

INNOVATIVE TECHNIQUES WITH MULTI-PURPOSE SURVEY VEHICLE FOR AUTOMATED ANALYSIS OF CROSS-SLOPE DATA

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ABSTRACT

Manual surveying methods have long been used in the field of highway engineering to determine the cross-slope, and longitudinal grade of an existing roadway. However, these methods are slow, tedious and labor intensive. Moreover, manual survey methods almost always require partial or full lane closure resulting in traffic delays, increase in costs, and inconvenience to the travelling public. In 2003, the Florida Department of Transportation (FDOT) acquired a state-of-the-art Multi-Purpose Survey Vehicle (MPSV) which combines the advantage of an inertial profiler with the additional ability to simultaneously collect images, cross-slope, longitudinal grade, curvature, rutting, and roughness at highway speed.

To complement the MPSV system, an automated analysis tool has been developed to process pavement geometry data for identifying areas with cross-slope and longitudinal grade deficiencies in a fast and efficient manner. In addition, this analytical tool computes a drainage path along the pavement surface. The program also displays the analysis results in two and three-dimensional graphical formats allowing for an easier interpretation of the data.

The MPSV technology coupled with the developed cross-slope analysis tool provide an effective, practical, and cost effective method to quickly identify potential problem-prone areas along a highway. This paper presents an innovative technique for the analysis of cross-slope and longitudinal profile data, which helps identify areas with cross-slope and surface drainage deficiencies. Highway agencies can successfully implement similar systems and analysis methodology to complement and enhance their existing safety and pavement management programs.

INTRODUCTION

Manual surveying methods have long been used in the field of highway engineering to determine the cross-slope, and longitudinal grade of an existing roadway. Analysis of this data helps engineers identify problem-prone areas like cross slope deficiency and inadequate surface drainage. However, these methods are slow, tedious and labor intensive. Moreover, survey crews often have to be physically in the travel lane, exposing themselves to potentially hazardous conditions. Therefore, a high-speed automated pavement evaluation system is an efficient and cost-effective alternative that assures the safety of the field survey personnel and the safety of motorists.

Advances in sensor and inertial navigation technologies facilitated their implementation into the pavement evaluation field, allowing highway engineers to capitalize on the large amount of information provided by this state-of-the-art equipment. Presently, the Florida Department of Transportation (FDOT) uses a Multi-Purpose Survey Vehicle (MPSV) to collect cross-slope and vertical grade data at normal operational speeds. The MPSV also collects radius of curvature, rutting, and roughness information using highway milepost for linear referencing with georeferencing capability through an on-board Differential Global Position System (DGPS).

OBJECTIVE

The objective of this paper is to describe an innovative technique developed for processing and analyzing cross-slope and other data collected by the MPSV to identify roadway deficiencies. Although the technique described in this paper was developed specifically for use with the MPSV, the basic principles can be applied to other similar systems which have the capability to simultaneously measure cross-slope, longitudinal grade, and rutting.

MULTI-PURPOSE SURVEY VEHICLE AND ITS SYSTEMS

Presently, the Florida Department of Transportation (FDOT) uses the MPSV (Figure 1) to collect pavement and roadway images at normal operational speeds. It also collects cross-slope, longitudinal grade, curvature, rutting, and roughness information using milepost for linear referencing of such data. The MPSV is outfitted with the following main on-board systems: (a) inertial profiling, (b) imaging, and (c) inertial navigation.



FIGURE 1 FDOT MPSV

The inertial profiling system aboard the MPSV consists of three laser sensors, two accelerometers, and a Distance Measuring Instrument conforming to ASTM E950 Class I. [1]. The MPSV uses two front-mounted high resolution (1300 x 1024) digital area-scan cameras for collecting of right-of-way and side-view images at highway speed. A rear-mounted pavement imaging system which consists of a two megapixel line-scan camera captures images of the pavement surface with a 1.9 by 1.9 mm resolution. The pavement imaging system is coupled with a lighting system consisting of ten high intensity discharge 150 watts lamps to facilitate night-time surveys and minimize the casting of shadows on the pavement [2].

The FDOT MPSV also incorporates a Position and Orientation System for Land Vehicles (POS-LV) that integrates a Differential Global Position System (DGPS) and inertial technology into one robust, precise position and orientation system. The core of the POS is the Inertial Measurement Unit (IMU), which is a self-contained sensor consisting of three accelerometers and three fiber-optic gyroscopes. The physical principle of this type of gyroscope operation is analogous to the Doppler effect, but in this instance it involves determination of the phase shift between two counter propagating light beams. The sensor is bolted to the vehicle so it undergoes same motions as the vehicle. The accelerometers are used to establish a vertical position reference of the vehicle while gyroscopes are used to determine vehicle orientation as well as grade and cross-slope. The IMU is complemented with two GPS receivers which provide the inertial solution with position updates, thereby controlling the error growth. If the GPS receiver is unable to provide position information due to weak satellite signal, the IMU continues to provide position and orientation information unaided. The POS-LV system uses strap down inertial navigation, Kalman filtering, GPS, GPS azimuth measurement and distance measurement indicators (DMI) to provide position and orientation data that have a high bandwidth, excellent short-term accuracy and minimum long-term errors. The cross-slope and grade data can be used to evaluate roadway geometry and identify areas of deficiency.

