Implementation of 3D Technology and Development of AMG Specifications for Placement of HMA Base Course Material

Final Report

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1. Background

During 2009, the Wisconsin Department of Transportation (WisDOT) developed and distributed an implementation plan for "3D Technologies in Design and Construction". The plan has a two-year horizon and includes five initiatives. During 2011, the Construction and Materials Support Center (CMSC) at UW-Madison was asked to assist WisDOT with determining the status of each initiative. A survey and interviews of initiative leads were conducted, with results summarized in a mid-year report (see Appendix A).

CMSC also assisted WisDOT on two of the most closely coupled initiatives (3D Design Process and Automated Machine Guidance (AMG)). During 2010, a specification for AMG and fine grading of hot mix asphalt (HMA) base course had been prepared. The AMG HMA specification was based upon an earlier AMG sub-grade specification and included modifications to the data development and exchange component and to the final field checking for acceptance component (see Appendix B). The HMA AMG specification was included as a special provision in four selected pilot projects along the USH10 expansion in the North Central Region between Stevens Point and Marshfield, WI. AMG roadway models were included in the let packages for the projects, so potential contractors had pre-bid access to the data. General objectives of the pilot projects were to determine 1) the "construction-readiness" of the data flowing from design and 2) the viability of the final field check component of the specification.

Information on pre-bid use of the AMG roadway models was obtained by personal and telephone interview of contractors, including all who requested let packages. Information on post-award and construction use of the data by contractors, sub-contractors, and project engineers was obtained by site visits, personal interviews, and telephone interviews. AMG HMA base course fine-grading was observed during site visits and check data were obtained later by request.

CMSC also gave presentations in two venues on WisDOT's 3D technologies implementation efforts: 1) 2011 TRB annual meeting and 2) summer meeting of TRB Committee AFB80 Spatial Data Acquisition Technologies for Design and Construction.

2. Pre-Bid AMG Roadway Model Content and Format

2.1. Components and Format

Let packages for the four pilot projects contained reference line and profile information in LandXML format as well as the following TIN Civil 3D surfaces in AUTOCAD 2010 DWG format:

1. Existing Ground (see Figure 1). This is the pre-design existing ground surface obtained by photogrammetric and ground survey.

2. Proposed Top (see Figure 2). This is 1) the top of topsoil outside the roadway sub-grade shoulder points, extended to the slope intercepts and 2) the top of shoulder and top of pavement within the roadway sub-grade shoulder points.

3. Proposed Datum (see Figure 3). This is 1) the top of topsoil outside the roadway sub-grade shoulder points, extended to the slope intercepts and 2) the sub-grade surface within the roadway sub-grade shoulder points.
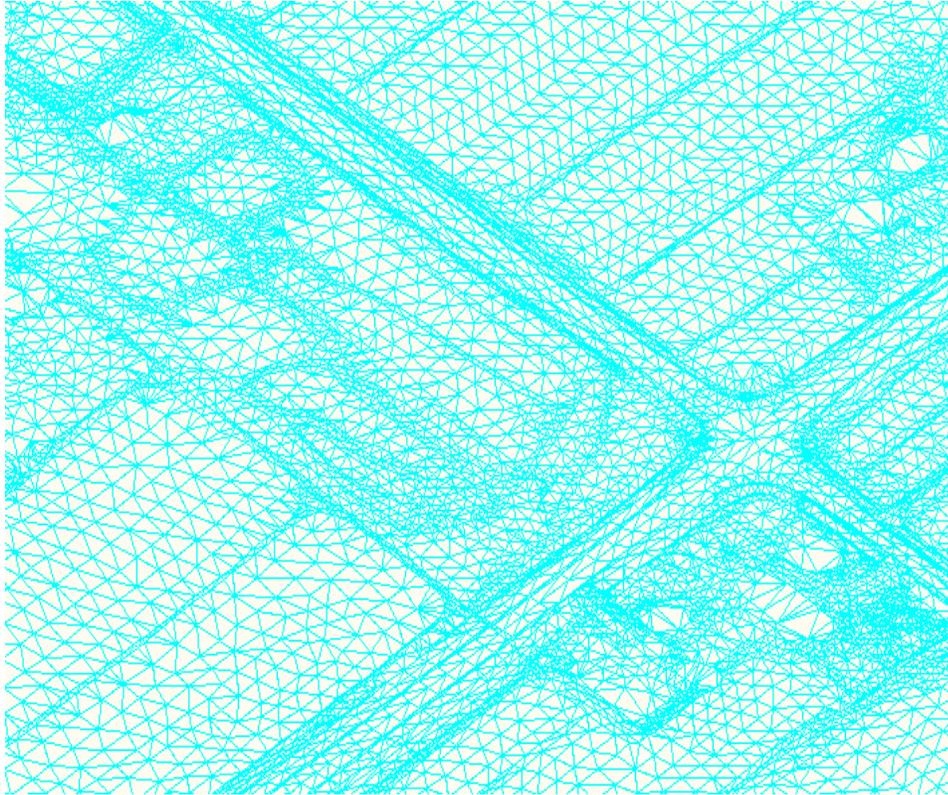

Figure 1.
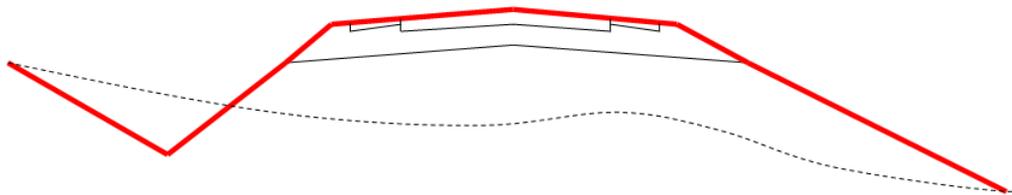An Example of Existing Ground Surface Representation

Figure 2.
Components and Extent of Proposed Top Surface
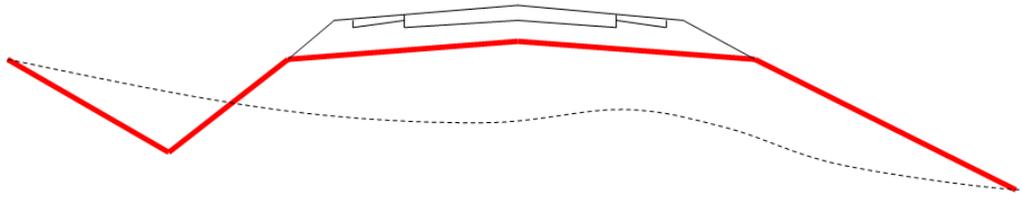
Figure 3.
Components and Extent of Proposed Datum Surface

4. Proposed Base Course (see Figure 4). This is the top of base course within the roadway edges of traveled way.
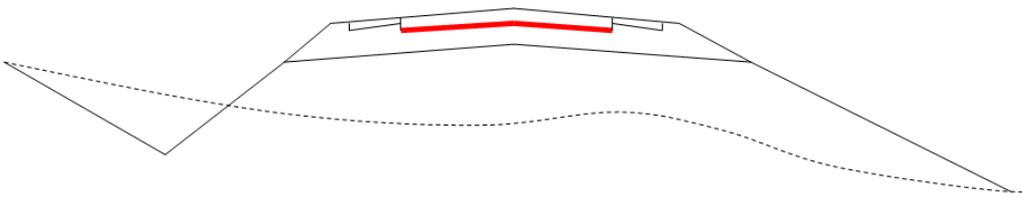
Figure 4.
Components and Extent of Proposed Base Course Surface

2.2. Interim Standard for Data Density (Sub Grade and Base Surfaces)

Notes:

1. The conceptual model for computing data density requirements, presented in Section 2.2, was developed by Brad Hollister (Methods Development Unit, WisDOT). Mr. Hollister also developed data density values for the pilot projects using a graphical measurement method and Civil 3D. He also developed the language in Appendix E.

