainline thickness | 10% | 74% | 16% |

In the literature review from this WHRP study, several points regarding shoulder performance and thickness design were summarized. It was noted that thinner shoulder pavement is more susceptible to environmental effects such as frost penetration and thermal stresses. Factors affecting thickness design of the paved shoulders included the mainline pavement type (concrete or HMA), environmental conditions, subgrade condition, shoulder maintenance strategy, estimated truck traffic encroachment, and planned future use of the shoulders. The authors stated that the shoulders should be designed using truck percentages equal to the mainline outer travel lane, if the shoulders are planned to accommodate temporary traffic during future maintenance and construction activities. [*2*]

The authors of the WHRP study listed several benefits of FDS relating to uniform base layer thickness. With FDS, the base can be constructed in one operation, resulting in more uniform compaction and reducing differential settlement between the shoulder and mainline pavement. The uniform base layer can also enhance the water flow between the base and the bottom of the pavement sections. In addition, because the base layer is at a uniform depth, there could be a resulting reduction in differential frost heave. [*2*]

2.2 Shoulder Use During Emergencies and Evacuations

Use of shoulders as temporary travel lanes is a viable option to improve traffic flow in the case of emergencies or a mass evacuation. This topic has seen increased awareness in light of evacuations ahead of major weather events or, rarely, threats of terrorist activities. A 2010 study by the FHWA listed the principal causes of mass evacuations (1,000 or more people) in the U.S. from 1990 to 2003. [*3*] These evacuation triggers are shown in Figure 1. Several of the more common evacuation causes, such as flooding and hazardous material incidents, are potential dangers in Wisconsin.

Figure . Principal causes of mass evacuations in the U.S. (from [*3*]).

In the 2010 FHWA study, 26 U.S. metropolitan regions with large populations and high levels of congestion were asked to identify impediments to efficient mass evacuation. The impediments that were most commonly cited involved highway capacity issues. Congestion and inadequate traffic capacity was cited by 14 regions. Infrastructure issues, such as bottlenecks and emergency vehicle access lanes, were noted by 17 regions. [*3*] Use of one shoulder as a temporary travel lane could ease the capacity problem during evacuations.

Several metropolitan regions had specific points relating to shoulder use: [*3*]

* *Baltimore* - Not enough travel lanes exist for an effective evacuation, but "movement is less constrained" when the shoulders are utilized.
* *Boston* - Shoulders cannot safely support the level of traffic predicted for an evacuation. Also, if shoulders were used, it would impede emergency vehicle access.
* *Detroit* - Deteriorated shoulder condition would make it difficult to use the shoulders to access stranded vehicles and respond to emergencies.

A 1999 study by the Texas Transportation Institute investigated shoulder use for hurricane evacuations. It suggested that one paved shoulder be used as an additional lane during an evacuation. The other paved shoulder should be reserved for emergency vehicle access and stranded vehicles. Clear signing or law enforcement is necessary, since driving on the shoulders is not a typical option for motorists. [*4*]

2.3 Other State Practices

In October 2007, WisDOT conducted a survey of state shoulder design practices. Twenty-six states provided responses. Descriptions of these states' shoulder thickness design practices are provided in Appendix 1. A summary of the practices is provided in Figure 2.

Of the 26 responding states, 8 (31 percent, shown in green in Figure 2) reported that FDS was not used. These states' typical shoulder thicknesses ranged from 1 inch of pavement over stabilized base to 6 inches of pavement over subgrade or non-stabilized base. Of the two states in the "other" category (shown in red in Figure 2), one designed its shoulder thickness based on a percentage of the mainline ESAL level, and one did not provide a detailed design practice.

Sixteen states (62 percent, shown in shades of blue in Figure 2) responded that FDS were used in some or all roadway designs. Seven states reported that shoulder thicknesses matched mainline thickness in all or most cases, while five states used this design practice on Interstates and other high volume roadways. Two states utilized trapezoidal shoulder sections, which provide full depth thickness adjacent to the travel lanes and taper to a thinner section at the outside edges. Two states mentioned that FDS were specified if the shoulder was anticipated to be used as a temporary travel lane in the future.

Most states that use FDS do so for principal arterials; lower functional classification roadways have thinner shoulders.

Other relevant notes based on individual states' comments are as follows:

* *Alabama* - Shoulders that were thinner than the mainline thickness were determined to be structurally inadequate if opened to traffic for extended periods of time.
* *Connecticut* - Full depth thickness is used if the shoulder is expected to carry traffic in the future. This practice has been implemented since 1994 or 1995. Some existing thinner shoulders have failed under significant traffic during construction projects.
* *New Jersey* - FDS are currently used, but previous practice was to design the shoulder thickness for ten percent of mainline traffic.
* *Idaho* - Rationale for FDS:
  + Easier to construct a consistent section
  + More support for temporary traffic
  + Cost savings for thinner shoulders are considered marginal
* *Nevada* - Rationale for FDS:
  + Shoulders used during lane closures
  + Shoulders turned into travel lanes
  + Shoulders used if travel lanes are widened

Figure . State shoulder thickness design practices.

3. Current Wisconsin Shoulder Design Practices (2012)

3.1 Thickness

Paved shoulder thickness is determined using the same design procedures as the mainline pavement. The number of equivalent single axle loads (ESALs) used in the shoulder design is specified as 2.5 percent of the ESAL level used for the mainline pavement design. The standard minimum thickness for concrete and HMA shoulders is 6 and 3.5 inches, respectively. [*5*]

HMA pavement is often placed in multiple layers to achieve the final paved thickness. When HMA shoulders are paved separately from the mainline pavement, the maximum layer thickness is four inches. [*6*]

Guidelines also note that construction efficiencies should be considered in thickness design. For instance, a 12-foot mainline travel lane can be paved simultaneously with a 3-foot shoulder in a single 15-foot pass. [*5*]

There is no policy on pavement type selection for shoulders. HMA mainline pavements are constructed with HMA shoulders. Concrete mainline pavements may be constructed with either concrete or HMA shoulders; this decision is made by the Regions during the design phase.

3.2 Geometry

Paved shoulders are constructed on all STN roadways classified as arterials, and on collector or local roads with an annual average daily traffic (AADT) greater than 1250. The paved shoulder width depends on the roadway's functional classification. Paved shoulder widths for rural arterials are shown in Table 2. Additional noteworthy policy is as follows for rural concrete pavement with an AADT greater than 1250:

* For two-lane, two-direction highways, the 3-foot paved shoulder shall be paved simultaneously with the 12-foot travel lane (15-foot wide pass). [*7*] The 3-foot shoulder thickness is therefore equal to the mainline thickness. This situation is depicted in Figure 3.
* For multi-lane divided highways, two feet of the right shoulder shall be monolithic with the driving lane. [*7*] The first two feet of the right shoulder therefore has a thickness equal to the mainline thickness. This situation is depicted in Figure 4.

The typical downward shoulder slope is 4 percent. If the shoulder is paved concurrently with the mainline (i.e., in one paver pass) and the paved shoulder width is less than 6 feet, the shoulder slope is equal to the slope of the travel lane. [*7*] If the shoulder width is greater than 6 feet, the shoulder cross slope is 4 percent. [*8*]

Specific geometric criteria are specified for Interstate highways. For 4-lane divided Interstates, the right and left shoulders have paved widths of 10 and 4 feet, respectively. The right and left paved shoulders are both 10 feet wide for Interstates with 6 or more lanes. Shoulder cross slopes are specified to be between 4 and 6 percent on Interstates highways and at least 1 percent steeper than the travel lane cross slope. [*9*]

Table . Paved Shoulder Widths, Rural Arterial State Trunk Highways, feet [*10*]

|  |  |  |  |
| --- | --- | --- | --- |
| **Roadway Type** | **Right** | **Left** | **Total paved width** |
| Two-lane, two-direction | 3 | 3 | 30 |
| 4-lane divided expressway | 8 | 3 | 35\* |
| 6-lane divided expressway | 8 | 8 | 52\* |
| 4-lane Interstate or freeway | 10† | 4 | 38\* |
| 6-lane Interstate or freeway | 10† | 10† | 56\* |
| 1-lane ramp | 5 | 3 | 23 |

\*Per travel direction

†Shoulder width is increased to 12 ft if truck traffic > 250 DHV (design hour volume), or if there is a high degree of congestion or incidents

15-ft continuous slab

3'

3'

12'

12'

Figure . Example of a two-lane, two-direction concrete mainline pavement and shoulder section.

2' integral right paved shoulder

Remaining right paved shoulder

Left paved shoulder

12'

12'

14-ft continuous slab

Figure . Example of a divided highway concrete mainline pavement and shoulder section.

4. Temporary Pavement Performance Observations

WisDOT project managers and pavement design engineers were interviewed regarding their experiences with existing shoulders subjected to temporary traffic loads. The North Central Region responded that shoulders are typically thickened prior to use as temporary travel lanes. [*11*] In the Northwest Region, random failures used to occur on temporary Interstate pavement with a structure of 5 inches of HMA over 12 inches of base material. Better performance has been noted more recently with a temporary pavement structure of 6 inches of HMA over 12 inches of base. [*12*]

In the Northeast Region, shoulders and other temporary pavement have been used in the reconstruction of USH 41 in Brown and Winnebago Counties. One stage of this project moved traffic to the existing shoulder. The existing shoulder structure was 3.25 inches of HMA over 4 inches of recycled HMA (7.25 inches total) over base material. The average daily traffic (ADT) on this segment was 60,000 (two directions), with 18 percent trucks. Traffic ran on the shoulder for just over a month in fall 2010 and for six months in summer 2011, and no performance issues were noted. [*13*]

In 2009, another Northeast Region construction project on I-43 utilized existing shoulders for temporary traffic. In one portion, temporary traffic ran on existing 3-inch HMA shoulders. These shoulders did not withstand the traffic loading and required emergency repairs. In another section of the project, shoulders had 6 inches of total HMA thickness. These shoulders had better performance under temporary traffic. It was also noted that the base material in the failed area was of poor quality, while the stabilized base and subgrade were solid in the portion with good performance. [*14*]

In the Southeast Region, the ongoing reconstruction of I-94 (North-South Freeway) requires use of shoulders for temporary traffic lanes. The existing concrete shoulders were trapezoidal sections, with 10-inch thickness next to the mainline pavement, tapering to 6-inch thickness at the outside edge. In one segment of the reconstruction project, some areas of the shoulder were repaired prior to use as temporary lanes. Performance was adequate after two months of traffic loading. However, much of the shoulder, including the portions that had been repaired, had cracked and settled. [*15*]

In these examples, the temporary pavement had better performance with thicker pavement structure. HMA pavement with a thickness less than 6 inches could not support high volume traffic for the duration of the construction project. In general, the 6- and 7-inch temporary HMA pavement had better performance. The trapezoidal concrete pavement sections (6- to 10-inch thickness) had adequate short-term performance but neared the end of their serviceable lifetime after two months of temporary traffic. It was also noted that the quality of the base and subgrade materials played a role in performance of the temporary pavements.