EVALUATION OF ROADWAY GEOMETRY

Lack of adequate drainage across a roadway due to inadequate geometry may lead to hydroplaning. A highway agency interested in minimizing this occurrence has minimal control over driver, vehicle, and environmental factors. However, an agency has more control identifying and mitigating causal or contributing factors to vehicle departure or hydroplaning by analyzing geometric characteristics of a roadway.

The cross-slope influences the drainage across the road pavement and can affect the operational characteristics of a vehicle moving along the road. Other factors that can influence surface drainage across a pavement are longitudinal grade and rutting. The cross-slope and longitudinal grade values change over time due to surface deformation caused by traffic loads, environmental effects, and pavement settlement. Other factors contributing to a change in cross-slope and, to a lesser degree, longitudinal grade are improper asphalt mix overlays and milling operations. Moreover, the actual values can differ from designed values and, therefore, knowledge of current cross-slope and longitudinal grade is important for evaluation of roadway geometry. In the past, these measurements were performed using conventional survey methods, which are slow, tedious, and expensive. In addition, manual surveys often require roadway closures leading to traffic delays, which impact safety and inconvenience to the traveling public.

In 2003, the FDOT acquired an MPSV to determine overall pavement quality at highway speeds. The MPSV collects a plethora of data simultaneously and at highway speed. This data provides critical information about a roadway's ability to drain surface runoff and therefore minimize the potential for hydroplaning. The relationship between cross-slope (S_C), longitudinal grade (S_G), and pavement drainage width (W_C) can be calculated through the drainage path based on the following equation [3]:

$$L_F^2 = W_C^2 \left[1 + \left(\frac{S_G}{S_C} \right)^2 \right] \quad (1)$$

where:

L_F = drainage path length (ft)

W_C = pavement drainage width (ft)

S_C = cross-slope (ft/ft)

S_G = longitudinal grade (ft/ft)

Drainage path length, which is computed at discrete station locations, is the distance that water travels before it leaves the pavement. The drainage path length increases with longitudinal grade, and decreases with increasing cross-slope. It is also influenced by pavement drainage width that represents the width of pavement water is collected from. A longer drainage path, sometimes combined with road depressions or wheel ruts, creates susceptible areas for hydroplaning on high speed roadways.

The dominant factor in draining the water from the pavement surface is cross-slope [4]. The IMU measures cross-slope as an angular rate of rotation around the roll axis of the vehicle body and cross-slope value reported by the IMU is input into the Equation 1. Another roadway

characteristic that affects surface drainage is the longitudinal grade. The longitudinal grade prolongs the drainage path length if it is substantially larger than the cross-slope. It also impacts heavy vehicle operation as it affects their stopping and passing distances. Therefore, longitudinal grade is an important factor of the roadway geometry evaluation and is incorporated into Equation 1. Figure 2 illustrates an example of an area prone to potential water sheeting due to a relatively large grade in comparison to cross-slope.