2. The mathematics, presented in Section 2.2 and Appendices C and D, were developed later by the author.

2.2.1. Smooth Curves and Surfaces Versus Line Segments and TINs

In highway design, horizontal curves are arcs of circles and vertical curves are arcs of parabolas. Such parametrically-described objects cannot be perfectly represented in TINs because a TIN is a set of contiguous triangular facets. The triangles are formed automatically from input 3D breaklines and individual 3D data points. Breaklines consist of line segments connecting consecutively-designated 3D data points. Along curves, the line segments are sub-chords of the arc. In a TIN, each data point is a vertex of one or more triangles and each line segment in a breakline is constrained to be an edge of one or two triangles. No mathematically smooth curves or surfaces, other than straight lines and triangles, exist in a TIN (see Figure 5).

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Parametrically-Described Curve

Representation in a TIN
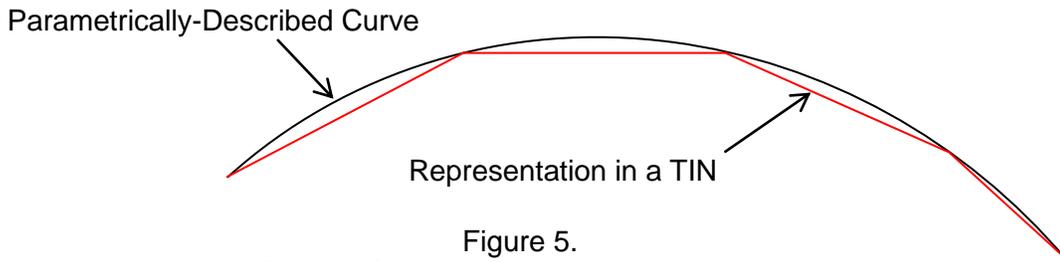
Figure 5.
A Smooth Curve and Its Representation in a TIN

Clearly, curves are represented more accurately by breaklines with shorter line segments. On the other hand, shorter line segments lead to more data to develop, manage, and analyze; larger files; and greater compute times. An optimum line segment length is found by addressing the question, "What is the greatest line segment length such that the maximum introduced error in representation of the curve does not exceed a pre-determined tolerance?" Here, we define the introduced error at any point on a line segment as the distance between the line segment and the curve, measured along the perpendicular to the line segment at that point. In Figure 6, the curve passes through the data point at each end of the line segment. The line segment is parallel with the x axis. For horizontal curves,

$$f(x,y) = (x - x_0)^2 + (y - y_0)^2 - r^2 = 0 \qquad (1)$$

and the error is maximum at the midpoint of the line segment. For crest vertical curves,

$$f(x,y) = ax^2 + bx + c - y = 0 \qquad (2)$$

and the error is maximum at the apex of the curve. In each case, the maximum allowable length (d_{max}) of the line segment can be computed from the parameters of the curve and a specified tolerance for e_{max}. Appendices C and D contain the derivations for horizontal curves and equal-tangent crest vertical curves, respectively.

Figure 6.
Curve, Line Segment with Length d, Error at Point p, and Maximum Error (e_{max})

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2.2.2. Tolerances

For the pilot projects, values for e_{max} were based upon the horizontal and vertical tolerances for sub grade and base staking as they appear in WisDOT's Standard Specifications. These are, respectively,

$$t_h = 0.25ft \; ; \; t_v = 0.03ft \tag{3}$$
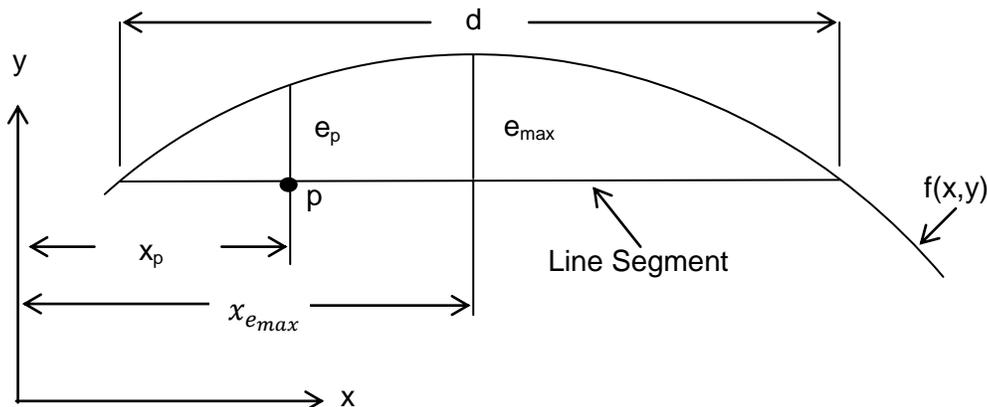
In the Standard Specifications, these tolerances are identical for both sub grade and base staking. By using these tolerances, the maximum error, on horizontal and vertical curves, in any AMG roadway model surface representation will be no larger than the allowable errors in staking used to check construction for acceptability.

2.2.3. Data Density on Horizontal Curves

The maximum line segment length for any horizontal curve is

$$d_{h_{max}} = 2\sqrt{t_h(2R - t_h)} = \sqrt{2R - 0.25} \tag{4}$$

where R is the radius of the curve (see Appendix C for derivation). Exhibit 5.1 in WisDOT's Facilities Development Manual (FDM) presents tables of minimum radius for various design speeds and superelevations of 4% and 6%. Greater superelevation yields shorter minimum radius. Columns 1 and 2 in Table 1 repeat the FDM values for design speed and minimum radius for 6% superelevation. Column 3 in Table 1 contains corresponding values for maximum line segment length, computed with equation 4.

It was decided to aggregate design speed into groups that could be supported by 10ft, 25ft, and 50ft line segment lengths so that data points would be included at full and half stations. Table 2 presents the aggregated results used as a component of the interim standard.

2.2.4. Data Density on Equal-Tangent Crest Vertical Curves

According to Attachment 5.4 of the FDM, the minimum length (and, thus, maximum curvature) of a crest vertical curve on a category 1 roadway is controlled by the stopping sight distance to a 24-inch object. The maximum line segment length for such a vertical curve is

$$d_{v_{max}} = \frac{S_{24-inch}\sqrt{t_v}}{1.642} = (0.1055)S_{24-inch} \tag{5}$$

where $S_{24\text{-inch}}$ is the stopping sight distance to a 24-inch object (see Appendix D for derivation). A table in Attachment 5.1 of the FDM relates stopping sight distance to design speed. Columns 1 and 2 in Table 3 repeat the FDM values. Column 3 in Table 3 contains corresponding values for maximum line segment length, computed with equation 5. Table 4 presents the results, aggregated as in Table 2, and used as a component of the interim standard.

Table 1.
Design Speed*, Minimum Radius*, and Maximum Line Segment Length for Horizontal Curves

Design Speed (mph)	Minimum Radius (ft)	$d_{h_{max}}$(ft)
25	144	17.0
30	231	21.5
35	340	26.1
40	485	31.1
45	643	35.9
50	833	40.8
55	1060	46.0
60	1330	51.9
65	1660	57.6
70	2040	63.9

*Exhibit 5.1 FDM for 6% superelevation

Table 2.
Interim Standard for Line Segment Length on Horizontal Curves

Design Speed Range (mph)	Line Segment Length (ft)
<= 30	10
35 - 55	25
>= 60	50

Table 3.
Design Speed*, Minimum Stopping Sight Distance*, and Maximum Line Segment Length for Equal Tangent Crest Vertical Curves

Design Speed (mph)	Minimum Stopping Sight Distance (ft)	$d_{v_{max}}$(ft)
25	155	16.3
30	200	21.1
35	250	26.4
40	305	32.2
45	360	38.0
50	425	44.8
55	495	52.2
60	570	60.1
65	645	68.0
70	730	77.0

*Attachment 5.1 FDM for category 1 roadways

Table 4.
Interim Standard for Line Segment Length on Equal-Tangent Crest Vertical Curves on Category 1 Roadways

Design Speed Range (mph)	Line Segment Length (ft)
<= 30	10
35 - 50	25
>= 55	50

2.2.5. Additional Components of the Interim Standard for Data Density

The interim standard also addresses horizontal geometry points, superelevation transition points, profile geometry points, profile high/low points, other points of interest, and intersection regions. See Appendix E for a complete and concise statement of the interim standard.