5. FDS Construction and Cost Considerations – Industry’s Perspective

Leaders of Wisconsin's concrete and HMA paving associations were interviewed to gain an industry perspective on FDS construction. [*16, 17*] Details of these discussions are summarized below.

Several construction efficiencies are possible with FDS. If shoulders are constructed at the same thickness as the mainline pavement, grade trimming can take place in one operation. Conversely, grading for thinner shoulders requires a separate operation for the inside and outside shoulders, as the base thickness is greater than for the mainline pavement. Eliminating these grading operations would result in cost savings for both concrete and HMA FDS designs. The project's total construction time could also be reduced, which is a high priority for most highway construction projects.

Shoulder design specifies that concrete shoulders be tied to the mainline concrete pavement. When the shoulders are paved separately, an additional construction sequence is necessary after mainline paving to straighten and position the tie bars. This process is not required if FDS are paved concurrently with the mainline concrete pavement. Although tie bar positioning is a relatively simple operation, cost and time savings would result if this step were eliminated.

Paving shoulders concurrently with mainline pavement is an option with FDS design. This is only feasible, however, if the mainline and shoulder materials match. Concrete mainline pavement is often constructed with HMA shoulders. HMA mainline pavement is often constructed with a different shoulder mixture type (e.g., E-10 mainline mixture with E-0.3 shoulder mixture). In these cases, separate paving operations are necessary for mainline and shoulder pavement, regardless of shoulder thickness.

If mainline pavement and FDS shoulders are constructed with one paver pass, the paver equipment must have adequate width. For a four-lane Interstate, the minimum required width is 38 feet (see Table 2). Concrete and HMA pavers are capable of paving at this width. However, other construction limitations must be considered, such as material production and delivery. For thick pavement sections, trucking the necessary volume of material might be impractical for continuous paving at a 38-foot width. Full-width concrete paving was considered for one recent Wisconsin highway construction project, but the unreliability of delivering the required material in heavy construction traffic eliminated this possibility.

For both concrete and HMA shoulders, the material bid costs would not increase linearly with increasing thickness. For example, if the total mixture tonnage required for full depth HMA shoulders was two times that for thinner shoulders, the total bid amount would not necessarily increase by a factor of two. The situation is similar for concrete, which is bid per square yard at a specified thickness. Twelve-inch concrete shoulders would cost less than twice the amount that six-inch shoulders would cost. The non-linear cost increase is a result of set production and construction costs that can be spread over the larger material requirement for thicker pavement.

The resulting cost increase for concrete FDS would be due primarily to the cost of the additional material, with a possible increase as low as one dollar per inch of thickness. For HMA FDS, the cost increase would scale similarly to changes in thickness for mainline HMA pavement. However, a firm cost increase for FDS materials and construction would depend on individual project requirements and construction staging. For that reason, one set value could not be calculated for the construction projects analyzed in this study. The shoulder thickness analysis in the next section therefore assumes a linear escalation of material costs. This results in conservative estimates for the cost difference between FDS and conventionally designed shoulders.

6. Construction Cost Analysis

6.1 Project Selection

Ten highway construction projects, listed in Table 3, were selected for shoulder construction cost analysis. The project selection criteria were as follows:

* Reconstruction or new alignment pavement projects
* At least two travel lanes in each direction
* Principal arterial highways or high-volume minor arterial highways
* Conventional (non-FDS) shoulder design

The original objective of this study was to evaluate five concrete mainline projects and five HMA mainline projects, but it was difficult to find HMA mainline reconstruction projects that met the above listed criteria. Therefore, additional concrete mainline projects were evaluated instead. With the exception of project numbers 9 , the highways listed in were four-lane divided reconstruction or new alignment projects. Project 9 was a two-lane highway reconstruction project. Projects 1 through 8 (concrete mainline) were principal arterial highways, while the remaining highways (HMA mainline) were minor arterials. All projects had HMA shoulders. Recent construction projects that incorporated concrete shoulders were typically already designed with FDS and were therefore not suitable for this analysis.

Table 3. Shoulder Evaluation Construction Projects

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Project** | **Highway** | **County** | **Construction ID** | **Contract ID** | **Construction Year** |
| Concrete mainline | 1 | USH 10 | Portage | 6351-00-78 | 20090609040 | 2010-11 |
| 2 | USH 53 | Douglas | 1196-00-75 | 20111108008 | 2012 |
| 3 | I-94 | St. Croix | 1020-07-74 | 20120313030 | 2012-13 |
| 4 | I-94 | Eau Claire & Trempealeau | 1022-00-77 | 20110913007 | 2012-13 |
| 5 | USH 151 | Dodge | 1111-09-73 | 20110510002 | 2011-12 |
| 6 | USH 12 | Sauk | 1674-00-76 | 20100914001 | 2011 |
| 7 | STH 26 | Rock | 1390-04-79 | 20120410003 | 2012-13 |
| 8 | STH 26 | Jefferson & Dodge | 1390-04-87 | 20110913001 | 2012 |
| HMA mline | 9 | STH 22 | Oconto | 9180-18-71 | 20120410041 | 2012 |
| 10 | STH 13 | Adams | 6140-00-79 | 20110614029 | 2011 |

6.2 Methodology

The as-designed shoulder structure was evaluated using typical sections from project plans for the ten study projects listed in . As-designed shoulder information for each project is provided in Appendix 2. Material requirements were calculated for the as-designed shoulders and for theoretical FDS sections. These materials included HMA mixture, asphaltic material, tack coat, and base aggregate dense (BAD). Figure 5 depicts the assumed shoulder cross-section material requirements.

Unit weights and the tack application rate stipulated in the WisDOT Facilities Development Manual (FDM) were used in material requirement calculations. [*18*] The asphaltic material content was 5.5 or 6.0 percent, depending on the project. These values were obtained from individual project plans and are provided in Appendix 3. A maximum HMA layer thickness of 4 inches was used in calculations, and it was assumed that one tack application would be applied between each layer. [*6*]

Using WisDOT data from the online Bid Express bid tabulation system, construction and material costs for the shoulders were calculated using the unit prices bid by the winning contractor. The total shoulder cost was divided by project length to obtain a shoulder "cost per mile" value for the as-designed and FDS scenarios. This cost included one pair of left and right shoulders in one travel direction. Unit bid costs are provided in Appendix 3.

Figure . Material requirements for as-designed shoulder sections and FDS sections.

6.3 Results

Shoulder costs calculated in the FDS analysis are shown in Table 4. The results in the “*Shoulder Costs*” section of Table 4 show the unit cost per mile to construct paved shoulders as designed and the unit cost per mile of FDS construction for both concrete and composite(HMA with 2 feet of integral) paved shoulders. The cost per mile includes one direction or pair of left and right shoulders including any portion paved integrally with the mainline and any aggregate quantities. These results are presented graphically in Figure 6. The cost increase factor is also presented in Table 4; this factor represents the increase in cost of FDS as compared to the conventional design, as described in Equation 1:

Equation 1

For HMA shoulders next to concrete mainline, the average cost for conventional shoulders and FDS was $183,000 and $346,000 per mile, respectively (). For concrete shoulders next to concrete mainline, the average cost for the FDS was approximately $265,000. There was wide variation in cost per mile among the projects, which was due to variation in unit bid costs. Most FDS costs were in the range of $200,000 to $300,000 per mile (). The unusually high cost for FDS with project number 3 (I-94 in St. Croix County) was due to high bid costs as well as a thick FDS section (13 inches). The unit cost per mile for HMA shoulders with HMA mainline pavement was lower: the costs for conventionally designed shoulders and FDS averaged $123,000 and $172,000 per mile, respectively.

For HMA shoulders next to concrete mainline, the cost for FDS construction was almost twice that of conventionally designed shoulders; the cost increase factor averaged 1.89 (Table 4). The cost increase factor was lower for concrete shoulders next to concrete mainline at an average of 1.47 (Table 4). The lowest cost increase was for HMA shoulders next to HMA mainline pavement with an average of 1.40. There was good agreement in cost increase among projects, as demonstrated by the low coefficients of variation in each mainline pavement type category.

The final columns of demonstrate the effect of FDS construction on total project cost. The cost increase associated with FDS ranged from 1 percent to 15 percent of the total as-designed project cost. This wide range depended on unit bid costs, overall project complexity, and the pavement type selected. The average project cost increase for concrete mainline pavement with HMA shoulders was approximately 7 percent and for concrete shoulders approximately 4 percent. For HMA mainline and shoulders, the average total project cost increase was lower at approximately 3 percent.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Table . Shoulder Costs and Impact of FDS on Total Project Cost | | | | | | | | | | |
|  |  | *Shoulder Costs* | | | | | | *Impact on Total Project Cost* | | |
|  |  |  | **Shoulder Construction Costs per Mile** | | | **Cost increase Factor HMA** | **Cost increase Factor Concrete** |  | **Cost Increase with HMA FDS** | **Cost Increase with Concrete FDS** |
|  | **Project** | **Length (miles)** | **As-Built** | **FDS HMA** | **FDS Concrete** | **As-bid Total Project Cost** |
| Concrete mainline | 1 | 7.8 | $156,989 | $329,296 | $224,954 | 2.10 | 1.43 | $24,890,628 | 5% | 2% |
| 2 | 3.5 | $158,393 | $263,047 | $262,555 | 1.66 | 1.66 | $4,891,945 | 7% | 7% |
| 3 a | 4 | $316,169 | $562,607 | $392,431 | 1.78 | 1.24 | $24,762,161 | 4% | 1% |
| b | 4 | $275,871 | $562,015 | $392,431 | 2.04 | 1.42 | $24,762,161 | 5% | 2% |
| 4 | 17.6 | $190,371 | $376,317 | $300,092 | 1.98 | 1.58 | $34,050,000 | 10% | 6% |
| 5 | 3.9 | $147,243 | $293,599 | $220,277 | 1.99 | 1.50 | $21,702,321 | 3% | 1% |
| 6 | 9 | $146,836 | $257,308 | $212,393 | 1.75 | 1.45 | $6,839,629 | 15% | 9% |
| 7 | 11.3 | $132,591 | $249,650 | $202,713 | 1.88 | 1.53 | $25,527,678 | 5% | 3% |
| 8 | 12.6 | $121,751 | $224,019 | $177,094 | 1.84 | 1.45 | $11,871,575 | 11% | 6% |
|  | *Average* | *$182,913* | *$346,429* | *$264,993* | *1.89* | *1.47* | *$19,922,011* | *7%* | *4%* |
|  | *Std. Dev.* | *$63,748* | *$123,123* | *$75,787* | *0.15* | *0.12* | *$9,795,378* | *4%* | *3%* |
|  | *COV\** | *34.9%* | *35.5%* | *28.6%* | *8%* | *8%* | *49%* | *54%* | *68%* |
| HMA mainline | 9 | 7.5 | $91,141 | $129,885 | N/A | 1.43 | N/A | $7,438,069 | 4% | N/A |
| 10 | 2.5 | $155,491 | $213,326 | N/A | 1.37 | N/A | $5,268,690 | 3% | N/A |
|  | *Average* | *$123,316* | *$171,606* | *N/A* | *1.40* | *N/A* | *$6,353,380* | *3%* | *N/A* |
|  | *Std. Dev.* | *$45,502* | *$59,002* | *N/A* | *0.04* | *N/A* | *$1,533,983* | *1%* | *N/A* |
|  | *COV\** | *36.9%* | *34.4%* | *N/A* | *3%* | *N/A* | *24%* | *25%* | *N/A* |