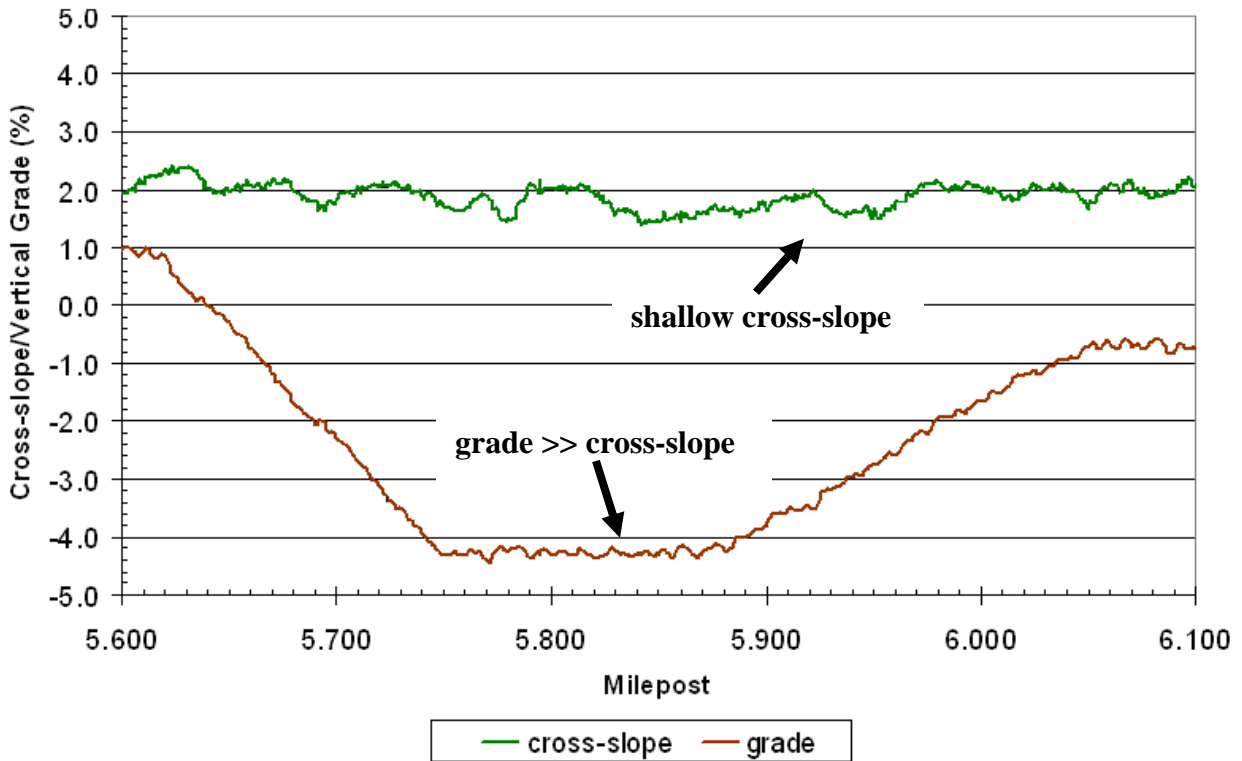


FIGURE 2 Potential Water Sheeting Area

An example of a pavement with poor surface drainage represented by a relatively long drainage path length (DP_2) due to shallow cross-slope in lane 2 is illustrated in Figure 3. Since the cross-slope runs in the same direction for both lanes and cross-slope of the lane 1 is significantly larger than its grade, most of the surface runoff from both lanes is carried by lane 2. This amplifies the drainage problem in lane 2 resulting in a large DP_2 .

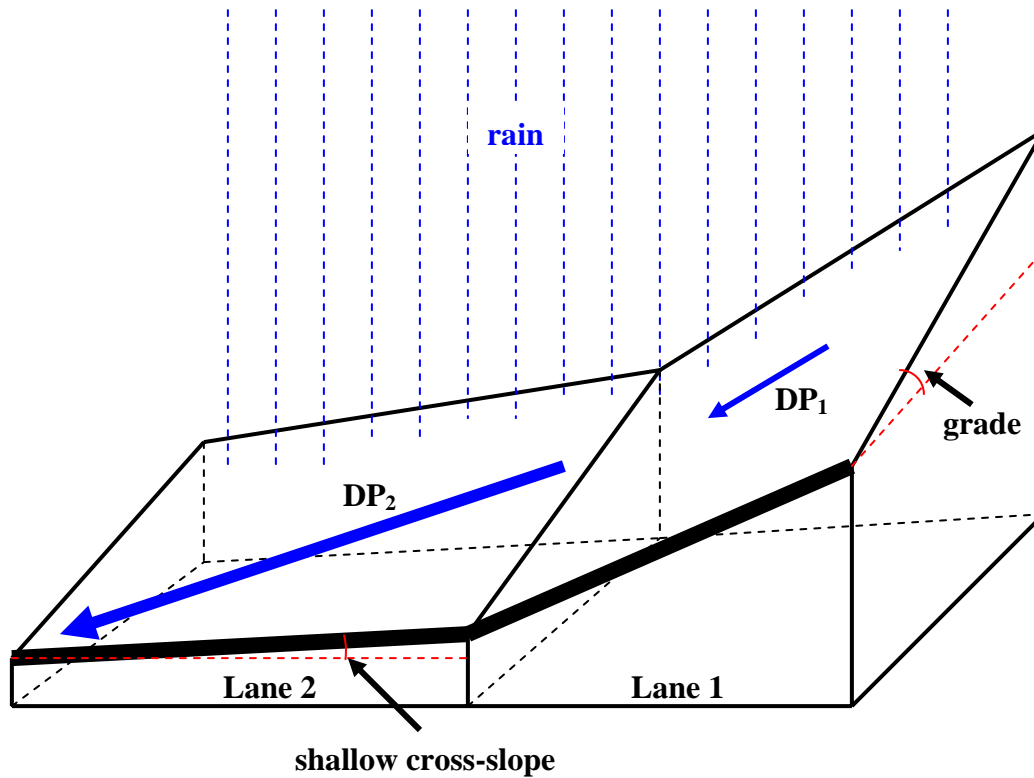


FIGURE 3 Long Drainage Path (DP₂) Due to Shallow Cross-slope

Rutting which is characterized as a cumulative, incremental, and permanent deformation of the pavement in the wheel paths, is another contributing factor that can lead to hydroplaning. In wet weather conditions a vehicle traveling at 50 mph can have its braking efficiency reduced by more than 80% due to water ponding in the ruts. A water depth of 0.15 inch can lead to hydroplaning for a passenger vehicle [5]. An example of severe rutting measured by the MPSV can be seen in Figure 4. Figures 3 and 4 illustrate the results of cross-slope analysis using the developed analysis program which is described in the next chapter.