3. Pilot Projects

The four pilot projects are briefly described here, from west to east along USH 10.

NOTES:
1. Select crushed material was required below the base course on all four pilot projects due to soil moisture conditions.
2. All four pilot projects were designed by WisDOT engineers.

3.1. Pilot 1

Project ID: 6350-06-76.
Primary Contractor: Hoffman Construction.
Concrete Base Course Sub-Contractor: Michaels Materials.
HMA Base Course Sub-Contractor: Michaels Materials.
Project Engineer: Scott Hintz (Gremmer and Associates).

This 3-stage project on USH 10 includes 3.7 miles of divided concrete highway, 2000 feet of HMA pavement on side roads and frontage roads, and two structures. The project runs from Stadt Road to White Oak Road in Wood County. Figure 7 depicts HMA base course fine grading operations and finished base course.

a) Grader and Roller on Last Pass.   b) Finished Base Course.

Figure 7.
HMA Base Course on Pilot Project #1.

3.2. Pilot 2

Project ID: 6350-06-71.
Primary Contractor: Mashuda Contractors.
Concrete Base Course Sub-Contractor: Duffek Sand and Gravel.
HMA Base Course Sub-Contractor: Duffek Sand and Gravel.

Project Engineer: Mike Bohn (WisDOT).

This project on USH 10 includes 6000 feet of divided concrete highway bridge approaches, two structures, and a small amount of HMA pavement on two cul-de-sacs. The project runs from Brookside Road to Blenker Road in Wood County.

The WisDOT project engineer was assisted by the WisDOT design engineer who designed the project. Civil 3D was running on a computer at the project field headquarters and was used for visualization and analysis (e.g., extracting cross sections). Figure 8 depicts the datum surface for Pilot 2 as originally provided by WisDOT.
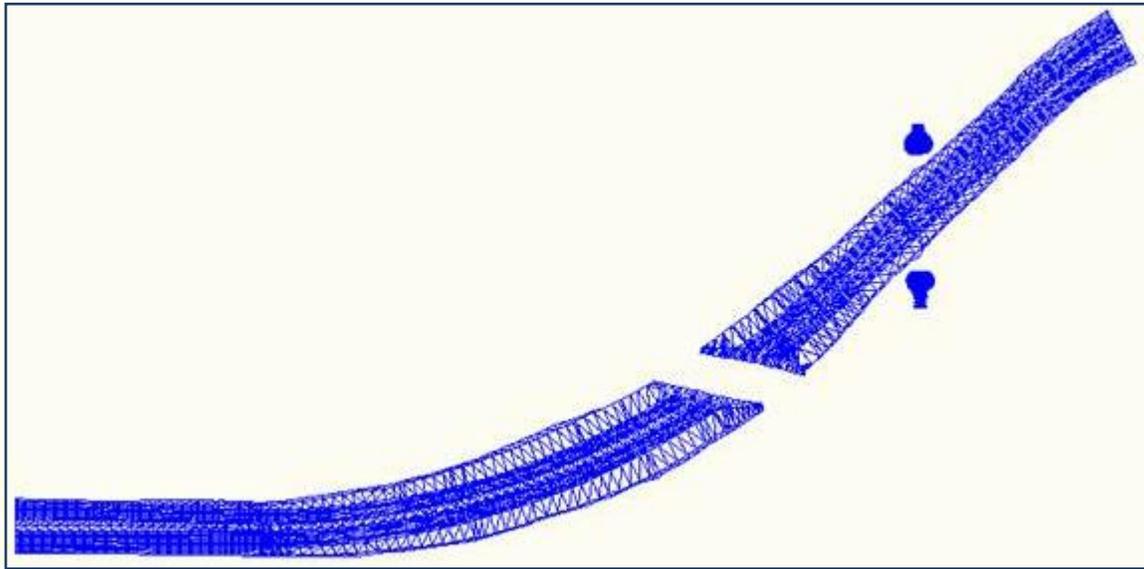
Figure 8.
Datum Surface for Pilot Project #2.

3.3. Pilot 3

Project ID: 6350-06-80.
Primary Contractor: Mashuda Contractors.
Concrete Base Course Sub-Contractor: Duffek Sand and Gravel.
HMA Base Course Sub-Contractor: Duffek Sand and Gravel.
Project Engineer: Blake Elsinger (Quest).

This project on USH 10 includes 4.1 miles of divided concrete highway, one structure, and 1.75 miles of HMA pavement on county and town roads. The project runs from Blenker Road to Trestik Road in Wood County.

3.4. Pilot 4

Project ID: 6350-06-78.
Primary Contractor: Mashuda Contractors.
Concrete Base Course Sub-Contractor: None.
HMA Base Course Sub-Contractor: None.

Project Engineer: Steve Zblewski (AECOM).

This project on USH 10 includes 5.4 miles of divided concrete highway, three structures, and 1.75 miles of HMA pavement on county and town roads. The project runs from White Oak Road to Brookside Road in Wood County.

4. Findings

In addition to the primary contractors and sub-contractors identified above, the following contractors requested the AMG roadway models pre-bid:

- Earth, Inc.
- Edgerton Contractors.
- Integrity Grading.
- Relyco Contractors.

No contractors requesting the AMG roadway models failed to submit a bid or quote.

The AMG roadway models were also requested by a vendor of AMG technology. The vendor was curious about model content and was readily able to import the models into their software.

4.1. Pre-Bid Use of AMG Roadway Models

The contractors were all able to import the WisDOT-provided roadway models into their software. Incompatibility between data formats and various software packages appears to be diminishing as an issue, although in some instances TIN facets had to be imported as such and the topology of the surfaces needed to be re-constructed by the contractors' software.

One contractor did not use the data at all during bid preparation because the traditional plans were available earlier and they had used them to prepare their bid. This bid was unsuccessful, but it is not clear that lack of use of the AMG roadway models in bid preparation had anything to do with this.

Some contractors stated that costs of bid preparation are diminished by having the AMG roadway models available, but not significantly enough to make a tangible difference in the overall bid, especially on large projects. However, contractor personnel who are active in bid preparation are, quite often, also those with technical expertise in AMG roadway model building. This means that having the models available pre-bid from WisDOT frees those specialists to devote more time to preparation of multiple bids which should result in greater competition and more bids being submitted to WisDOT. No bid-submitters indicated that having the AMG roadway models pre-bid influenced their decision whether or not to bid. All bidders would have submitted in any case.

Contractors reported that the AMG roadway models convey design intent much better than traditional two-dimensional plans, through comprehensive visualization of project extent and details. This is especially true at transitions and intersections. An immediate benefit is reduction of uncertainty and risk-taking in bidding.

With traditional technologies and methods, cost-reduction incentives are typically identified post-award and even on-the-fly during construction. Having AMG roadway models pre-bid allows for early and more effective identification of cost-reduction incentives.

According to the special provision, the contractor must check AMG roadway models for conformance with the plans. Contractors also checked them for constructability (e.g., errors at locations not shown on the plans). These inspections and checking were enhanced by the visualization facilitated by the AMG roadway models and 3D software. Since the plans were derived from the models, very few discrepancies between the plans and models were encountered. Some minor discontinuities and issues with vertical faces that affected constructability were detected by the contractors and corrected by WisDOT.

One of the contractors used the AMG roadway models for pre-bid take-off verification (i.e., earthwork volumes), but most of them did not compute cut and fill with the models.

A number of contractors made extensive use of the existing ground surface representation. This surface, extending up to 900 feet beyond the right-of-way, facilitates a useful understanding of project surrounds and, thus, leads to much earlier and efficient project planning. For example, potential off-right-of-way turnarounds for construction equipment can be identified, as can potential sites for borrow and waste. In addition, since the existing ground is represented as a surface, preliminary volumes can be computed for potential borrow and waste sites. This eliminates the need for contractors to make preliminary site surveys.