\* COV = Coefficient of Variation = Standard Deviation ÷ Average

HMA

Mainline

Concrete

Mainline

Figure . Shoulder costs, dollars per mile

7. Use of FDS for Temporary Travel Lanes

Shoulders, FDS or conventional, have many temporary uses, such as a lane for disabled vehicles and emergency vehicle access. The full benefit of FDS is realized when the shoulder is utilized for longer term use as a travel lane. This occurs most commonly during construction activities. Prolonged heavy traffic is also a possibility if the shoulder is used during an emergency evacuation or another unplanned lane closure. These scenarios are discussed in the following sections. To be consistent with the projects analyzed in Section 6, the following examples consider multi-lane divided highways.

7.1 Construction Geometrics

When a multi-lane divided highway is reconstructed, traffic flow must be altered while construction takes place. Project staging requirements vary from project to project. Two options that allow for maintenance of traffic flow include counter-directional traffic flow and temporary shifting with or without widening. The former provides one temporary travel lane in each direction, and the latter can provide multiple temporary travel lanes in each direction. Examples of traffic flow in each scenario are shown schematically in Figure 7.

Shoulder use is not typically necessary in the counter-directional flow traffic control layout. Adequate width exists to place barrier walls or temporary flexible tubular posts between opposing temporary traffic lanes and maintain 11- or 12-foot wide lanes for traffic (Figure 7 [b]) making the need for FDS relatively unnecessary. However, FDS would still prove some benefit in counter-directional flow layouts where the barrier walls or tubular posts placed between opposing lanes provide for obstacles that many motorists will instinctively shy away from. This reaction often causes the traffic to ride on the lane/shoulder joint, leading to pavement failure at spot shoulder locations that has been observed on several recent construction projects. Had the shoulders been designed and constructed with sufficient structural thickness, these spot failures and the subsequent effects on the flow of construction traffic would have been reduced or eliminated.

The second traffic control option that would recognize benefits from FDS is temporary lane shifting. For this maintenance of traffic approach, the traffic flow is offset left or right of the permanent travel lanes. Existing paved shoulders can be used to carry temporary traffic. As WisDOT’s maintenance of traffic requirements have evolved to require more available travel lanes during construction; so has the Department’s design manual to call for the use of wider paved shoulders on high order, multi-lane facilities. For some projects this additional width is sufficient, however, on others, the paved shoulders simply do not provide enough surface width and the roadway requires temporary widening. FDS can benefit either type of project.

For projects with shoulders wide enough to accept temporary traffic flow, the primary concern FDS addresses is the failure of the Department’s manual to account for the additional structural strength these shoulders will require. The conventional shoulders often require repairs, and even thickening to full depth prior to use as temporary travel lanes. The cost implications of this FDS benefit are discussed in detail in Subsection 7.2

FDS can also be utilized during rehabilitation and maintenance projects. Options for traffic flow are shown in Figure 7 (d) and (e). When work is performed on the inside lanes, the outside lane and the outside shoulder could provide two travel lanes. Closure of the outside lanes would leave sufficient width for just one travel lane to remain open. These traffic layouts would also apply if the inside or outside lane was closed due to an accident.

When temporary widening is constructed to create additional travel lanes (Figure 7 [c]) widening can take place on either the median or outside edge of the existing pavement, as shown in Figure 8 and Figure 9, respectively. These configurations assume 11-foot travel lanes and 3-foot shoulders. The required amount of temporary pavement depends on whether barrier walls are necessary on the outside edge of the temporary travel lanes (Figure 8 [b] and Figure 9 [b]). By having existing shoulders constructed full depth, the existing shoulders can be incorporated into the temporary widening saving time and costs as is discussed in detail in Subsection 7.3.

The extent to which FDS could theoretically be incorporated into the temporary widening and used to support temporary traffic depends on the traffic control configuration. In Figure 8 and Figure 9, the areas outlined with red dashes indicate portions of existing FDS that would have traffic loading in each traffic control layout. The remainder of the existing FDS would be used as temporary shoulders and barrier placement and would therefore not be subjected to traffic loads. The greatest amount of existing FDS is utilized when temporary widening is constructed in the median (Figure 8). Existing FDS is utilized to a lesser extent when widening is constructed on the outside edge (Figure 9). In the outside edge scenario, much of the existing FDS is used for temporary shoulders and barrier placement.

(a) Normal operation

Work Zone

(b) Counter-directional flow

Work Zone

(c) Temporary widening

Work Zone

(d) Rehabilitation and maintenance, inside lane

Work Zone

Work Zone

Work Zone

(e) Rehabilitation and maintenance, outside lane

Figure . Traffic control options for temporary construction closures.

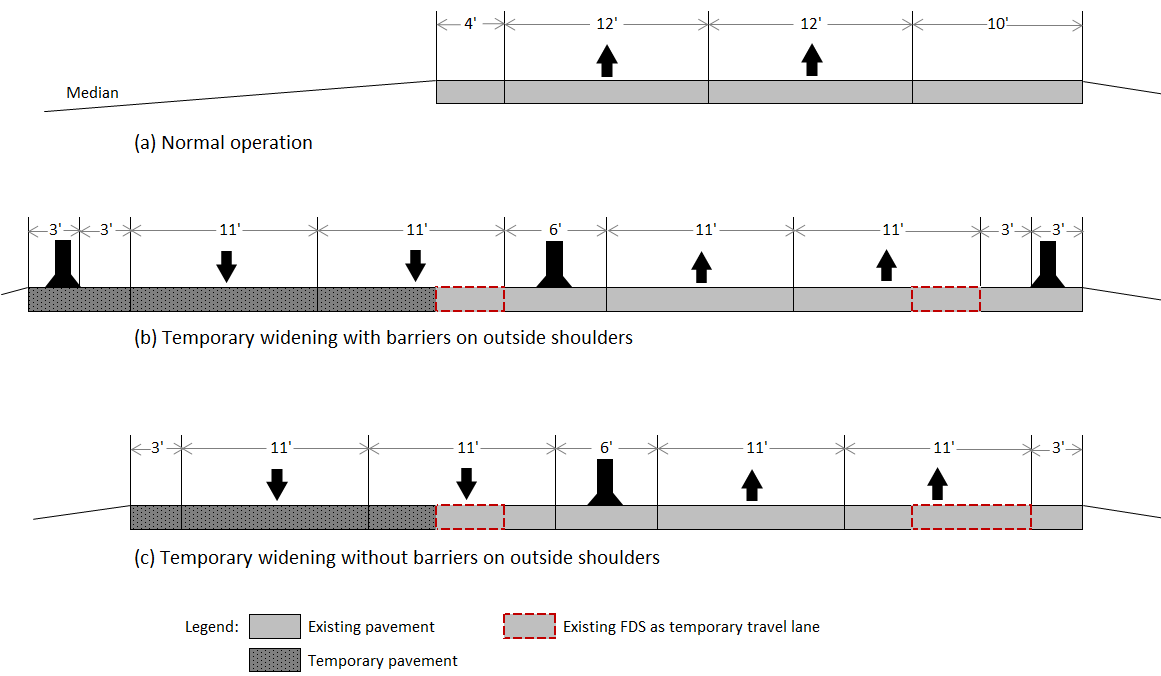
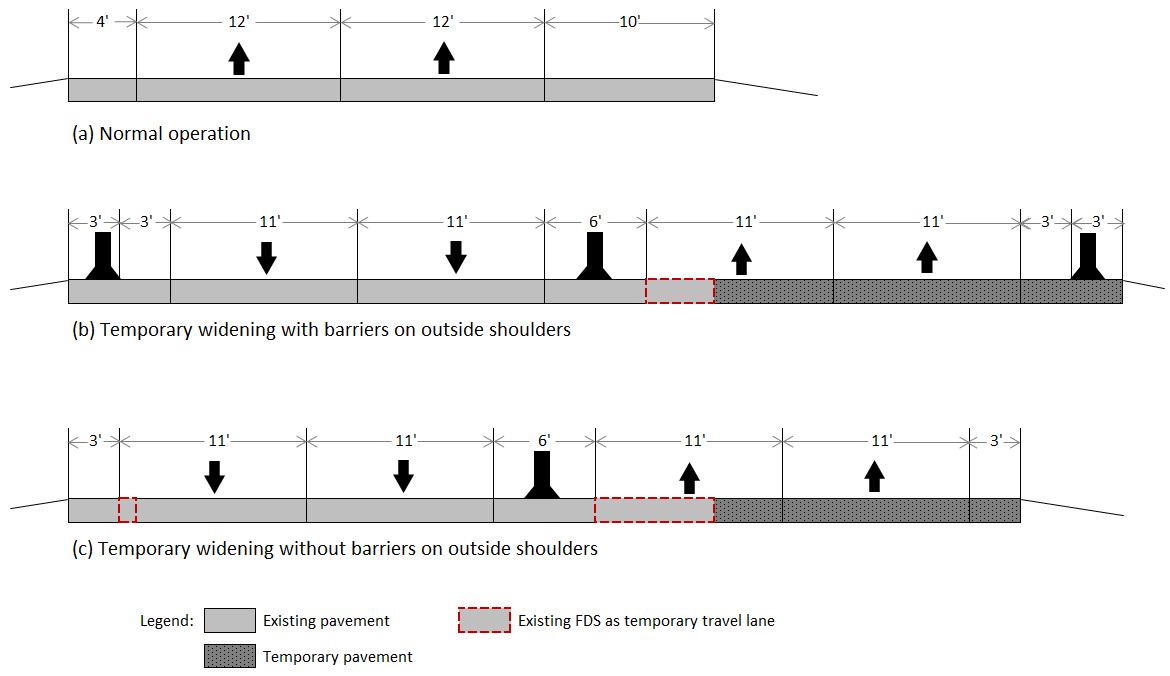


Figure . Traffic layouts for temporary shoulder widening into median.