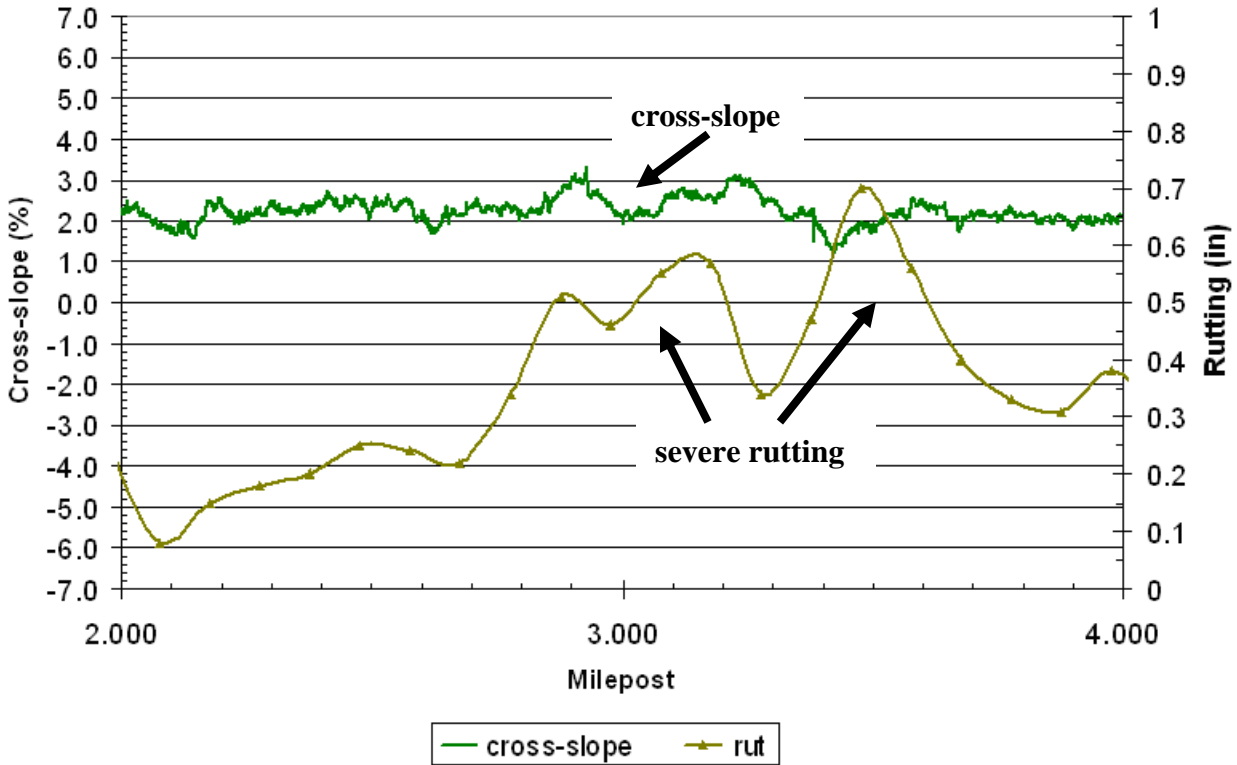


FIGURE 4 Severe Rutting Measured by MPSV

ACCURACY AND REPEATABILITY OF THE IMU UNIT

After acquiring the MPSV, the Florida Department of Transportation (FDOT) decided to assess limitation of the mounted IMU unit through evaluation of accuracy and repeatability. Therefore, a roadway containing a super-elevation was selected for this study and 37 distinctive locations, benchmarks, were manually surveyed using rod-and-level method. After, the MPSV measured cross-slope in ten repeated runs and results showed very high accuracy (cross-correlation R^2 of 99.4%) and a 94.7% repeatability. To minimize introduction of systematic error into cross-slope measurement, the test section has been selected for monthly verification of the IMU calibration. Example of result of improper IMU calibration on measurement of cross-slope data is shown in Figure 5.