From a design perspective, it is clear that an adjustment in the way engineers think about design products is important. AMG roadway models are design output, and are just as critical as plans. AMG roadway model surfaces should begin being developed during the initial stages of corridor design and then evolve throughout the iterative processes of design.

4.2. Post-Award and Construction Use of AMG Roadway Models

Linear features, that typically coincide with breaklines in surfaces, are critical to construction operations (e.g., steering of equipment, spatial orientation of field personnel). Examples of such features edge-of-pavement, shoulder breaks, and ditch flow lines. Although these features are imbedded in model surfaces, they cannot be separately color-coded or annotated, unless they are modeled as distinct objects. Contractors requested these features from WisDOT at early stages in the projects. Although WisDOT was able to provide this information, it was not without considerable effort because designation of these surface features as separate objects was not part of the initial design workflow. As a note on terminology, it is important to refer to these linear features as such and not as breaklines. They coincide with breaklines, but their utility in the field is for construction operations, not for building models. Moreover, there are breaklines in the AMG roadway models, specifically in the existing ground surface, that are not needed as linear features for construction. It is important to develop consistency in terminology to avoid confusion in the future.

As mentioned, the pilot projects included select crushed material below the base course gravel. WisDOT was able to provide a surface representation for the top of select

crushed material. As an alternative, equipment operators can input offsets from the base course surface or even from the final top surface, but having the select crushed material surface on board the machines reduces the risk of human error.

Design-speed criteria had been developed by WisDOT to control data density in the AMG roadway models. Data density along straightaways was lower than data density along curves and at intersections. This approach worked well and data density was, in general, appropriate for constructability. If data density is a concern, it is advisable to err on the side of too much data rather than on the side of too little. Data that are too sparse might lead to problems during construction that far offset the cost of additional data development during design.

The utility of AMG roadway modeling for staged construction is inconclusive. Some regard models for each stage (e.g., including switch-overs) as useful, for example, because of the need for staged earthwork quantities. Others indicated that the final constructed roadway model was all that was need for staged projects and that management of multiple surfaces might lead to confusion.

4.3. AMG HMA Base Course Final Checks

AMG was used for HMA base course on only one of the pilot projects. It was not used on the two projects having the most HMA paving. This is because, on one of those projects, the start date was delayed and HMA paving will not take place until the 2012 construction season. On the other, the contractor moved their AMG equipment to another project prior to HMA base course placement and the base course was placed and checked conventionally.

HMA base course check results for Pilot 1 appear in Table 5. All checks met the specified maximum tolerance of 0.10 feet and, also in conformance with specification, there are no instances of two or more checks in any consecutive five exceeding 0.06 feet. These results are promising, but the sample is far too small to lead to supportable conclusions concerning performance of the specification.

Table 5.
HMA Base Course Checks on Pilot #1 (<1000 Feet of Frontage Road)

Station	Left	Center	Right
152+50	16'lt (-.03)	0' (-.04)	16'rt (-.02)
158+00	16'lt (+.02)	0' (+.05)	16'rt (+.04)
12+50	12'lt (-.06)	0' (-.03)	12'rt (-.03)
16+00	12'lt (+.01)	0' (+.03)	12'rt (+.04)

4.4. Corridor Geodetic Control, Project Site Calibration, and Utility of WisCORS

The North Central Region established a consistent geodetic control framework for the USH10 corridor and provided the control point coordinates and descriptions to the contractors. Two or three of these control points were known to have weak geometries and these were pointed out to contractors so they could be avoided during site

calibration. It might have been wise to leave such points off the distributed list entirely, thus minimizing the likelihood of confusion. However, there were very few problems in the field with control points and site calibration.

WisCORS was used by the contractors and many of the project engineers to support the use of rovers. The Marshfield WisCORS station was being brought on-line at about the same time as initial work began on the first pilot project. As a result, a few problems were experienced with WisCORS reception until the Marshfield station was completely operational. Base stations were required for construction because none of the contractors or sub-contractors had yet rigged their machines for reception of WisCORS signals.

In some cases, site calibrations between adjacent projects used 2-3 common control points, thus forming a "bridge" of site calibrations along the corridor and minimizing the likelihood of discontinuities at project boundaries. The primary contractors, sub-contractors, and the project engineer typically performed separate site calibrations on a given project, but used the same control configurations for their calibration measurements. No appreciable geometric discrepancies between site calibrations or site calibration checks were reported.

The contractors requested that project control be made available pre-bid to facilitate project planning and help facilitate all participants be consistent their use of control as early as possible. In addition, project engineers suggested that WisDOT designate the control points to be used for site calibration on each project and that there be clarity in the GPS work plan that the prime contractor and all sub-contractors will use the same control for site calibration and all will conform to other aspects of the work plan.

The question was raised as to whether or not a single site calibration check point is sufficient in case a base station moves. However, no actual problems with this aspect of the specification have been reported.

It was learned during the site visits that Musson Brothers had AMG equipment rigged for direct use of WisCORS. Two follow-up interviews revealed that the company has had four bull dozers equipped for use of WisCORS for the past two years. They are looking forward to eventually rigging more equipment and to completion and increased robustness of WisCORS. With WisCORS in its current development/operational mode, Musson Brothers keeps a base station available on its projects, in case there are network down times.

4.5. Additional Findings

- In general, there is confirmation that WisDOT's design workflows produce models that are suitable for AMG.

- One model for all AMG operations (e.g., prime contractor, sub-contractors, engineer) minimizes confusion and conflicts.

- Provision of AMG roadway models by WisDOT facilitates contractor adoption of AMG technology.

- 3D design / AMG data flows begin to lower the technical, institutional, and cultural barriers between design and construction.

- There are fewer design revisions during construction and, therefore, fewer delays.

- Project engineers can check construction at will and do not have to wait for survey crews. Of course, this is true only if they have access to RTK rovers. The single WisDOT project engineer felt at a disadvantage without such access and actually relied upon the consultant engineer on the adjacent project to provide a rover for checking. This was done on an informal basis.

- The North Central Region had to send personnel to the field to stake limits for asphalt paving, because the special provision does not address this.

5. Recommendations

1. Develop and implement a strategy for updating the implementation plan for 3D technologies in design and construction according to the results of the survey presented in Appendix A.

2. Expand the AMG roadway model content to include sub-base surfaces and linear features. The linear features should be intended to be used as steering and other visual guidance during construction and not as breaklines for model building by contractors. Therefore, it might be feasible to provide them as two-dimensional objects to be viewed planimetrically.

3. Explore the potential for providing all AMG roadway model data in non-proprietary LandXML format. This results in reduced file size and elimination of proprietary formats.

4. Increase emphasis on model output during the design process and continue moving toward AMG roadway models as a universal deliverable on WisDOT projects. Develop an implementation timeline for this objective.

5. Explore standardization of AMG roadway model management and responsibility, including contractual mechanisms when models are found to have errors.

6. Explore the existing arrangements and coordination of GPS work plans between prime contractors and sub-contractors.

7. Consider having WisDOT designate project control points to be used for site calibration and also providing project control information pre-bid. Consideration should include feasibility of timing, appropriateness of being prescriptive, and utilization of existing resources.

8. Modify the specification to address staking of asphalt pavement limits.

9. For the 2012 construction season, select a pilot project focused on data development, exchange, and management.

10. For the 2013 construction season select one or more pilot projects focused on HMA base course, with the intent of comprehensive evaluation of QA/QC field components of the specification.

11. Further investigate the utility of construction equipment rigged for direct use of WisCORS.

Appendix A.

Status of
WisDOT Implementation Plan:
3D Technologies and Methods for Design and Construction

**STATUS OF
WisDOT IMPLEMENTATION PLAN:
3D TECHNOLOGIES AND METHODS FOR DESIGN AND CONSTRUCTION**

**Submitted by the Construction and Materials Support Center
University of Wisconsin - Madison**

August, 2011

Background

      During May, 2009, WisDOT distributed an implementation plan for 3D technologies and methods for design and construction. The plan had a two-year short-term horizon with six initiatives including goals and timelines. An update on the status of the plan's initiatives and goals has been requested by WisDOT's upper management. To assist, CMSC developed an on-line survey which was distributed to key WisDOT personnel. The survey was followed by telephone interviews to determine the status of each goal, identify successfully met goals as well as obstacles to unmet goals, and obtain preliminary ideas on updates to the implementation plan.