Outside edge

Figure . Traffic layouts for temporary shoulder widening at outside edge.

7.2 Shoulder Pavement Repair, Replacement, and Widening Implications

On recent highway construction projects, conventionally designed shoulders utilized as temporary travel lanes deteriorated and even failed prior to project completion. As previously discussed, existing paved shoulders may be wide enough to handle temporary traffic, but are structurally deficient, leading to the aforementioned deterioration or failure prior to project completion. To prevent the potentially dangerous pavement failures during temporary traffic operation WisDOT has performed structural rehabilitation on some projects and replaced the existing shoulder pavement with a thicker, even full depth, cross section on others. Though the Department has performed such projects for several years, even decades, the cost implications have never been enumerated. For this analysis, several projects where the shoulders were replaced or rehabbed were identified and one was investigated in detail.

Though all five of WisDOT’s regions provided examples of shoulders being addressed in the early stages of, or prior to, a construction project only four were investigated in more depth. Three of the projects were completed by WisDOT’s Southeast Region, two on I-43 and one on I-94. The fourth project, I-39 at the Dane-Columbia County line, was constructed by WisDOT’s Southwest Region. The cost implications of pavement replacement were analyzed in detail on the I-39 project. The results of this analysis are discussed in subsection 7.2.2.

7.2.1 Asphaltic Concrete Shoulder Rehabilitation/Replacement

The first of the I-43 projects addressed an asphalt overlay of a 1969 vintage concrete pavement. The original 9-inch concrete pavement constructed in 1969 was bordered by 3-inch asphalt shoulders. In 1992, the mainline travel lanes and shoulders were overlaid. Concrete base patching and longitudinal centerline joint repairs were completed in 2007, and finally, in 2012 the lanes and shoulders were again milled and overlaid. For the 2012 project, the first stage of operations was to mill and overlay the existing asphalt shoulders 2 inches.

The second I-43 project addressed a slightly newer overlay of a 1974 vintage concrete pavement. The original 8-inch concrete pavement was bordered again by 3-inch asphalt shoulders. In 1993 the travel lanes and shoulders were overlaid with 3.5 – 4.5 inches of asphalt. In 2012, the lanes and shoulders were milled and overlaid. Prior to the start of temporary traffic shifts, the project required that 3.5 inches of the existing asphalt shoulders be removed and replaced.

Both of these projects required replacement of an upper layer of asphalt pavement for the pavement structure to be suitable for use as temporary travel lanes. Though part of the driving factor for this replacement was to remove milled rumble strips, the depth of the pavement replacement suggests the pavement was distressed enough to question the structural integrity of the shoulder. It is hypothesized that the use of FDS would limit the distresses experienced to those environmental in nature, rather than the combination of loading and environmental distresses found in conventional shoulders. This hypothesis forms the basis for the life cycle cost analysis (LCCA) discussed in Section 8.

7.2.2 Portland Cement Concrete (PCC) Shoulder Projects

The final two projects examined for shoulder pavement rehabilitation or replacement were I-94 and I-39, both incorporated PCC paved shoulders.

The I-94 project was programmed to address a 1998 HMA overlay on the East-West Freeway. The original pavement was a 1960 vintage 9-inch concrete. The original construction did not provide for any adjacent shoulders. Instead, the travel lanes were hemmed in by curb-and-gutter with a thin asphalt surface behind it. The segment of I-94 received shoulders in 1976 when the concrete was overlaid with HMA. With that 1976 project, the curb and gutter were removed and replaced with a ten feet wide concrete shoulder. The first three feet of the shoulder were” full depth” (9 inches) not accounting for the asphalt thickness and the remaining seven feet was 6 inches. The HMA lanes were milled and overlaid in 1998 with the shoulders remaining as untouched. As traffic levels increased and WisDOT policies evolved, when the segment was milled and overlaid again in 2012, the shoulders were needed for traffic control. In order to handle the construction traffic, the varying depth paved shoulders were replaced with 12-inch concrete pavement prior to being used as temporary travel lanes during construction.

The shoulder replacement project investigated in the most detail was I-39 at the Dane/Columbia county line in WisDOT’s Southwest Region. This segment of I-39 is composed of 10-inch concrete pavement with 6-inch concrete shoulders that were placed in 1984. Prior to beginning work on the controlling contract items in 2012, the concrete shoulders were removed and replaced with 8-inch PCC pavement. Though not a perfect comparison with the shoulders not being replaced full depth, the estimated costs of constructing FDS originally were compared to the costs of removing and replacing the original shoulders with a thicker cross section.

The contract payment records for the 1984 were well beyond WisDOT’s record retention period and had therefore been destroyed decades ago. To estimate the cost of constructing the shoulders, a cost model was constructed using a combination of WisDOT historical construction data (1999 – present) and Federal historical construction and inflation data (1972 – present). These figures were then adjusted to take inflation into account and enable an accurate comparison to the actual 2012 construction costs for the 8-inch shoulder replacement. The results of the comparison are displayed in Table 5. As is shown, the estimated additional cost to construct the FDS in 1984 was $39,272/mile ($87,462/mile in 2012 inflation adjusted dollars); about 25% of the $333,847/mile expenditure made in 2012 to replace the 6-inch shoulders with 8-inch shoulders.

|  |  |  |
| --- | --- | --- |
| Table 5 : I-39 Cost Comparisons | | |
|  | **1984 Dollar Value** | **2012 Dollar Value** |
| Estimated 6-Inch Shoulder Costs/Mile | $ 151,571 | $ 337,548 |
| Estimated FDS (10-Inch) Costs/Mile | $ 190,843 | $ 425,010 |
| **Difference For Initial Construction Costs** | **$ 39,272** | **$ 87,462** |
| 8-inch Shoulder Replacement Let Cost/Mile | -- | $ 333,847 |

7.3 Shoulder Widening Cost Analysis

As discussed in previous sections, shoulders and temporary pavement widening can be used to maintain four lanes of traffic during construction of high volume roadways. In recent construction projects where temporary pavement widening was utilized, existing shoulders required removal because they were not anticipated to withstand temporary traffic loading. In these projects, the shoulders were removed and replaced with temporary pavement widening. This was the case on recent construction projects on USH 41 in Winnebago County and I-94 outside Madison. These projects are further examined and discussed in subsections 7.3.1 and 7.3.2 that follow.

Unfortunately, shoulder removal is often necessary on highways without FDS that require temporary widening for construction traffic. If these highways had originally been constructed with FDS, construction costs would have been lower during their eventual reconstructions. With FDS, the existing shoulder would have adequate structure to carry traffic during construction, and removal of the existing shoulders would not be necessary prior to widening. For example, four to five travel lanes needed to remain open during mainline reconstruction of the North-South Freeway (I-94), an ongoing project in Southeast Wisconsin. In this case, existing shoulders were 10-inch trapezoidal concrete sections. These shoulders were used in conjunction with temporary widening to maintain four or five lanes of traffic during construction. The cost of temporary widening for each portion of this 35-mile reconstruction effort was reduced by utilizing existing shoulders with structure similar to that of the mainline pavement.

7.3.1 USH 41 Shoulder Widening Analysis

At the time of publication, construction is underway on USH 41 in Wisconsin's Northeast Region. This project will expand 17 miles of the roadway from four lanes to six or ten lanes, along with other updates and improvements. Prior to mainline expansion, portions of the highway will require temporary widening to accommodate four lanes of traffic at all times during construction.

One such portion of USH 41 is the 8-mile segment from USH 45 to Breezewood Lane in Winnebago County.[[1]](#footnote-1) As part of the temporary widening, existing shoulders and underlying base layers in the northbound direction were removed and replaced with five inches of E-10 HMA over 12 to 15 inches of BAD and breaker run. The existing sections and design sections with temporary widening are shown in Figure 10 (a) and (b). Four lanes of traffic flowed on this widened section while the southbound lanes were reconstructed.

The existing shoulders did not have adequate structure to accommodate traffic during the extended closure of the southbound mainline roadway. Existing shoulders were therefore removed prior to construction of the temporary lanes. Had the existing shoulders been constructed with full depth thickness (Figure 10 [c]), it would have been possible to incorporate them as part of the temporary widening. In this scenario, the material requirement for temporary widening could be significantly reduced.

Actual bid costs for temporary widening on the USH 41 construction project were evaluated; results are shown in Table 5. If FDS could have been utilized for temporary widening, the construction costs would have been reduced by approximately $2 million, or 29 percent of the total widening cost. This equates to a cost savings of $272,000 per mile, which is similar to the initial cost of FDS construction (see Section 6.3).

Table 6. USH 41 Shoulder Widening Cost Analysis

|  |  |
| --- | --- |
| Temporary shoulder widening cost, existing shoulders removed\* | $7,280,000 |
| Temporary shoulder widening cost, FDS remain\* | $5,168,000 |
| Difference | $2,112,000 |
| Percent cost reduction | 29% |
| Material cost savings per mile | $272,000 |

\*Includes the following bid items: 204.0100 Removing pavement, 205.0100 Excavation common, 305.0120 BAD 1¼ inch, 311.0110 Breaker run, 455.0105 Asphaltic material PG58-28, 455.0605 Tack coat, 460.1110 HMA pavement type E-10

4'

8' to 10'

12'

14'

12" concrete pavement

Base

4" asphaltic concrete shoulder, typ.

Subbase

(a) Existing pavement section

13' to 28'

8' to 17'

14'

12'

Subbase, existing

Base, existing

12" concrete pavement, existing

5" HMA shoulder typ.

15" BAD 1 ¼ in

13" Breaker run

12" BAD 1 ¼ in

12" Breaker run

(b) As-designed widened pavement section, existing shoulders removed

0' to 9'

4'

9' to 24'

8' to 10'

14'

12'

12" concrete pavement, existing

15" BAD 1 ¼ in

Subbase, existing

Base, existing

5" HMA shoulder typ.