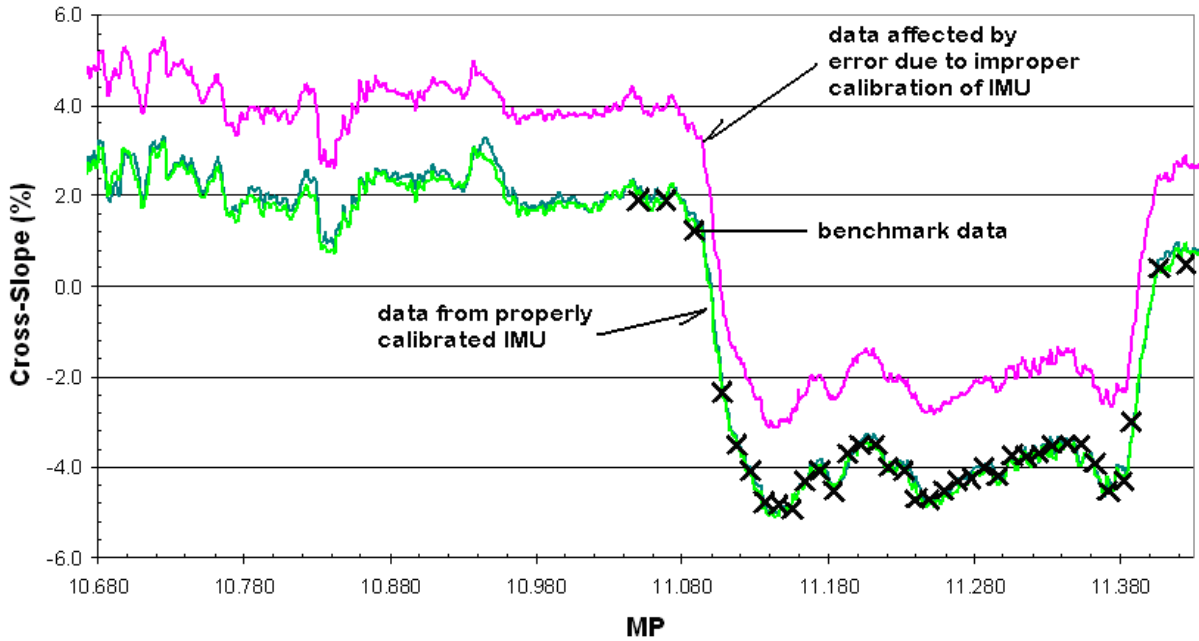


FIGURE 5 Systematic Errors in Cross-slope Data Due to Improper Calibration of the IMU Unit

AUTOMATED DATA ANALYSIS

The MPSV collects a large amount of data, which if processed manually, would take considerable amount of time. Therefore, in order to keep up with their production schedule, the FDOT needed a faster way of importing, processing, and analyzing the collected data. As a result, a Cross-slope Analysis Program was developed in Excel, using the Visual Basic for Application (VBA) programming language. The Cross-slope Analysis Program, (Figure 6), allows the user to import and simultaneously process cross-slope, longitudinal grade, and rut data used to calculate drainage path as defined in Eqn.1. The program outputs cross-slope, grade, drainage path, and rut measurements in tabular as well as graphical form as illustrated in Table 1 and Figure 7, respectively.

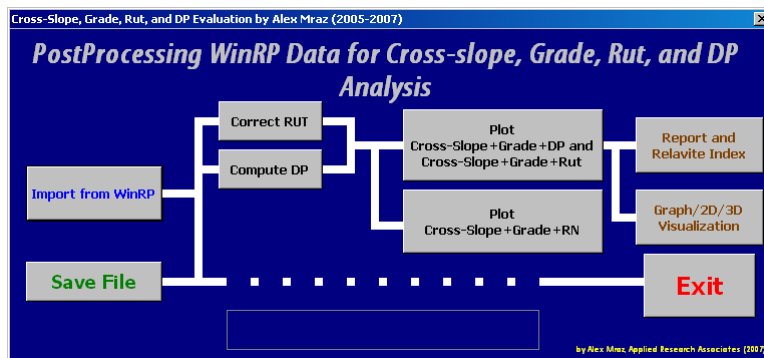


FIGURE 6 Cross-slope Analysis Program Main Menu

TABLE 1 Tabular Sample of Data Reported by the Cross-slope Analysis Program

Milepost (MP)	Cross-slope (%)	Longitudinal Grade (%)	Drainage Path (ft)
6.32	2.36	-2.37	17
6.33	2.62	-1.61	14
6.34	3.11	-0.87	12
6.35	3.29	-0.56	12
6.36	3.44	-0.51	12
6.37	2.74	-0.40	12
6.38	4.24	-1.22	12
6.39	3.34	-0.59	12
6.4	3.53	-1.03	13
6.41	2.93	-0.61	12
6.42	1.81	-0.45	12
6.43	2.80	-0.68	12
6.44	2.66	-0.89	13
6.45	2.97	-0.82	12
6.46	2.78	-0.94	13
6.47	3.10	-0.96	13
6.48	2.62	-0.79	13
6.49	3.50	-0.91	12