Summary of Findings

      The following tables and narrative present the results of the survey and telephone interviews. A few of the goals were met, many were initiated but are not yet complete, and a few were not addressed due to limited time and resources and other higher priorities. Some unmet goals result from hiring issues. Many of the unmet goals, and all of the ones that were undertaken but not completed, are viewed as important for inclusion in an updated plan. Some ideas for new goals were suggested. One of the first five initiatives had little activity and needs to be evaluated for inclusion in an updated plan. The sixth and final initiative was not detailed in the 2009 plan but was recognized as important for future development. Therefore, it also needs evaluation for inclusion and detailed description in an updated plan.

Summary by Initiative and Goal
Initiative 1: Height Modernization and CORS.

Table 1. Status of Initiative 1.

Goal	Goal Met?	Obstacles	Meet within 2 Years?	Include in Updated Plan?
Goal 1: Internal / External Support Groups Secure Funding. Timeline: On-going.	Started, but not complete.	See comments.	Yes, with increased effort.	Yes, it is an on-going effort.
Goal 2: Implement Five-Year Completion Plan (2009-2013).	Started, but not complete.	See comments.	Yes.	Yes, it is an on-going effort.

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Comments on Initiative 1:

1. To raise awareness and communicate the importance of the Wisconsin Height Modernization Program, presentations were made to WisDOT Board of Directors, upper management and continuously to division groups. Program staff and department consultants also attended professional groups and national meetings to keep abreast of developments and exchange ideas on funding sources applicable to the initiative. More work could be done in collaborating external group support.

2. The national economic downturn has affected direct support from many funding sources. In the 2010 construction season, the program encountered problems associated with the construction of passive monuments in the Northwest Region of the state. It was discovered during inspection that several of these monuments constructed by a particular construction company did not meet WisDOT specifications; many of these monuments had to be reconstructed. As a result, program staff had their efforts directed towards meeting the construction goal.

3. A 5-year completion plan is in process. Work is progressing. Avenues for securing sufficient funding to complete the project in Fall, 2013 must continue to be explored.

4. Federal earmark funds appear not to be forthcoming. A Federal Grant award of $1.3 m received in 2010 has enabled activities of the Wisconsin Height Modernization Program to progress at a steady rate. Other supplemental funds include SPR funds of $295,000.00 and state matching funds of $200,000.00. Recent retirement of the Program Manager is a set-back. This has led to re-assignment of staff duties. May hire the retiree as a consultant to train staff.

5. Request to fill the Program Manager position has been submitted. Assuming this position is filled soon, the 5-year Implementation Plan may get back on course.

6. Adequate funding to maintain the system once completed could be considered a new goal. About $19m has been invested in the program thus far with about $3m required for completion. Anticipating the cost of maintaining the system once completed is why a fee recovery program was submitted as part of WisDOT's 2011-2013 biennial budget request. However, this initiative was not approved.

7. The 3-member staff continue to do an outstanding job of ensuring the program meets its goals. Wisconsin is regarded as a national leader in this program area. Upper management support is therefore very much encouraged.

Initiative 2: DTM Data Collection and Analysis.

Table 2. Status of Initiative 2.

Goal	Goal Met?	Obstacles	Meet within 2 Years?	Include in Updated Plan?
Goal 1: Fill Survey Data Coordinator Positions. Timeline: Completion During 2009.	Started, but not complete.	See comments.	Yes. See comments.	Yes. See comments.
Goal 2: Determine Map-Check Frequency. Timeline: Completion During 3rd Quarter, 2009.	No. Several map checks are performed throughout the year, but a defined process to identify which and/or how many projects has not been developed.	See comments.	Yes. If a reasonable goal is set to start, it may be possible to ensure a minimum number of projects are checked.	Yes. Independent checks early in the process can resolve bigger problems later. DOT must be able to provide quality assurance of DOT and consultant mapping and DTM products.
Goal 3: Revise FDM and Business Practice for Map Checks. Timeline: Completion During 1st Quarter, 2010.	Started, but not complete. See comments.	Time and resources: it was not a priority to finalize process and document as compared to getting other projects completed.	Yes. If elevated as a priority and consensus on the process can be reached, it should be documented for future reference.	Yes. DOT should provide quality assurance and the process should be documented.
Goal 4: Develop Standards and Procedures. Timeline: Completion During 1st Quarter, 2010.	No. There was no effort to address this.	Stakeholder advisory group was not appointed. Time and resources: this was not a priority compared to completing other projects. The process to collect DTM has been left to the professional performing the work to ensure accuracy meets user needs.	No. But, If elevated as a priority and stakeholder advisory group is formed, guidance could be provided.	Yes. The goal to develop standards is reasonable. The goal to develop procedures will be difficult to address the many methods of data collection (conventional survey, photogrammetry, static Lidar, mobile Lidar, etc.)

Table 2. Status of Initiative 2 (continued).

Goal	Goal Met?	Obstacles	Meet within 2 Years?	Include in Updated Plan?
Goal 5: Pilot Standards and Procedures. Timeline: Completion During 3rd Quarter, 2010.	No. Dependent on Goal 4 which was not started.	Stakeholder advisory group was not appointed to address goal. Other priorities.	Yes. If elevated as a priority.	Yes. Any change in standards or procedures to address new technologies should be piloted to verify validity.
Goal 6: Implement Standards, Procedures, and Training on DTM Data Collection. Timeline: Begin During 4th Quarter, 2010.	No. There was no effort to address this. Dependent on Goal 4 which was not started.	Stakeholder advisory group was not appointed to address goal. Other priorities.	No. Given the need to complete the prior goals, 2 years may be optimistic to reach this one.	Yes. As the number of users having access to surface data increases, there is a need to educate them, even if they are not the ones collecting the data.
Goal 7: Implement DTM-to-DTM for Earthwork. Timeline: Completion During 3rd Quarter, 2010.	Do not know. Trend might be to pay plan quantity for items.	Unknown.	Unknown.	Unknown.
Goal 8: Evaluate Technologies (e.g., LiDAR, Airborne GPS). Timeline: Begin During 3rd Quarter, 2009.	Started, but not complete.	Time and resources to research and evaluate new technology.	No. On-going beyond 2 years. Some progress will be made with the terrestrial scanner.	Yes. There is always new technology to evaluate.

Comments on Initiative 2:

1. Concerning Goal 1: Regions were at various levels of need for the position. Some felt the small amount of work could be handled by current staff. Despite the DOT Strategic Direction goal to fill positions, the request to fill was not always approved and so one region moved forward with a consultant contract. See Table 3 for details on status at the region level.
2. Concerning Goal 1: DOA will be giving up its sole authority to approve requests to fill vacancies. DOT will better be able to manage filling priority vacancies. There still needs to be consensus in the Regions that these are

priorities. There will be more competition to fill if the new state budget includes the proposal to eliminate vacancies over 12 months old as this will be spread proportionally throughout the agency.

3. Concerning Goal 1: The surface model is a key component throughout the facilities development process. With the influx of mobile and static Lidar, and the need to merge with traditional field surveys and photogrammetric data, there needs to be DOT staff in responsible charge of the data throughout the process.

4. Concerning Goal 2: When map checks were completed and data did not meet passing criteria, there was not enough time and resources to investigate without dropping other priority work. It seemed counter productive to ask regions to collect field data on more projects if the analysis would not be completed, analyzed or used to resolve problems. Internally, there is disagreement on the field check process, which needs to be resolved.

5. Concerning Goal 3: Progress was made by forming a manual update team in 5/2010 resulting in a publication unrelated to map checks in 12/2010. The team will continue efforts in 2011. There are various versions of the field check process, but there is some disagreement on the process to be followed.