12" HMA shoulder, typ., existing

13" Breaker run

12" Breaker run

12 "BAD 1 ¼ in

(c) Potential widened pavement section design, existing FDS remain

Figure . Shoulder widening pavement cross sections, USH 41.

7.3.2 I-94 Shoulder Widening Analysis

In 2009, a five-mile portion of I-94 east of Madison was expanded from four to six lanes.[[2]](#footnote-2) Four lanes of traffic were maintained during construction; this was accomplished with temporary widening. Existing shoulders were removed prior to widening and replaced with 5 inches of temporary asphaltic surface, as shown in Figure 11 (a) and (b).

If the existing shoulders were FDS, the widening option shown in Figure 11 (c) would have been possible. The material and construction costs of the widening stage would have been lower with this option. Actual bid data were evaluated to determine the cost of the widening options shown in Figure 11 (b) (temporary widening with existing shoulder removal) and Figure 11 (c) (temporary widening using existing FDS). The analysis results are shown in Table 6.

Utilizing existing FDS would lower the cost of temporary pavement widening by 23 percent, resulting in a material cost savings per mile of approximately $178,000. This is 70 percent of the initial cost estimated for FDS construction, as presented in Section 6.3.

Table 7. I-94 Shoulder Widening Cost Analysis

|  |  |
| --- | --- |
| Temporary shoulder widening cost, existing shoulders removed\* | $3,990,000 |
| Temporary shoulder widening cost, full depth shoulders remain\* | $3,070,000 |
| Difference | $920,000 |
| Percent cost reduction | 23% |
| Material cost savings per mile | $178,000 |

\*Includes the following bid items: 305.0110 BAD ¾ inch, 305.0120 BAD 1¼ inch, 312.0110 Select crushed material, 465.0125 Asphaltic surface temporary.

(c) Potential widened pavement section design, existing FDS remain

(b) As-designed widened pavement section, existing shoulders removed

12'

12'

6'

10'

asphaltic concrete shoulder, typ.

4" asphaltic concrete pavement

Base

9" concrete pavement

(a) Existing pavement section

Subbase

25'

10'

12'

12'

4" asphaltic concrete pavement, existing

Subbase, existing

Base, existing

5" asphaltic surface, temporary

5" asphaltic surface, temporary

12" BAD 1 ¼ in

9" concrete pavement, existing

12" Select crushed material

2" BAD, ¾-in

6'

19'

4" asphaltic concrete pavement, existing

Subbase, existing

Base, existing

9" concrete pavement, existing

10'

12'

12'

12" Select crushed material

12" BAD 1 ¼ in

5" asphaltic surface, temporary

Figure . Shoulder widening pavement cross sections, I-94.

7.3 Emergency Evacuation Geometry

Use of the shoulder during a mass evacuation would provide additional capacity and allow for faster evacuation of a region. This would typically be an emergency situation, with little or no advance warning. There would likely not be time for installation of traffic control and other modifications, such as temporary widening.

In the case of an evacuation, traffic would be routed onto the shoulder by emergency personnel. The potential evacuation traffic layout is shown in Figure 12 for travel in one direction on a four-lane divided Interstate highway. The shoulder traffic lane would be 10 feet wide, one to two feet less than a typical temporary travel lane. However, ten-foot lanes are possible in lower-speed situations. [*19*] The congestion during an evacuation would reduce speeds to a point that drivers would feel comfortable in a ten-foot wide lane. Buses and trucks should stay in the wider lanes.

The addition of one temporary travel lane for a mass evacuation is possible with current Interstate shoulder geometry. With FDS, traffic could be safely routed onto the shoulder without concern for early pavement failure. Thinner shoulder sections might fail or require repairs if used as a temporary evacuation lane.

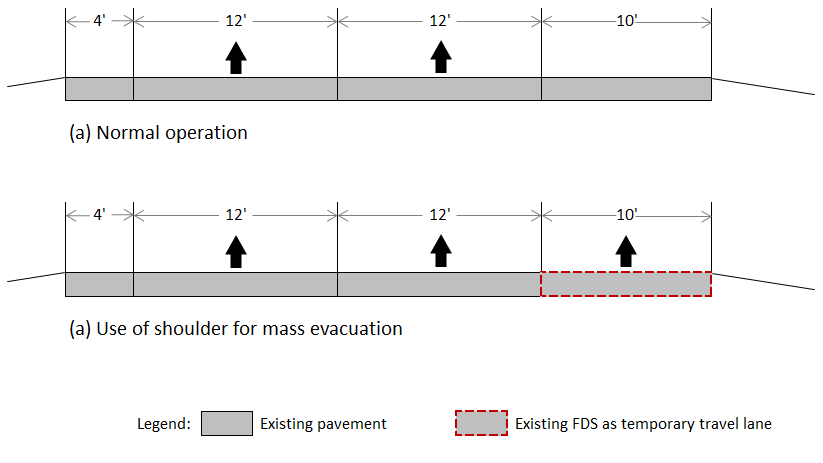


Figure . Traffic layout for shoulder use during mass evacuation.

8.Life Cycle Cost Analyses

The construction costs presented in Sections 6 and 7 represent only a snap shot in time of the cost implications of full depth or conventional shoulders. To truly compare which alternative is the most cost effective, a life cycle analysis was required.

8.1 Maintenance Schedule Development

The first step in completing the life cycle analysis was to determine a maintenance schedule for each of the shoulder types. As was discussed in the literature review, unlike mainline pavements, there is very little research completed with regards to paved shoulder performance. Given this limitation, many assumptions were required to compile the conventional and full depth shoulder maintenance schedules.

The first assumption that was made was necessary to differentiate between the full depth and conventional shoulders. It was assumed that the full depth paved shoulders would be structurally sufficient to prevent any loading or fatigue stress; limiting any full depth shoulder distress to those caused by weathering. Whereas the conventionally designed shoulders were assumed to be subjected to both fatigue and weathering distresses.

Based on this assumption, the second assumption was made that for the full depth shoulders, due to the predicted limited distress rate, any shoulder maintenance would mirror the mainline maintenance. Using this assumption, the full depth shoulder maintenance schedules depicted in Table 8 and Table 9 were compiled based on the standard mainline pavement maintenance schedules outlined in WisDOT’s FDM.

|  |  |
| --- | --- |
| Table 8 : Full Depth Composite (2’ Integral Concrete and Remaining HMA) Shoulder Maintenance Schedule | |
| Year | Description |
| 0 | Initial Construction |
| 3 | FDM Routine HMA Maintenance Crack Sealing (AC Transverse Cracking) |
| 13 | FDM Routine HMA Maintenance Crack Sealing (AC Transverse Cracking) |
| FDM Routine Maintenance (Concrete) |
| 19 | Routine Concrete Maintenance |
| 22 | Routine Maintenance Crack Sealing (AC Transverse Cracking) |
| 25 | 4" HMA overlay (Full width; price reflects only shoulders; 12 year service life) |
| 28 | FDM Routine HMA Maintenance Crack Sealing (AC Transverse Cracking) |
| 34 | FDM Routine HMA Maintenance Crack Sealing (AC Transverse Cracking) |
| 40 | 3" HMA mill and overlay (full width; price reflects only shoulders; 12 year service life) |
| 43 | FDM Routine HMA Maintenance Crack Sealing (AC Transverse Cracking) |
| 50 | Remaining Service Life |

|  |  |
| --- | --- |
| Table 9 : Full Depth Portland Cement Concrete Maintenance Schedule | |
| **Year** | **Description** |
| 0 | Initial Construction |
| 13 | FDM Routine Maintenance (Concrete) |
| 19 | FDM Routine Maintenance (Concrete) |
| 25 | 4" HMA overlay (Full width; price reflects only shoulders; 15 year service life) |
| 28 | FDM Routine Matienance (Asphalt Overlay) |
| 34 | FDM Routine Maintenance (Asphalt overlay) |
| 40 | 3" HMA mill and overlay (full width; price reflects only shoulders; 12 year service life) |
| 43 | FDM Routine HMA Maintenance Crack Sealing (AC Transverse Cracking) |
| 50 | Remaining Service Life |

To account for the additional loading or fatigue distresses anticipated in the conventionally designed shoulders, a WHRP report published in 2003 on the topic of “*Performance of Shoulders Adjacent to Concrete Pavements”* was utilized. This report contained pavement distress progression models constructed with the results of 289 one-mile paved shoulder performance surveys located on 133 different WisDOT construction projects. The conventionally designed shoulder maintenance schedules depicted in Tables 10 and 11 were compiled by combining the mainline schedules in the FDM with the progression models from WHRP project 0092-02-05. As can be seen, the conventionally designed shoulders are assumed to require two to four additional maintenance strategies, depending upon shoulder type. The rows highlighted in Tables 10 and 11 are the additional strategies required for the conventionally designed shoulders.

|  |  |  |  |
| --- | --- | --- | --- |
| Table 10 : Conventional Composite (2’ Integral Concrete and Remaining HMA) Shoulder Maintenance Schedule | | | |
| Year | Description | | |
| 0 | Initial Construction | | |
| 3 | FDM Routine HMA Maintenance Crack Sealing (AC Transverse Cracking) | | |
| 13 | FDM Routine HMA Maintenance Crack Sealing (AC Transverse Cracking) | | |
|  |  | Minor Concrete Pavement Crack and Joint Repair |
| FDM Routine Maintenance (Concrete) | | |
| 19 | Major Joint Repair (PCC Distressed Cracks and Joints) | | |
| Routine Concrete Maintenance | | |
| Shoulder Repairs (Wedge, Crack Sealing, etc) | | |
| 22 | Routine Maintenance Crack Sealing (AC Transverse Cracking) | | |
| 25 | Concrete Pavement Repair | | |
| 4" HMA overlay (Full width; price reflects only shoulders; 12 year service life) | | |
| 28 | FDM Routine HMA Maintenance Crack Sealing (AC Transverse Cracking) | | |
| 34 | FDM Routine HMA Maintenance Crack Sealing (AC Transverse Cracking) | | |
| 40 | 3" HMA mill and overlay (full width; price reflects only shoulders; 12 year service life) | | |
| 43 | FDM Routine HMA Maintenance Crack Sealing (AC Transverse Cracking) | | |
| 50 | Remaining Service Life | | |

|  |  |
| --- | --- |
| Table 11 : Conventional Portland Cement Concrete Maintenance Schedule | |
| Year | Description |
| 0 | Initial Construction |
| 13 | FDM Routine Maintenance (Concrete) |
| 19 | Major Joint Repair (PCC Distressed Cracks and Joints) |
|  | Routine Concrete Maintenance |
| 25 | Concrete Pavement Repair |
| 4" HMA overlay (Full width; price reflects only shoulders; 15 year service life) |
| 28 | FDM Routine Matienance (Asphalt Overlay) |
| 34 | FDM Routine Maintenance (Asphalt overlay) |
| 40 | 3" HMA mill and overlay (full width; price reflects only shoulders; 12 year service life) |
| 43 | FDM Routine HMA Maintenance Crack Sealing (AC Transverse Cracking) |
| 50 | Remaining Service Life |

