A Case Study on the Use of Mobile LiDAR to Produce a Preliminary Drainage Design

Charles F. Gurganus, Corresponding Author
Associate Research Engineer, Texas A&M Transportation Institute, 3135 TAMU, College Station, TX 77843
E-mail: c-gurganus@tti.tamu.edu
Phone: 979-845-5995

Nasir G. Gharaibeh
Associate Professor, Texas A&M University, Zachry Department of Civil Engineering, 3136 TAMU, College Station, TX 77843
E-mail: ngharaibeh@civil.tamu.edu
Phone: 979-845-3362

Tom Scullion
Senior Research Engineer, Texas A&M Transportation Institute, 3135 TAMU, College Station, TX 77843
E-mail: t-scullion@tamu.edu
Phone: 979-845-9913

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ABSTRACT
Inadequate and ineffective roadway and roadside drainage causes highway pavements to fail prematurely. For rehabilitation techniques to perform as desired, surface and subsurface drainage conditions must first be addressed. Mobile LiDAR is emerging as a safe and effective tool for collecting vast amounts of surface data that can assist in developing drainage designs. This paper presents a case study on the application of mobile LiDAR to develop a preliminary drainage design on US 75 in north Texas. A design is provided for an underdrain system that includes both longitudinal and lateral pipes. A roadside grading design is provided that works in concert with the underdrain design to move the water away from the pavement structure. Design constraints and challenges include, a roadside ditch flowline higher than the pavement structure, slope stability concerns along the frontage road, frontslope steepness along a high speed corridor, and depth of cut within the pavement for installation of the underdrain. The preliminary design, developed based on data collected using mobile LiDAR, was provided to TxDOT. This design has already been used to improve the drainage in the roadside ditch.

Keywords: LiDAR, subsurface drainage, underdrain, surface drainage, surface geometry, data collection, laser scanner
INTRODUCTION
This case study evaluates a 700 m (0.4 mi) segment of US 75 in northern Texas that has persistent drainage related failures and distresses. Annual maintenance costs for this section exceed $500,000 with many treatments lasting less than one year. The primary culprit appears to be water under and within the pavement structure. Concrete rubblization, followed by an overlay is currently being considered as a rehabilitation tactic. Prior to rubblization, the base and subgrade must be dried with the installation of an underdrain system. The underdrain system must be constructed in a way that efficiently moves water to the roadside and the roadside must be graded to ensure positive drainage continues away from the pavement.

The present study uses mobile light detecting and ranging (LiDAR) equipment to measure surface features and provide a preliminary design for the roadside drainage and underdrain. The objective of this paper is to demonstrate how mobile LiDAR can be used to develop a preliminary design and work through various design scenarios. The drainage issue within the case study presents both subsurface and surface drainage design components. LiDAR is utilized to link these design components into a preliminary design.

In many cases, civil engineering structures do not fail because of overloading, rather supporting foundation layers become compromised by water infiltration. For highway pavements, extensive damage can be caused by both surface and subsurface water entering base layers more quickly than it can exit (1). When water becomes entrapped within the pavement structure, the strength of unbound layers and subgrade soils is greatly reduced. Pumping begins to occur that can lead to faulting, cracking and shoulder deterioration. Loading a pavement with wet sublayers results in moving the fines out of those layers, leading to a loss of support (2). An example of this type of pumping and faulting, from the case study area, is shown in Figure 1.

FIGURE 1 Water Pumping through Pavement and Shoulder Faulting

LITERATURE REVIEW AND BACKGROUND INFORMATION
The impact of poor drainage on pavement performance and maintenance costs has been noted by many researchers. A case study on Route 656 in Hanover County, Virginia was undertaken to demonstrate the damage associated with poor subsurface drainage. Along Route 656, water was seeping through the asphalt surface. This case study found that the subsurface water was primarily due to groundwater, rather than infiltration through surface cracks. Another case study has been performed that evaluates premature rutting along I-20 in Louisiana. This study concluded that water in underlying layers was the cause of the failures. It was found that the underdrain system was not functioning properly and the water was being forced upward, out of the pavement surface. As the water moved through the layers, underlying layers were weakened further as fine material was transported outward.