6. Concerning Goal 8: No airborne GPS. Still going on 2003 evaluation that it was not worthwhile for corridor mapping. A couple airborne Lidar projects were completed, but did not find any time or cost savings, or other benefits; actually more difficult to work with deliverable. SER initiated their own mobile Lidar project; yet to evaluate results. BTS in conjunction with SER have procured a terrestrial scanner, but training will not take place until 8/2011. Digital sensor imagery was requested from consultants but was not provided in spring 2011.

7. General Comment: We have a lot to do. It is hoped that the efforts of the new administration to fill positions will help to focus some efforts on this initiative.

Table 3. Status of Initiative 2, Goal 1: Fill Survey Data Coordinator Positions. Timeline: Completion during 2009.
By Region.

Region	Goal Met?	Obstacles	Meet within 2 Years?	Include in Updated Plan?
Southwest	Not filled. Position on critical fill list, but not approved to fill.	Lack of hiring approval for many positions.	Yes, maybe by end of calendar year 2011.	Goal should continue until it's been filled across the division.
Southeast	Filled with FTE, but will be replaced with consultant in July 2011. See comments.	See comments.	Perhaps the FTE could replace the consultant, if we are able to receive approval to fill the position.	Yes.
Northwest	Not filled. See comments.	Lack of hiring approval for many positions.	Unknown.	Unknown.
North Central	Filled with FTE 11/2010.	We did not experience difficulties filling the position.	N/A.	Goal should be continued for those regions that have not been successful with filling the Survey Data Coordinator position.
Northeast	Filled with consultant. See comments.	Received approval to fill with transfer only. See comments.	Goal could be met if position is prioritized to approve to fill.	Yes.

Comments:
1. SE Region: Plan is for current Survey Data Coordinator to transfer to vacant Survey Coordinator position. Region is finalizing paperwork for 1-year contract with consultant. Hope to fill Survey Data Coordinator with FTE when vacancy priorities allow.
2. SE Region: The SE Region only received approval to fill by contractual transfer and then non-contractual transfer. Unfortunately, nobody responded at the Advanced level so we had to drop the position down to a Senior level in order to get transfer candidates. If the position could have been approved for competition, we would have kept it at the Advanced level.
3. NW Region: There are three vacancies in surveys (Survey Coordinator, Survey Crew Chief, and Engineering Specialist – Transportation Senior), currently waiting for approval to move forward with outside recruitment since they had no success with an internal transfer.

4. NE Region: The consultant is doing a very good job, but would prefer FTE. Have saved money by reducing redundant work on multiple projects by having someone in that oversight position.
5. NE Region: Did not receive any transfer interest at Advanced level, so pursued filling with consultant.

Initiative 3: 3D Design Process.

Table 4. Status of Initiative 3.

Goal	Goal Met?	Obstacles	Meet within 2 Years?	Include in Updated Plan?
Goal 1: Execute Existing Civil 3D Pre-Deployment Plan. Timeline: Completion During 3rd Quarter, 2009.	Yes.	Development of 3D workflows and mindset.	N/A.	N/A.
Goal 2: Civil 3D New User Training. Timeline: Begin During 3rd Quarter, 2009.	Yes. Started training during 1st quarter, 2010, as planned.	Development of 3D workflows and mindset	N/A.	N/A.
Goal 3: Develop and Execute Existing Deployment Plan. Timeline: On-Going.	Yes. Civil 3D deployed. 3D design process not yet in place. Affects all design resources.	Resistance to change.	Implementation of 3D design process is on-going.	Yes. Implementation of 3D design process is on-going.
Goal 4: Annual Users Conference Process. Timeline: Begin During 4th Quarter, 2009.	No.	Limited time and resources.	Yes. Matter of prioritization. Multiple stakeholders help set priority.	Yes.
Goal 5: 3D Model Content and Format Standards. Timeline: Begin During 4th Quarter 2009.	Started, but not complete. In process. Piloting this summer. Still has work to be done.	Limited resources.	Yes. Need timeline definition.	Yes.
Goal 6: Establish Date for 3D Models for PS&E. Timeline: Begin During 4th Quarter, 2010.	Started, but not complete. Done for pilots, but no date set for all projects.	Need completion of proof of concept. Need coordination with design consultants as priority.	Yes.	Yes.
Goal 7: Evaluate 3D Models as Construction Contract Documents. Timeline: Begin During 4th Quarter, 2010.	No.	Need model requirements first.	Not likely. Multi-faceted question. Many stakeholders.	Yes.

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Comments:

        1. Evaluation of BIM technology for transportation projects should be a new goal.

Initiative 4: Automated Machine Guidance.

Table 5. Status of Initiative 4.

Goal	Goal Met?	Obstacles	Meet within 2 Years?	Include in Updated Plan?
Goal 1: Monitor and Refine Grading Specification. Timeline: Begin 3rd Quarter, 2009.	Yes. AMG for subgrade is included as contractor option in Standard Specifications.	N/A	N/A.	N/A.
Goal 2: Develop, Pilot, and Implement Base Course Specification. Timeline: Begin 3rd Quarter, 2009.	Started, but not complete. AMG pilot spec for base course included on 4 USH 10 projects to be constructed this summer. CMSC is monitoring for possible updating and future implementation.	None encountered.	Yes.	Yes.
Goal 3: Investigate and Evaluate Need for Paving Specification. Timeline: Begin 1st Quarter, 2010.	No. We've only had general/preliminary conversations with WCPA and WAPA. There is some interest, but they are not "pushing".	Other higher priorities.	Yes.	Yes.
Goal 4: Study Bridges and Utilities and Make Recommendation. Timeline: Begin 3rd Quarter, 2010.	No.	Other higher priorities.	Yes. We willl be adding a BOS rep to this workgroup.	Yes.

Initiative 5: Field Technology and Inspection.

Table 6. Status of Initiative 5 (See Note below Table).

Goal	Goal Met?	Obstacles	Meet within 2 Years?	Include in Updated Plan?
Goal 1: Investigate Scenarios and Feasibility (Rovers for Construction Group). Timeline: Completion 2nd Quarter, 2010.				
Goal 2: Pilot, Evaluate, and Develop Implementation Plan (Rovers for Construction Group). Timeline: Begin 3rd Quarter, 2010.				
Goal 3: Investigate Feasibility (Inspection Automation Group). Timeline: Completion 3rd Quarter, 2010.				
Goal 4: Develop Implementation Plan (Inspection Automation Group). Timeline: Begin 4th Quarter, 2010.				

NOTE: Some discussions concerning this initiative took place, but no formal study groups were formed. More information needs to be gathered on the status of use of rovers, smart phones, web-based project record keeping, and other related technologies.

Initiative 6: Infrastructure Lifecycle Uses of 3D Data. For this initiative, the 2009 implementation plan identified benefits, issues, stakeholders, recommendations, and relationships with other initiatives. Specific goals were intended to be developed at a later date.

Appendix B.

AMG HMA Base Course Specification (Included as Special Provision in Pilot Project Contracts)

1.   3D Roadway Model Data.

In addition to but separate from the contractor staking packet, the department will provide detailed 3D proposed roadway model data for 6350-06-76.   The department will provide the data prior to project LET date within 5 business days of a contractor request submitted as follows: by email to Kevin Garrigan at Kevin.Garrigan@dot.wi.gov.

The roadway model data consists of LandXML v1.2 files containing reference line and proposed profile information as well as AutoCAD 2010 DWG files containing TIN Civil 3D surfaces as follows:
- Existing ground.
- Proposed top.
    - Top of topsoil outside the roadway subgrade shoulder points extended to the slope intercepts.
    - Top of shoulder and top of pavement within the roadway subgrade shoulder points.
- Proposed datum.
    - Top of topsoil outside the roadway subgrade shoulder points extended to the slope intercepts.
    - Subgrade surface within the roadway subgrade shoulder points.
- Proposed base course.
    - Top of base course within the roadway edges of traveled way.

Construction Staking Base, Item 650.5000

Conform to subsection 650 of the standard specifications as modified in this special provision.