8.2 Life Cycle Costs

Using the maintenance schedules, estimated distress quantities were calculated. The maintenance costs to address the distresses at the various schedule years were determined using the estimated distress quantities and WisDOT average bid price data. To equate for the time value of money, the costs were equated to a net present value (NPV) using a discount rate in the following equation:

Equation 2

where: *n* = time (year)

*Rn* = real cost in year *n*

*r* = discount rate = 3.5 or 5%

For the purposes of this investigation, the NPV for a 50 year life cycle was calculated using both the WisDOT standard 5% discount rate and a more widely accepted 3.5% discount rate. Table 12 summarizes the life cycle costs using the 5% rate and Table 13 summarizes the life cycle costs using the 3.5% rate.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Table 12. Shoulder Life Cycle Costs using 5% Discount Rate | | | | | |
|  |  |  | Life Cycle Costs per Mile | | |
|  | Project | | As-Built | FDS HMA | FDS Concrete |
| Concrete Mainline (As-Built shoulders all HMA) | 1 | | $ 224,943 | $ 388,350 | $ 282,700 |
| 2 | | $ 216,123 | $ 311,938 | $ 309,738 |
| 3 | a | $ 389,950 | $ 627,470 | $ 456,153 |
| b | $ 349,652 | $ 627,470 | $ 456,153 |
| 4 | | $ 256,494 | $ 433,521 | $ 355,526 |
| 5 | | $ 209,854 | $ 347,376 | $ 272,284 |
| 6 | | $ 199,967 | $ 301,540 | $ 255,248 |
| 7 | | $ 187,486 | $ 295,711 | $ 247,397 |
| 8 | | $ 178,415 | $ 271,849 | $ 223,547 |
| *Average* | | *$ 245,876* | *$ 400,580* | *$ 317,638* |
| *Std Dev* | | *$ 70,181* | *$ 130,068* | *$ 82,211* |
| *COV\** | | *28.5%* | *32.5%* | *25.9%* |
| HMA Mainline and Shoulders | 9 | | $ 124,312 | $ 160,682 | N/A |
| 10 | | $ 220,941 | $ 276,402 | N/A |
| *Average* | | *$ 172,626* | *$ 218,542* | *N/A* |
| *Std Dev* | | *$ 68,327* | *$ 81,827* | *N/A* |
| *COV\** | | *39.6%* | *37.4%* | *N/A* |

\* COV = Coefficient of Variation = Standard Deviation ÷ Average

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Table 13. Shoulder Life Cycle Costs using 3.5% Discount Rate | | | | | |
|  |  |  | Life Cycle Costs per Mile | | |
|  | Project | | As-Built | FDS HMA | FDS Concrete |
| Concrete Mainline (As-Built shoulders all HMA) | 1 | | $ 258,425 | $ 418,710 | $ 312,849 |
| 2 | | $ 243,904 | $ 336,621 | $ 334,145 |
| 3 | a | $ 426,590 | $ 660,980 | $ 489,480 |
| b | $ 386,291 | $ 660,980 | $ 489,480 |
| 4 | | $ 288,741 | $ 462,639 | $ 384,357 |
| 5 | | $ 240,317 | $ 374,742 | $ 299,364 |
| 6 | | $ 225,845 | $ 324,296 | $ 277,782 |
| 7 | | $ 214,270 | $ 319,398 | $ 270,862 |
| 8 | | $ 206,100 | $ 296,438 | $ 247,913 |
| *Average* | | *$ 276,720* | *$ 428,312* | *$ 345,137* |
| *Std Dev* | | *$ 73,654* | *$ 133,703* | *$ 85,617* |
| *COV\** | | *26.6%* | *31.2%* | *24.8%* |
| HMA Mainline and Shoulders | 9 | | $ 141,203 | $ 176,827 | N/A |
| 10 | | $ 254,888 | $ 309,603 | N/A |
| *Average* | | *$ 198,046* | *$ 243,215* | *N/A* |
| *Std Dev* | | *$ 80,388* | *$ 93,887* | *N/A* |
| *COV\** | | *40.6%* | *38.6%* | *N/A* |

It should be noted that these figures are considered to be conservative. There are several economic impacts that were not considered when these costs were compiled. The first, any potential costs implications on contract bid prices due to a reduction in work operations in the case of full depth paved shoulders or a change in material quantities was not taken into account. Secondly, the potential cost to repair or replace existing shoulders or to construct a temporary road to accommodate construction traffic was not included in the maintenance schedules. These costs are certainly significant when considering the cost implications of shoulder design and for this reason the analyses and discussions regarding I-39, I-94, and USH 41 in section 7 were completed.

9. Benefit Cost Analysis

According to the US DOT the aforementioned and completed life cycle cost analysis is the appropriate economic tool for comparing and selecting various project alternatives producing essentially identical performance levels and benefits to society. As has already been thoroughly discussed as part of this investigation and report, full depth paved shoulders provide many benefits to the agency and traveling public alike that the conventionally designed shoulders do not. To quantify and value the dissimilar life cycle benefits, a benefit cost analysis (BCA) can be used. Similar to a life cycle cost analysis (LCCA), a BCA employs a discount rate that is applied to costs and benefits over the life of the project to determine each alternative's net present value (NPV).

The LCCA, which can be considered a sub-total of the BCA, accounts for the tangible agency costs over the life of a project; for example, materials, construction, and maintenance. The benefit cost portion of the BCA also accounts for the intangible costs to society that might differ among project options, such as user delay, safety concerns, vehicle operating costs, and environmental impacts. Decreased user delay is the greatest identified societal benefit of FDS, as the shoulder can reliably provide additional capacity during construction and emergencies (see Section 7). For this BCA example, the differences in user delay were applied as costs to the conventional shoulder design scenario.

The user delay categories included in the BCA are described in Table 14. These events would theoretically cause less delay for the traveling public if FDS could be used as a temporary travel lane. All user delay costs assumed that FDS would be used as an additional travel lane during planned or unplanned events, while the conventional shoulder would not be used.

Table 14. User Delay Impacts During 50-Year Analysis Period

|  |  |  |  |
| --- | --- | --- | --- |
| **Event** | **Number of Events** | **Duration, *L* (days)** | **Comments** |
| Functional repair | 2 | 2 | FDS used as additional travel lane during maintenance and repair activities. Two travel lanes available versus one. |
| Structural repair | 1 | 10 |
| Maintenance | 2 | 1 |
| Accident w/lane closure | 14 | 0.25 |
| Reconstruction | 1 | 3 | Additional work zone user delay during removal and replacement of existing conventional shoulders. |
| Closure of opposing lanes | 2 | 14 | Opposing travel lanes closed due to unplanned event (e.g., flood, bridge damage, etc.). Three travel lanes available versus two. |
| Emergency evacuation | 1 | N/A | Three travel lanes available in one direction versus two. |

The difference in user delay costs was calculated based on the following relationship:

Equation 3

where: Δ*D* = difference in user delay costs, $

Δ*V* = difference in delay per vehicle, hours

*L* = duration of delay, days

*AADTn* = average annual daily traffic in year *n*

*Pt* = truck traffic percentage = 25.6%

*Pp* = passenger vehicle percentage = 1 - *Pt*

*Ot* = truck occupancy rate = 1.12 [*21*]

*Op* = passenger vehicle occupancy rate = 1.59 [*21*]

*Wt* = truck driver hourly value of time travel savings = $24.08/hour [*22*]

*Wp* = personal hourly value of time travel savings = $16.97/hour [*22*]

The cost of an emergency evacuation was based on the difference in evacuation time using two lanes (conventional shoulder design scenario) and three lanes (FDS scenario). The evacuation time difference was calculated for each scenario as follows:

Equation 4

where: Δ*T* = evacuation time difference, hours

*M* = number of evacuees

*C* = lane capacity = 2,500 people/hour/lane [*23*]

*Nc* = available lanes of traffic, conventional design = 2

*NFDS* = available lanes of traffic, FDS design = 3

To determine the user delay cost, the difference in evacuation time was multiplied by the number of evacuees (*M*) times the personal hourly value of time travel savings (*Wp*). The total cost was then divided by an estimated evacuation route length (*le* = 5 miles in this example) to derive a user delay cost per mile:

Equation 5

The following bullet points summarize the major input values in this BCA example. Additional information is provided in Appendix 4.

* All user delay costs were calculated for a theoretical mile of four-lane divided Interstate highway. One direction (i.e., two travel lanes) of concrete mainline pavement with HMA shoulders was used for analysis. This design was chosen for the BCA because it corresponded with this study's shoulder cost calculation designs (Section 6).
* Input values for traffic volume (*AADTn*) and truck percentage (*Pt*) were based on the design values used in project number 3 listed in Table 3 (I-94 in St. Croix County).
* Vehicle delay (Δ*V*) was based on estimated reductions in speed and travel time. Values for Δ*V* are provided in Appendix 4.
* To approximate a small to medium sized evacuation scenario, the number of evacuees (*M*) used in mass evacuation calculations was 25,000.[[3]](#footnote-3)
* The rehabilitation and maintenance schedule used for the BCA was based on a typical concrete pavement project life with reconstruction after 50 years. [*18*]

The real costs for each of the events described in Table 14 are listed in Table 15 and shown in the time series presented in Figure 13. Discounted costs were calculated again using the WisDOT policy discount rate of five percent and the more widely accepted 3.5 percent. [*18*] The NPV of each scenario was determined by summing the discounted costs, as described in Equation 2.

The real costs, discounted costs, and NPV for each scenario are presented in Table 15. The NPV for the conventional shoulder, FDS composite and FDS concrete design scenarios were approximately $470,500, $428,000 and $345,000 per mile, respectively. With the user delay costs included in this BCA example, FDS was a cost effective design method.

The likelihood of an unplanned event is difficult to estimate, but the user delay costs associated with these events are high, as shown in Table 15. The cost to society of lost time can escalate quickly, especially during an emergency evacuation. The evacuation user delay cost increases with the square of the evacuation size, as shown in Equations 3 and 4; doubling the number of evacuees results in a quadruple real cost difference. It should also be noted that this BCA example did not include the high costs of work zone safety and the risk of loss of life. These factors increase with user delay, which would raise the NPV of the conventional shoulder design.