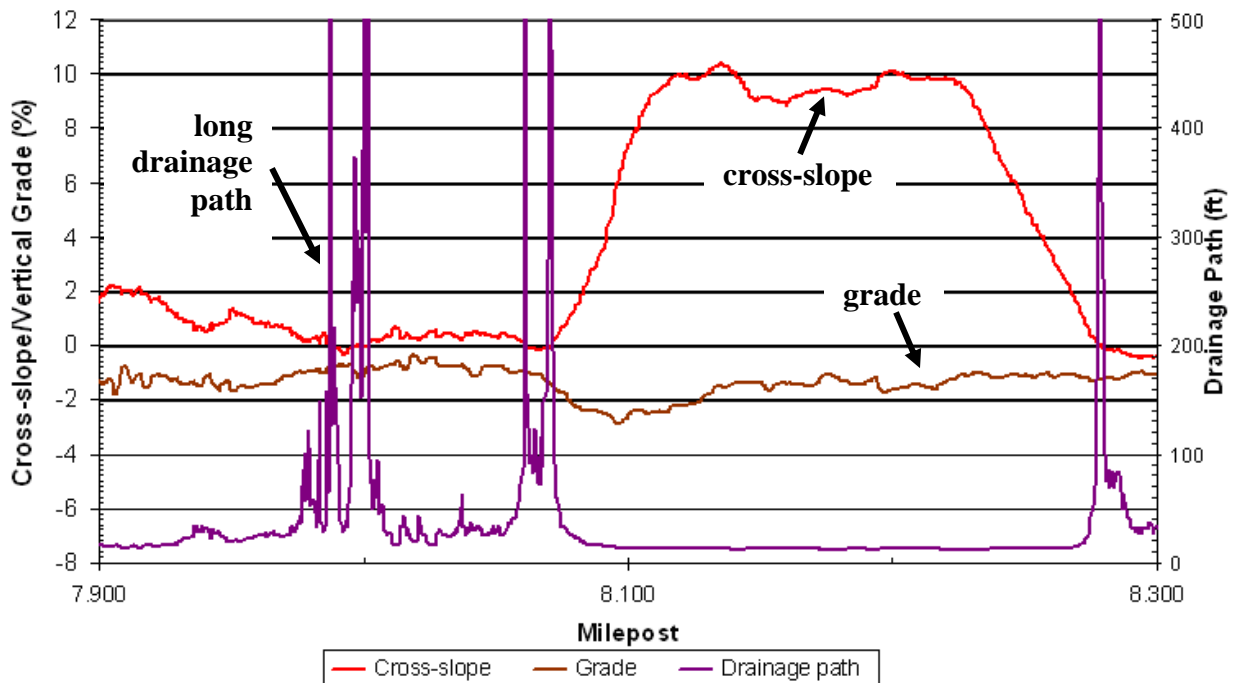


FIGURE 7 Illustration of Cross-slope Data Created by the Analysis Program

The analysis program has the ability to create 3-D renderings of cross-slope and longitudinal grade data as a function of mile post (MP) and plots them in real-time. An example of a 3-D

visualization graph of cross-slope is shown in Figure 8. This representation of cross-slope data provides pavement engineers the ability to better visualize roadway geometry and take appropriate corrective measures. The graphs are color-shaded to allow a better visualization of the cumulative effect of the cross-slope. The shades of blue color represent negative cross-slope (negative signs in Figure 8) and shades of green color represent positive cross-slope (positive signs in Figure 8), respectively.