Replace subsection 650.3.4 of the standard specifications with the following:
650.3.4 Base
650.3.4.1 General
(1) Under the Construction Staking Base bid item the contractor may substitute global positioning system (GPS) machine guidance for conventional base staking on all or part of the base for hot mix asphalt (HMA) pavement. The engineer may require the contractor to revert to conventional base staking methods for all or part of the base for hot mix asphalt (HMA) pavement at any point during construction if, in the engineer's opinion, the GPS machine guidance is producing unacceptable results.

(2) Use GPS machine guidance for base in all areas where GPS machine guidance was used on subgrade under HMA pavement. GPS machine guidance is not required for base on short side road, driveway, or field entrance tie-ins of 200 feet or less.

650.3.4.2 Base Staking

(1) Set construction stakes or marks at 100-foot intervals for rural sections and 50-foot intervals for urban sections. Set and maintain sufficient stakes at each cross section to match plan cross-section, achieve the required accuracy, and to support the method of operations. Set and maintain stakes as necessary to establish horizontal and vertical position along intersecting road radii, auxiliary lanes, vertical and horizontal curves, and curve transitions. Locate stakes within 0.25 feet horizontally and establish the grade elevation to within 0.03 feet vertically.

650.3.4.3 GPS Machine Guidance
650.3.4.3.1 General

(1) No base stakes are required for work completed using GPS machine guidance.

(2) Coordinate with the engineer throughout the course of construction to ensure that work performed using GPS machine guidance conforms to the contract tolerances and that the methods employed conform to the contractor's GPS work plan and accepted industry standards. Address GPS machine guidance issues at weekly progress meetings.

650.3.4.3.2 GPS Work Plan

(1) Submit a comprehensive written GPS work plan for department review at least 5 business days before the preconstruction conference. The engineer will review the plan to determine if it conforms to the requirements of this special provision.

(2) Construct the base as the contractor's GPS work plan provides. Update the plan as necessary during construction of the subgrade.

(3) The GPS work plan should discuss how GPS machine guidance technology will be integrated into other technologies employed on the project. Include, but do not limit the contents to, the following:
- Designate which portions of the contract will be done using GPS machine guidance and which portions will be done using conventional base staking.
- Describe the manufacturer, model, and software version of the GPS equipment.
- Provide information on the qualifications of contractor staff. Include formal training and field experience. Designate a single staff person as the primary contact for GPS technology issues.
- Describe how project control is to be established. Include a list and map showing control points enveloping the site.
- Describe site calibration procedures. Include a map of the control points used for site calibration and control points used to check the site calibration. Describe the site calibration and checking frequency as

well as how the site calibration and checking information are to be documented.

- Describe the contractor's quality control procedures. Describe procedures for checking, mechanical calibration, and maintenance of equipment. Include the frequency and type of checks performed to ensure that the constructed base conforms to the contract plans.

650.3.4.3.3 Equipment

(1) Use GPS machine guidance equipment to meet the requirements of the contract.

(2) Perform periodic sensor calibrations, checks for blade wear, and other routine adjustments as required to ensure that the final base conforms to the contract plans.

650.3.4.3.4 Geometric and Surface Information
650.3.4.3.4.1 Department Responsibilities

(1) At anytime after the contract is awarded the contractor may request the contractor staking packet. The department will provide the packet within 5 business days of receiving the contractor's request.

650.3.4.3.4.2 Contractor Responsibilities

(1) Develop and maintain the initial design surface DTM for areas of the project employing GPS machine guidance. Confirm that the design surface DTM agrees with the contract plans.
(2) Provide design surface DTM information to the department in LandXML v1.2, AutoCAD 2010 DWG, or other engineer-approved format.

650.3.4.3.4.3 Managing and Updating Information

(1) Notify the department of any errors or discrepancies in department-provided information. The department will determine what revisions may be required. The department will revise the contract plans, if necessary, to address errors or discrepancies that the contractor identifies. The department will provide the best available information related to those contract plan revisions.

(2) Revise the design surface DTM as required to support construction operations and to reflect any contract plan revisions the department makes. Perform checks to confirm that the revised design surface DTM agrees with the contract plan revisions. Provide a copy of the resultant revised design surface DTM to the engineer in LandXML or other engineer-approved format. The department will pay for costs incurred to incorporate contract plan revisions as extra work.

650.3.4.3.5 Site Calibration

(1) Designate a set of control points, including a total of at least 6 horizontal and vertical points or 2 per mile, whichever is greater, for site calibration for the

portion of the project employing GPS machine guidance. Incorporate the department-provided control framework used for the original survey and design.

(2) Calibrate the site by determining the parameters governing the transformation of GPS information into the project coordinate system. Use the full set of control points designated under 650.3.4.3.5 (1) for the initial site calibration. Provide the resulting site calibration file to the engineer before beginning base construction operations.

650.3.4.3.6 Construction Checks
650.3.4.3.6.1 Daily Calibration Checks
(1) In addition to the site calibration, perform site calibration checks. Perform these checks at individual control points not used in the initial site calibration. At a minimum, check the calibration at the start of each day as described in the contractor's GPS work plan. Report out-of-tolerance checks to the engineer. The measured position must match the established position at each individual control point within the following tolerances:
- Horizontally to 0.10 feet or less.
- Vertically to 0.05 feet or less.

(2 Discuss the previous week's daily calibration check results at the weekly progress meeting for monitoring the GPS work.

650.3.4.3.6.2 Final Base Elevation Checks

(1) Check the base against the plan elevation at randomly selected points on cross sections located at stations evenly divisible by 100. Conduct at least 20 random checks per stage, per project, or per roadway mile whichever results in the most tests. Also check the base at additional points as the engineer directs. Notify the engineer at least 2 business days before making base checks so the engineer can observe the process.

(2) In lieu of the tolerances specified in 301.3.4.1(2), ensure that no individual check is off by more than 0.10 foot vertically and at least 4 of any 5 consecutively tested random base points are within 0.06 foot vertically of the plan elevation. Notify the engineer if either criterion is exceeded.

(3) The department may conduct periodic independent base checks. The department will notify the contractor if any individual check differs by more than 0.06 foot from the design.

Appendix C.
Derivation of Maximum Line Segment Length for Horizontal Curves

Figure C.1 illustrates a circular arc with radius R, subtended by a chord of length c, and having central angle δ. The perpendicular distance (m) from the midpoint of the chord to the arc is the middle ordinate.
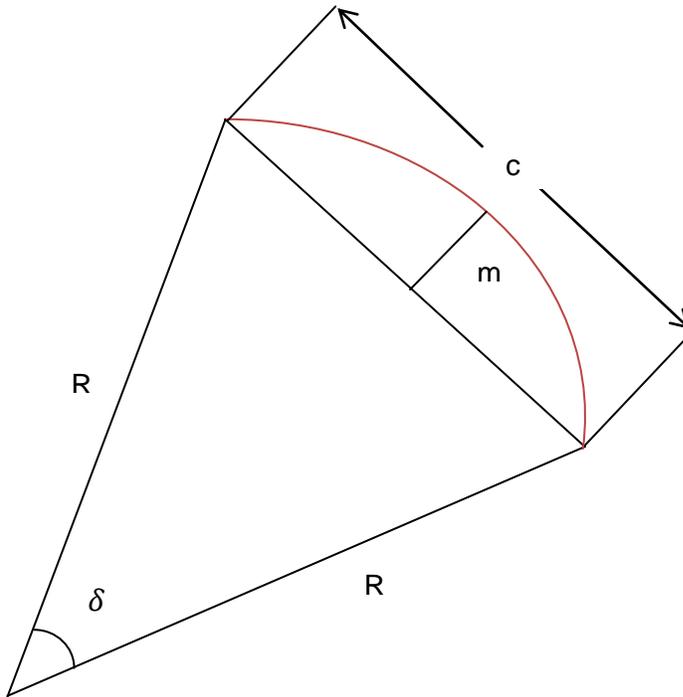