**30**

**20**

**50**

**10**

**Year 0**

Legend:

Rehab. - functional repair

Reconstruction

Rehab. - structural repair

Accidents

Opposing lane closure

Emergency evacuation

Maintenance

Agency expenditures

Figure 13. Time series of real costs of conventional shoulder design during the 50-year project lifetime.

Table 15. Real and Discounted Costs Included in BCA Example (3.5% Discount Rate)

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Year** | Conventional Design | | FDS Composite Design | | FDS Concrete Design | | **Description** |
| **Real** | **Discounted Cost** | **Real** | **Discounted Cost** | **Real** | **Discounted Cost** |
| **Cost** | **Cost** | **Cost** |
| 0 | $182,912 | $182,912 | $346,428 | $346,428 | $264,993 | $264,993 | Initial Construction |
| 50 |  | $93,808 |  | $81,882 |  | $80,144 | Total NPV of LCCA minus initial construction cost |
| *User Delay Costs - Scheduled Maintenance, Rehabilitation, Reconstruction* | | | | | | | |
| 3 | $2,787 | $2,514 |  |  |  |  | Maintenance |
| 13 | $6,676 | $4,268 |  |  |  |  | Rehab - Functional |
| 19 | $7,336 | $3,816 |  |  |  |  | Rehab - Functional |
| 22 | $2,875 | $1,349 |  |  |  |  | Maintenance |
| 25 | $29,987 | $12,689 |  |  |  |  | Rehab - Structural |
| 28 | $3,123 | $1,192 |  |  |  |  | Maintenance |
| 34 | $3,370 | $1,046 |  |  |  |  | Maintenance |
| 40 | $7,236 | $1,828 |  |  |  |  | Rehab - Functional |
| 43 | $3,742 | $852 |  |  |  |  | Maintenance |
| 50 | $12,092 | $2,165 |  |  |  |  | Reconstruction |
| *User Delay Costs - Unplanned Events* | | | | | | | |
| \* | $63,774 | $27,548 |  |  |  |  | Accidents resulting in lane closure |
| † | $116,809 | $74,789 |  |  |  |  | Closure of opposing lanes |
| 25 ‡ | $141,393 | $59,830 |  |  |  |  | Emergency evacuation of 25,000 people |
|  |  | **$470,606** |  | **$428,310** |  | **$345,137** | **Total discounted cost (NPV)** |

\*One accident every third year. See Appendix 4 for details.

†Two events assumed, occurring in years 5 and 21 (randomly generated).

‡Randomly generated.

10. Study Conclusions

**1. Conventionally designed shoulders do not have adequate structure to withstand temporary traffic loading.**

Several failures have been documented on Wisconsin highways when temporary traffic was routed onto existing shoulders or other thin temporary pavement during a construction project. In several other recent Wisconsin construction projects, existing shoulders have been removed and replaced when they were to be used as temporary travel lanes. In a number of other states, FDS have been constructed with a specific intent to use the shoulders as future temporary travel lanes.

**2. The cost of full depth HMA shoulders next to concrete mainline pavement and the cost of full depth concrete shoulders next to concrete mainline pavement was approximately twice and 1.5 times the cost of conventionally designed shoulders respectively.**

Eight highway reconstruction projects were analyzed in this category. Conventionally designed shoulders cost, on average, $183,000 per mile, while the cost for composite and concrete FDS averaged $346,000 per mile and $265,000 per mile respectively. There was variability in shoulder costs among projects, which was a result of unit bid price variability. However, the nearly twofold increase in cost of composite FDS and the nearly 1.5 time increase in cost of concrete FDS were fairly constant among projects, with a coefficient of variation of 8 percent. The additional FDS costs resulted in a total project cost increase ranging from 1 to 15 percent (Table 4). These were conservative estimates, as it was not possible to include economies of scale savings due to larger material quantities, nor savings due to reduction in number of construction operations.

**3. The cost of full depth HMA shoulders next to HMA mainline pavement was approximately 1.5 times the cost of conventionally designed shoulders.**

Two highway reconstruction projects were analyzed in this category. The average cost for conventionally designed shoulders and HMA FDS was $123,000 and $172,000 per mile, respectively. These figures were somewhat lower than the cost for HMA shoulders next to concrete mainline pavement because the two HMA mainline projects analyzed were lower volume highways with thinner pavement sections. The total project cost increase with FDS ranged from 3 to 4 percent. These estimates were also conservative, as increased material requirements and construction operation reductions would likely result in cost savings.

**4. If FDS became an established design practice, funds used for temporary travel lane construction could instead be used for FDS construction.**

Temporary shoulder widening costs were analyzed for two projects where four or more lanes of traffic were maintained during reconstruction. Construction staging involved removal of existing shoulders because they could not support temporary traffic loads. If the existing shoulders were FDS, there would have been adequate structure for temporary traffic, and the existing shoulders could have been left in place. The theoretical reductions in temporary construction costs for the two projects were $178,000 and $272,000 per mile; these figures were on par with the initial construction costs calculated for FDS. If use of FDS became an established practice, these funds could be shifted from construction of temporary pavement to construction of FDS.

**5. FDS construction is cost effective over the life of a concrete mainline pavement with HMA shoulders.**

If FDS were used as additional temporary travel lanes, the traveling public would experience less user delay during planned and unplanned highway lane closures. When costs associated with these user delays were included in a benefit-cost analysis over the pavement lifetime, the net present value for FDS was lower than for conventionally designed shoulders. This was shown to be the case for an theoretical four-lane divided Interstate highway.

**6. The base layer is uniform with FDS, resulting in better performance and lower cost.**

Previous research has shown that a uniform base layer between mainline pavement and the shoulders has several performance benefits, such as reduced differential settlement and enhanced drainage. [*2*] In addition, the base layer can be graded in one operation, eliminating a step in the construction process. This results in time and cost savings. The magnitude of these savings is dependent on individual project characteristics.

**7. FDS would provide a reliable travel lane for emergency traffic needs.**

Inadequate traffic capacity has been cited as one of the major impediments to fast, safe mass evacuations. [*3*] Use of the shoulder as an additional travel lane could ease the congestion during an evacuation. Current Wisconsin Interstate shoulder geometry would allow for the use of the 10-foot outside shoulder as a temporary travel lane during a mass evacuation. With FDS, traffic could reliably use the shoulder without concern for early pavement failure.

11. Recommendations

Shoulders on Wisconsin highways are currently designed to have "adequate strength and stability to support occasional vehicle traffic loads." [*7*] However, there are potential applications for more continuous traffic loading on shoulders, most notably during highway construction projects. It is therefore recommended that longer term use of the shoulder be taken into consideration during design of the shoulders. Conventionally designed shoulders have failed when used as temporary travel lanes during several recent Wisconsin highway construction projects. A mechanistic evaluation of FDS and conventionally designed shoulders may be beneficial as an analytical confirmation of this observation.

It is recommended that FDS be constructed for select Interstate and other high volume principal arterial highways. For these roadways, it is likely that future construction staging will require multiple travel lanes in each direction. It is also important to maintain adequate capacity on these highways during unplanned events such as accidents or evacuations. FDS can be utilized in all of these scenarios. Although FDS construction has a greater initial cost, the added benefit of decreased user delay costs over the project lifetime makes FDS a cost effective option.

It is assumed that the segments of highway selected for application would be composed primarily of concrete mainline pavements. Given the cost data produced for this investigation, it is recommended that full depth concrete shoulders be constructed.

Conservative cost estimates prepared as part of this investigation yielded an average cost difference to include full depth concrete shoulders in place of conventional composite/HMA shoulders of $164,000 per mile. When the cost estimates were prepared to replace conventional concrete shoulders with full depth concrete there was actually a cost savings of approximately $41,500 per mile. This cost savings would be realized through the reduction in the number of individual construction operations occurring on that project.

Construction of FDS is not recommended for lower-volume highways where use of the shoulders as temporary travel lanes is not typically required. The maximum benefit of FDS would not be utilized on these roads.

Use of existing and future FDS should be incorporated into mass evacuation planning. If FDS exist on an evacuation route, the outside shoulder can be used for additional capacity to improve traffic flow. It is recommended that construction of FDS be considered along mass evacuation routes as an option for a reliable additional travel lane during an emergency.

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Appendix 1 - State Shoulder Design Practices

|  |  |  |
| --- | --- | --- |
| **State** | **Paved Width** | **Structure** |
| Alabama | Full width | 3 to 5 inch HMA plus HMA surface |
| Arizona | Full width | Equal to mainline thickness |
| California | Full width | Minimum design - First 2 feet of shoulder matches mainline thickness, remainder designed for 2 percent of adjacent lane traffic. Full depth is encouraged. |
| Colorado | Full width | Typically equal to mainline thickness |
| Connecticut | Full width | 3 inch HMA minimum. Equal to mainline thickness if shoulder to be used for traffic in the future. |
| Florida | 5 feet (rural pavements) | 1 inch HMA over 4 inch limerock. High truck traffic: option of designing for 3 percent of mainline traffic. |
| Georgia | 12 feet (Interstates) | Interstates: Equal to mainline thickness |
| Idaho | Full width | Equal to mainline thickness |
| Illinois |  | HMA - 6 inch. Concrete - Trapezoidal section: 6 inch at outside edge, tapering to mainline thickness at edge of pavement. |
| Indiana |  | Same thickness as mainline for roadways with > 30 million ESALs |
| Iowa | 4 feet paved if current AADT > 3,000 | 6 inch HMA over 6 inch rock base |
| Louisiana |  | 2 inch HMA over stone over soil cement |
| Michigan | Full width | 3.5 inch HMA minimum |
| Minnesota | 10 feet | 3 to 4 inch HMA |
| Missouri | Full width | 5.75 inch typical. Equal to mainline thickness if shoulder is expected to be used for traffic in the future. |
| Nebraska | 8 feet | 6 inch HMA or concrete |
| Nevada | Full width | Equal to mainline thickness |
| New Hampshire | Full width | 3.5 inch HMA. If select materials used as foundation for mainline, they are extended under shoulders. |
| New Jersey |  | Equal to mainline thickness |
| New York | Full width | Most cases: equal to mainline thickness. Some HMA pavements with lower traffic have partial depth shoulders. |