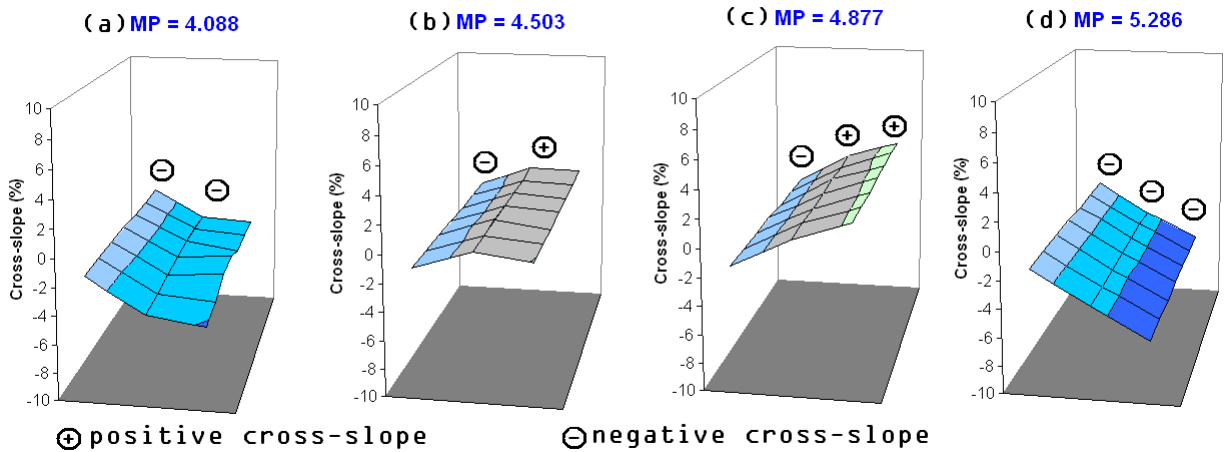


FIGURE 8 (a) Vehicle Entering Super-elevation (Flat Cross-slope in Outside Lane); (b) Vehicle Within Super-elevation (Nearly Zero Cross-slope In Outside Lane); (c) Vehicle Within Super-elevation (Adequate Cross-slope In Both Lanes); (d) Vehicle Exiting Super-Elevation (Adequate Cross-slope In Both Lanes)

The Cross-slope Analysis Program allows for easy input, processing, analysis, and reporting of roadway geometry and visualization of localized deficiencies. Using the cross-slope, longitudinal grade, rut data, the drainage path, and 3-D graphics computed by the program, engineers can better visualize the geometric characteristics of the pavement, identify trouble spots, and develop appropriate mitigating solutions.

CASE STUDY

A rural four-lane interstate highway was selected for a case study. There had been reports of vehicle departures from the roadway during heavy rain on one isolated section of the facility. District engineers requested the use of the MPSV to determine the possible cause of vehicle departures that would assist in formulating appropriate corrective measures. After the MPSV survey was performed, skid marks were noted in the side-view images as shown in Figure 9.



FIGURE 9 Skid Marks on the Shoulder Recorded in MPSV Side-view Images

The results from the analysis of cross-slope, longitudinal grade, and rut data identified an isolated area within the horizontal curve with a relatively small cross-slope and a relatively large longitudinal grade. As illustrated in Figure 10, the corresponding drainage path within the horizontal curve is large due to the shallow cross-slope. Based on these results, district engineers were able to use this information to take immediate short-term actions and plan for a long-term mitigating solution.

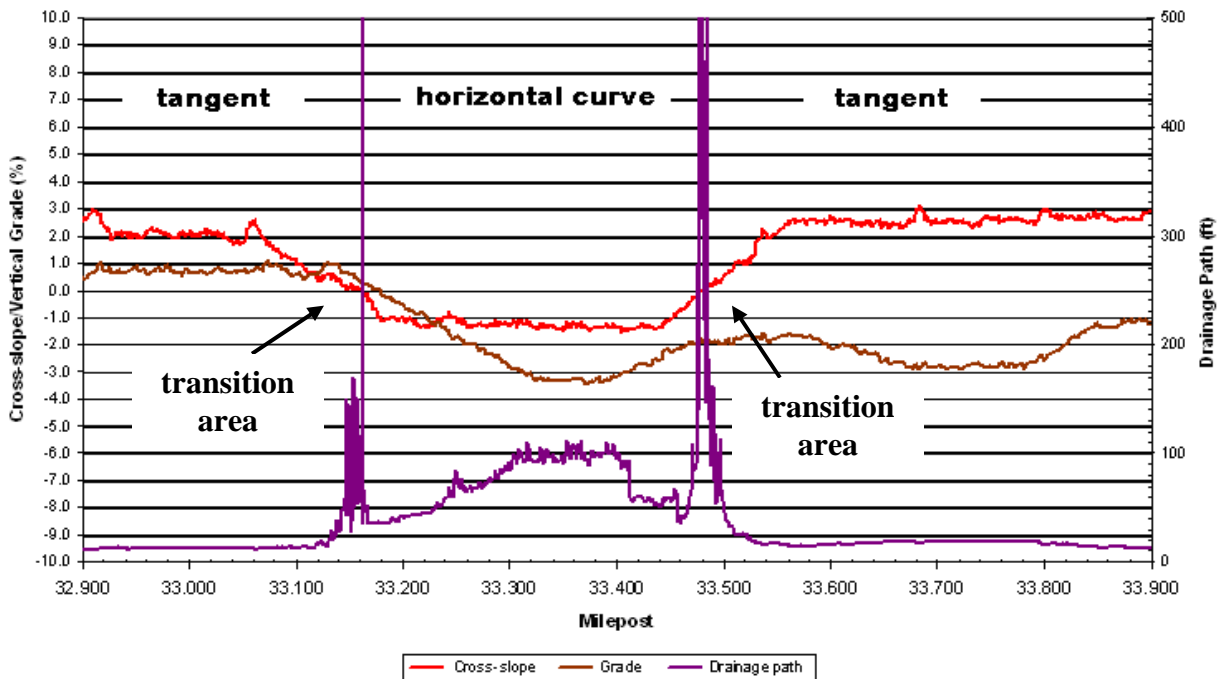


FIGURE 10 Large Drainage Path Within Horizontal Curvature Identified with MPSV

As a short-term solution, transverse angled grooves were cut into the friction layer of the pavement to improve surface drainage (Figure 11). In addition, variable message signs were used to inform motorists to exercise caution when driving through the area during heavy rains.