Figure C.1.
Circular Horizontal Curve Parameters

c and m are related to R and δ by the well-known equations C.1 and C.2:

$$c = 2Rsin\left(\frac{\delta}{2}\right) \tag{C.1}$$

$$m = R\left(1 - cos\left(\frac{\delta}{2}\right)\right) \tag{C.2}$$

Rearranging equation C.2:

$$cos\left(\frac{\delta}{2}\right) = \frac{R-m}{R} \tag{C.3}$$

Now

$$sin\left(\frac{\delta}{2}\right) = \sqrt{1 - \left(\frac{R-m}{R}\right)^2} \tag{C.4}$$

Substituting equation C.4 into equation C.1 and simplifying yields

$$c = 2\sqrt{m(2R - m)} \tag{C.5}$$

If

$$m = t_h \tag{C.6}$$

where t_h is the maximum allowable error in representation of horizontal curves, then

$$c = d_{h_{max}} \tag{C.7}$$

where $d_{h_{max}}$ is the maximum allowable line segment length for a horizontal curve with radius R:

$$d_{h_{max}} = 2\sqrt{t_h(2R - t_h)} \tag{C.8}$$

Furthermore, if, as in equation 3,

$$t_h = 0.25 ft \tag{C.9}$$

then

$$d_{h_{max}} = \sqrt{2R - 0.25} \tag{C.10}$$

Appendix D.
Derivation of Maximum Line Segment Length for Equal-Tangent Crest Vertical Curves

Figure D.1 illustrates a parabolic equal-tangent crest vertical curve with components used in this derivation. The origin of the coordinate system is at the beginning of the curve. L is the length of the curve. The grade lines are tangent at $x = 0$ and $x = L$ and their gradients are g_1 and g_2. The apex of the curve is at x_{max}, y_{max}. A horizontal chord, of length k, connects points 1 and 2. j is the perpendicular distance between the apex and the chord.
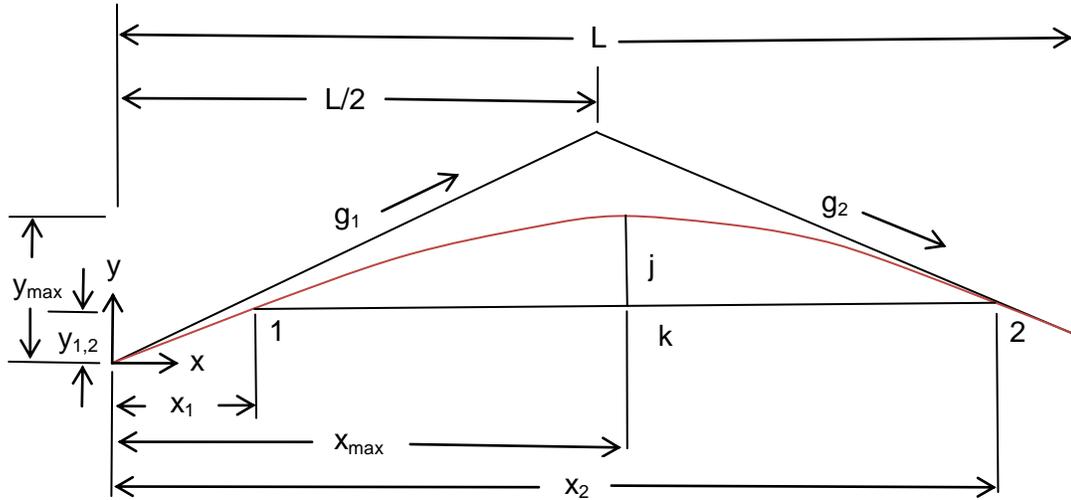

Figure D.1
Parabolic Equal-Tangent Crest Vertical Curve with Components Used in the Derivation

Clearly,

$$k = x_2 - x_1 \tag{D.1}$$

and

$$j = y_{max} - y_{1,2} \tag{D.2}$$

The equation for the curve is

$$y = \left(\frac{r}{2}\right) x^2 + g_1 x \tag{D.3}$$

where r is the rate of change in gradient along the curve and is given by

$$r = \frac{g_2 - g_1}{L} \tag{D.4}$$

x_{max} is found by setting the derivative of equation D.3 equal to zero and solving for x:

$$x_{max} = \frac{-g_1}{r}$$ (D.5)

y_{max} is found by substituting equation D.5 into equation D.3 and simplifying:

$$y_{max} = \left(\frac{r}{2}\right)\left(\frac{-g_1}{r}\right)^2 + g_1\left(\frac{-g_1}{r}\right) = -\frac{g_1^2}{2r}$$ (D.6)

From equation D.2,

$$y_{1,2} = y_{max} - j$$ (D.7)

Then, x_1 and x_2 are the solutions to

$$-\frac{g_1^2}{2r} - j = \left(\frac{r}{2}\right)x^2 + g_1 x$$ (D.8)

which are

$$x_1 = \frac{g_1 - \sqrt{-2rj}}{r}; x_2 = \frac{g_1 + \sqrt{-2rj}}{r}$$ (D.9)

Substituting equations D.9 into equation D.1 and simplifying yields

$$k = 2\sqrt{\frac{-2j}{r}}$$ (D.10)

Substituting equation D.4 into equation D.10 and solving for L yields

$$L = \frac{-k^2(g_2 - g_1)}{8j}$$ (D.11)

According to WisDOT's Facilities Development Manual, the minimum length of an equal tangent crest vertical curve for category 1 roadways can be computed from the stopping sight distance to a 24-inch object:

$$L_{min} = \frac{AS_{24-inch}^2}{2158}$$ (D.12)

where

$$A = 100(|g_2 - g_1|)$$ (D.13)

For crest vertical curves

$$g_2 < g_1 \tag{D.14}$$

So

$$L_{min} = \frac{-(g_2-g_1)S^2_{24-inch}}{21.58} \tag{D.15}$$

Equating equations D.11 and D.15 and simplifying yields

$$k = \frac{S_{24-1nch}\sqrt{j}}{1.642} \; ; \; S_{24-inch} = \frac{1.642k}{\sqrt{j}} \tag{D.16}$$

If

$$j = t_v \tag{D.17}$$

where t_v is the maximum allowable error in representation of equal tangent crest vertical curves, then

$$k = d_{v_{max}} \tag{D.18}$$

where $d_{v_{max}}$ is the maximum allowable line segment length for an equal tangent crest vertical curve with stopping sight distance $S_{24\text{-inch}}$:

$$d_{v_{max}} = \frac{S_{24-1nch}\sqrt{t_v}}{1.642} \tag{D.19}$$

Furthermore, if, as in equation 3,

$$t_v = 0.03ft \tag{D.20}$$

then

$$d_{v_{max}} = (0.1055)S_{24-inch} \tag{D.21}$$

Appendix E.
Interim Standard for Data Density
(Sub Grade and Base Surfaces)

Maximum Corridor Frequency Spacing Standard for Civil 3D:

<u>Roadway Regions:</u> All regions outside of intersection footprint as defined below.

1. When roadway is in horizontal and vertical tangency, Maximum Corridor Frequency = 50' for all Design Speeds
2. When roadway is on a horizontal curve:
    a. Design Speed <= 30mph, Maximum Corridor Frequency = 10'
    b. 35mph <= Design Speed <= 55mph, Maximum Corridor Frequency = 25'
    c. Design Speed >= 60 mph, Maximum Corridor Frequency = 50'
3. When roadway is on a vertical curve:
    a. Design Speed <= 30mph, Maximum Corridor Frequency = 10'
    b. 35mph <= Design Speed <= 50mph, Maximum Corridor Frequency = 25'
    c. Design Speed >= 55 mph, Maximum Corridor Frequency = 50'
4. Add frequency lines for all horizontal geometry points, superelevation transition points, profile geometry points, and profile high/low points.
5. Designer to add frequency lines at other points of interest such as change of typical section, critical drainage location, etc.

<u>Intersection Regions:</u> Intersection Regions are those which fall within footprint of the intersection and its acceleration/deceleration lanes and tapers.

1. Maximum Corridor Frequency = 5' for all Design Speeds
2. Add frequency lines for all horizontal geometry points, superelevation transition points, profile geometry points, and profile high/low points.
3. Designer to add frequency lines at other points of interest such as change of typical section, critical drainage location, etc.