Appendix 1, continued

|  |  |  |
| --- | --- | --- |
| **State** | **Paved Width** | **Structure** |
| Ohio | Reference standards | Equal to mainline thickness |
| South Carolina | Interstates - full width | Designed to carry 5 percent of critical lane traffic. |
| Tennessee | N/A |  |
| Virginia | Full width | Interstates: Equal to mainline thickness. This is also recommended for other high volume roadways that are likely to be widened. Otherwise, designed for 2.5 percent of mainline ESALs. |
| Washington | Full width | Urban: Equal to mainline thickness Rural: 0.35 feet (~4 inch) |
| West Virginia | Full width | 4 inch minimum. Equal to mainline thickness: All urban arterials; or if ADT > 6,000 and trucks > 15 percent; or if ADT > 15,000 |

Appendix 2 - As-Designed Shoulder Details

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Project** | **Highway** | **County** | **Mainline Thickness (in)** | **As-Designed Shoulder Thickness (in)** | **Left Paved Shoulder Width (ft)** | **Right Paved Shoulder Width (ft)** |
| 1 | USH 10 | Portage | 10 | 3.5 | 4 | 8 |
| 2 | USH 53 | Douglas | 9 | 4 | 3 | 6 |
| 3 | I-94 | St. Croix | 13 | 6/4\* | 4 | 10 |
| 4 | I-94 | Eau Claire & Trempealeau | 12 | 4† | 4 | 8 |
| 5 | USH 151 | Dodge | 10 | 3.5 | 4 | 8 |
| 6 | USH 12 | Sauk | 10 | 3.5 | 4 | 8 |
| 7 | STH 26 | Rock | 9.5 | 3.5 | 4 | 8 |
| 8 | STH 26 | Jefferson & Dodge | 8.5 | 3.5 | 4 | 8 |
| 9 | STH 22 | Oconto | 6.5 | 4 | 5 | 5 |
| 10 | STH 13 | Adams | 5.75/6.5 | 4 | 10/8 | 10/8 |

\* Westbound = 4 in, Eastbound = 6 in

†Some portions: 6 in shoulders

Appendix 3 - Material and Unit Bid Cost Information

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  | *Asphaltic Material* | | | *HMA Mixture* | | *Base Aggregate Dense (BAD)* | | *Tack Material* |
| **Project** | **Highway** | **County** | **Content (%)** | **Grade** | **Unit Cost ($/ton)** | **Type** | **Unit Cost ($/ton)** | **Size (in)** | **Unit Cost ($/ton)** | **Unit Cost ($/gal)** |
| 1 | USH 10 | Portage | 5.5 | PG58-28 | $555 | E-0.3 | $40.76 | 1 ¼ | $7.20 | $5.29 |
| 2 | USH 53 | Douglas | 6.0 | PG58-28 | $100 | E-0.3 | $66.76 | 1 ¼ | $7.98 | $6.49 |
| 3 | I-94 | St. Croix *EB* | 5.5 | PG58-34\* | $700\* | E-10 | $40.50 | 1 ¼ | $11.34 | $6.25 |
|  |  | *WB* | 5.5 | PG58-34 | $700 | E-0.3 | $46.45 | 1 ¼ | $11.34 | $6.25 |
| 4 | I-94 | Eau Claire & Tremp. | 6.0 | PG58-28 | $100 | E-0.3 | $61.03 | ¾ | $9.93 | $5.86 |
| 5 | USH 151 | Dodge | 5.5 | PG58-28 | $630 | E-0.3 | $27.65 | 1 ¼ | $8.15 | $3.00 |
| 6 | USH 12 | Sauk | 5.5 | PG58-28 | $100 | E-0.3 | $44.86 | 1 ¼ | $11.75 | $2.64 |
| 7 | STH 26 | Rock | 5.5 | PG58-28 | $100 | E-0.3 | $47.53 | 1 ¼ | $8.24 | $1.98 |
| 8 | STH 26 | Jefferson & Dodge | 5.5 | PG58-28 | $100 | E-0.3 | $50.10 | 1 ¼ | $6.52 | $1.45 |
| 9 | STH 22 | Oconto | 6.0 | PG58-28 | $100 | E-3 | $45.70 | 1 ¼ | $7.20 | $2.90 |
| 10 | STH 13 | Adams | 5.5 | PG58-28 | $100 | E-3 | $47.83 | 1 ¼ | $10.91 | $2.88 |

\*Top layer PG64-22 at $613/ton

Appendix 4 - Benefit-Cost Analysis Information

Constants:

*AADT0* = 24,300 AADT in year 0, one direction

510 AADT growth per year, one direction

*Pt* = 25.6% truck traffic percentage

*Ot* = 1.12 truck occupancy rate [*21*]

*Op* = 1.59 passenger vehicle occupancy rate [*21*]

*Wt* = $24.08/hr truck driver hourly value of time travel savings, adjusted to 2012 dollars [*22*]

*Wp* = $16.97/hr personal hourly value of time travel savings, adjusted to 2012 dollars [*22*]

*C* = 2,500 ppl/hr mass evacuation lane capacity [*23*]

Accident rate information and assumptions:

Fact Source

743 Wisconsin Interstate miles WisDOT Research and Library

http://www.dot.wisconsin.gov/library/history/50/glance.htm

551 Rural Interstate miles; 74.2% rural FHWA, U.S. DOT

<http://www.fhwa.dot.gov/policy/2008cpr/es.htm>

4218 Average annual Interstate accidents WisDOT Dept. of Motor Vehicles

http://www.dot.wisconsin.gov/drivers/drivers/traffic

/crash/final.htm

7.7 Annual rural accidents per mile

If 5% of these accidents cause an inside lane closure, then this type of accident occurs approximately once every third year, for a total of 14 events over the 50-year project life.

BCA Costs for Conventional Shoulder Design

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Scheduled Maintenance/Rehab/Reconstruction | | | | | |  |  |
| **Year** | **Speed differential (mph)** | **Delay per vehicle, Δ*V* (hr)** | **AADT** | **Length of delay, *L* (days)** | **Real cost** | **Discounted Cost** | **Type** |
| 3 | 55 to 45 | 0.004 | 25830 | 1 | $2,787 | $2,514 | Maintenance |
| 13 | 55 to 45 | 0.004 | 30930 | 2 | $6,676 | $4,268 | Rehab - Functional repair |
| 19 | 55 to 45 | 0.004 | 33990 | 2 | $7,336 | $3,816 | Rehab - Functional repair |
| 22 | 55 to 45 | 0.003 | 35520 | 1 | $2,875 | $1,349 | Maintenance |
| 25 | 55 to 45 | 0.003 | 37050 | 10 | $29,987 | $12,689 | Rehab - Structural repair |
| 28 | 60 to 50 | 0.003 | 38580 | 1 | $3,123 | $1,192 | Maintenance |
| 34 | 60 to 50 | 0.003 | 41640 | 1 | $3,370 | $1,046 | Maintenance |
| 40 | 60 to 50 | 0.003 | 44700 | 2 | $7,236 | $1,828 | Rehab - Functional repair |
| 43 | 65 to 55 | 0.003 | 46230 | 1 | $3,742 | $852 | Maintenance |
| 50 | 65 to 55 | 0.003 | 49800 | 3 | $12,092 | $2,165 | Reconstruction |
| Unplanned Events | | |  |  |  |  |  |
| **Year** | **Speed differential (mph)** | **Delay per vehicle, Δ*V* (hr)** | **AADT** | **Length of delay, *L* (days)** | **Real cost** | **Discounted Cost** | **Type** |
| 1 | 40 to 25 | 0.015 | 24,810 | 0.25 | $2,510 | $2,425 | Accident - lane closure |
| 4 | 40 to 25 | 0.015 | 26,340 | 0.25 | $2,665 | $2,322 | Accident - lane closure |
| 7 | 40 to 25 | 0.015 | 27,870 | 0.25 | $2,820 | $2,216 | Accident - lane closure |
| 10 | 40 to 25 | 0.015 | 29,400 | 0.25 | $2,974 | $2,109 | Accident - lane closure |
| 13 | 40 to 25 | 0.015 | 30,930 | 0.25 | $3,129 | $2,001 | Accident - lane closure |
| 16 | 40 to 25 | 0.015 | 32,460 | 0.25 | $3,284 | $1,894 | Accident - lane closure |
| 19 | 40 to 25 | 0.015 | 33,990 | 0.25 | $3,439 | $1,789 | Accident - lane closure |
| 22 | 40 to 25 | 0.015 | 35,520 | 0.25 | $3,594 | $1,686 | Accident - lane closure |
| 25 | 40 to 25 | 0.015 | 37,050 | 0.25 | $3,748 | $1,586 | Accident - lane closure |
| 28 | 40 to 25 | 0.015 | 38,580 | 0.25 | $3,903 | $1,490 | Accident - lane closure |
| 31 | 40 to 25 | 0.015 | 40,110 | 0.25 | $4,058 | $1,397 | Accident - lane closure |
| 34 | 40 to 25 | 0.015 | 41,640 | 0.25 | $4,213 | $1,308 | Accident - lane closure |
| 37 | 40 to 25 | 0.015 | 43,170 | 0.25 | $4,368 | $1,223 | Accident - lane closure |
| 40 | 40 to 25 | 0.015 | 44,700 | 0.25 | $4,522 | $1,142 | Accident - lane closure |
| 43 | 40 to 25 | 0.015 | 46,230 | 0.25 | $4,677 | $1,065 | Accident - lane closure |
| 46 | 40 to 25 | 0.015 | 47,760 | 0.25 | $4,832 | $993 | Accident - lane closure |
| 50 | 40 to 25 | 0.015 | 49,800 | 0.25 | $5,038 | $902 | Accident - lane closure |
| 5\* | 50 to 40 | 0.005 | 26,850 | 14 | $50,700 | $39,725 | Opposing lane closure |
| 21\* | 50 to 40 | 0.005 | 35,010 | 14 | $66,109 | $23,729 | Opposing lane closure |
| Emergency Evacuation | | |  |  |  |  |  |
| **Year** |  | **Evacuation time - 2 lanes (hr)** | **Evacuation time - 3 lanes (hr)** | **Delay difference (hr)** | **Real cost** | **Discounted Cost** |  |
| 25\* |  | 5 | 3.33 | 1.67 | $141,393 | $41,754 |  |

\*Randomly generated year

1. Construction ID: 1120-09-83; Contract ID: 20100511033. [↑](#footnote-ref-1)
2. Construction ID: 1066-02-72; Contract ID: 20090623001. [↑](#footnote-ref-2)
3. For reference, this value is 4.4 percent of the Madison metropolitan population, 16 percent of the Eau Claire metropolitan population, and two-thirds the average attendance of a Milwaukee Brewers baseball game. [*24, 25*] [↑](#footnote-ref-3)