FIGURE 11 Transverse Angled Grooves as a Short-term Solution to Water Drainage Problem

As a long-term solution to the drainage problem, the designers updated the resurfacing project scope to include the use of overbuild to correct the shallow cross-slope. After the resurfacing was completed, the section was resurveyed with the MPSV and the results are shown in Figure 12. From this figure it can be seen that the cross-slope was substantially improved, resulting in an elimination of the surface drainage problem. Figure 12 also shows that the narrow peaks of drainage path at the transition areas are indicative of a smooth transition into and out of the horizontal curve. It is important to note that there was no roadway departures reported after the corrective measures were implemented.

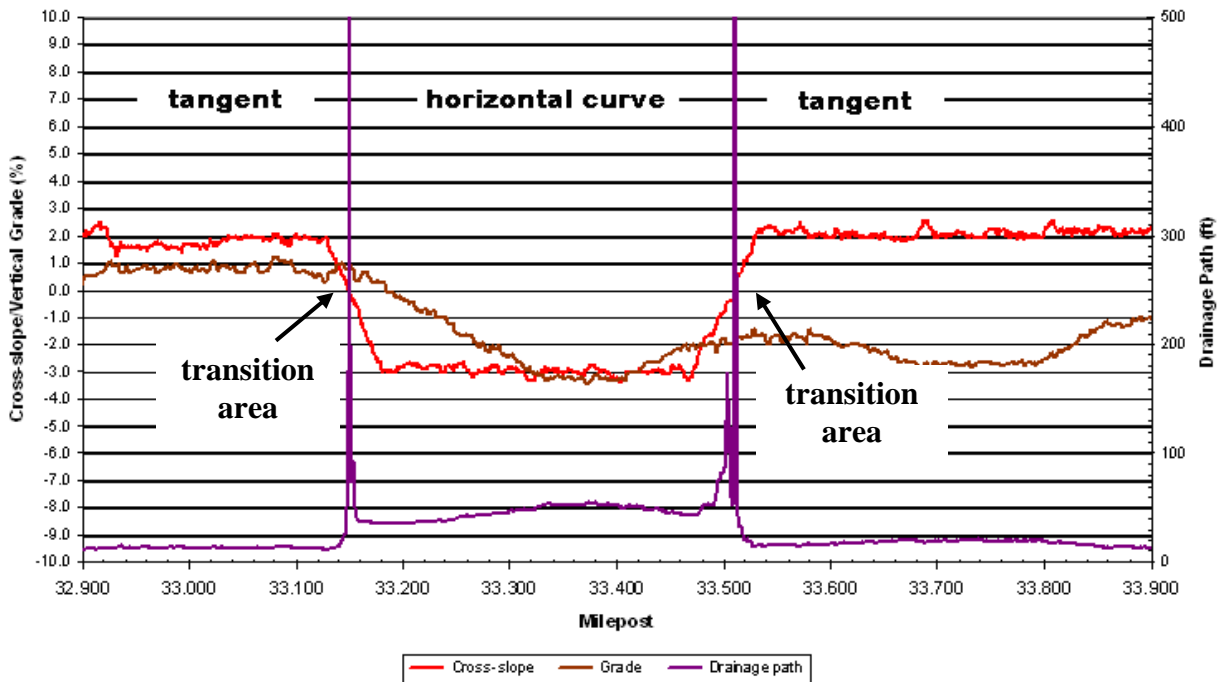


FIGURE 12 MPSV Cross-slope After Overbuild Correction was Applied

CONCLUSIONS

The advantage offered by a state-of-the-art MPSV coupled with the Cross-slope Analysis Program provide pavement engineers and highway practitioners with effective tools to identify roadway geometry problems and aid in formulating short-term and long-term solutions. In addition, such automated survey methods do not require partial or full lane closure thus eliminating traffic delays, improves safety, and reduces cost. Although the analysis methodology presented in this paper was developed specifically for data generated by the MPSV, the basic principles can be applied to any device that is capable of simultaneously collecting cross-slope, longitudinal grade and rutting data.

DISCLAIMER

The content of this paper reflects the views of the authors who are solely responsible for the facts and accuracy of the data as well as for the opinions, findings and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Florida Department of Transportation. This paper does not constitute a standard, specification, or regulation. In addition, the above listed agency assumes no liability for its contents or use thereof.

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