Industry is well aware of the need to properly move surface and subsurface water away from the pavement structure. The rapid evolution and integration of LiDAR as a data collection technique offers engineers a newer method of gathering the necessary information to ensure water is moving in the correct direction. The evolution and deployment of LiDAR technology has spawned an NCHRP report and synthesis study. The report encourages the publication of LiDAR work so that researchers and practitioners can learn and improve the use of the technology. This case study assists in filling this need.

During a survey of state DOTs, researchers found that Nevada and Tennessee have or are currently using mobile LiDAR for drainage studies. These studies are predominantly isolated drainage issues that are analyzed at a project level. North Carolina evaluated the use of LiDAR on a test network of over 90 miles. In that study, the use of LiDAR compared well with visual inspection and manual data collection. One of the primary advantages to using LiDAR sited in the North Carolina study was the improved safety element. LiDAR provides engineers with a method to collect vast amounts of data in a safe environment with no need for traffic control, thus also proving safer for motorists.

An active project within Arkansas State Highway and Transportation Department (AHTD) evaluates the use of mobile LiDAR to create datasets that can be mined for roadway and roadside elements. The AHTD project will evaluate the use of mobile LiDAR compared with traditional surveying techniques and stationary LiDAR. Kentucky has posted multiple articles regarding the use and evolution of mobile LiDAR within its Quality Matters periodical. One article touts the safety improvement of mobile LiDAR while collecting more data in a single pass than conventional means could collect in a month. Possible applications of LiDAR include drainage analysis and the increased number of cross sections. Another article touches on applying mobile LiDAR to forensic evaluations and cross slope evaluations.

PROJECT SITE INFORMATION

The project site is located on US 75, on the north side of Sherman, TX, within the TxDOT Paris District. US 75 is a divided highway traveling north and south, with two lanes in each direction, separated by a large grass median. The pavement structure consists of 0.25 m (10 in) of jointed plain concrete pavement over 0.15 m (6 in) of flexible aggregate base, constructed in the early 1980s. The section originally consisted of flexible shoulders, replaced in 1998 with 0.25 m (10 in) jointed plain concrete shoulders. The pavement structure was obtained from previous plan sets. Because LiDAR is a surface measurement tool, subsurface information must be acquired through other means, such as old plans, coring, or radar. Dynamic cone penetrometer (DCP) testing was also performed to evaluate subsurface layers. The most recent traffic data from 2016 indicates an average annual daily traffic (AADT) of 54,544 vehicles per day (vpd).
The area is continually being patched, thus the northbound lanes are being evaluated for potential concrete rubblization followed by a hot-mix overlay. A 2012 internal TxDOT report noted poor drainage at multiple locations along the corridor. The report indicates that long after rain events, water can be seen standing in ditches and there is clear evidence of water pumping through pavement joints (10). Site visits conducted in 2016 verified these observations. Figure 2 is a photo of the site with water pumping through the joints and literally squirting up as a truck passes over the pavement. The subgrade material is typically AASHTO classified as either A-6 or A-7 with a plasticity index in the high 20s or low 30s. The material is high in fines, with 75 to 80 percent of material passing the No. 200 sieve. Bedrock is fairly shallow in the area. It is believed that most of the water is surface water. The study area along US 75 has a natural desire to drain to the east. Between north- and southbound lanes is a large grass median that is flat and holds water. This surface water infiltrates and begins to drain subsurface to the east. As the water slowly drains through the clay, it encounters the northbound mainlanes where it is pumped into and out of the pavement structure by passing traffic. The weakening of the subsurface materials through water infiltration is leading to surface failures, including lane settling, creating a longitudinal lip between the mainlanes and shoulder. Transverse joints are in surprisingly good condition, but signs of water and fines exiting at these locations are evident.

Another issue is a shallow ditch with its flowline near the edge of pavement that does not drain well. Figure 3 is a photo of this ditch with water standing over a week after the last rain event. At this location, the frontage road rises above the mainlanes, creating a frontslope off of...
the frontage road that drives the ditch flowline toward the mainlanes. This presents a significant challenge within the project level analysis.

FIGURE 3 Flat and Shallow Ditch along US 75

POTENTIAL PROJECT SCOPE AND DESIGN CONSTRAINTS
The local TxDOT district is considering the rehabilitation of US 75 through rubblizing the existing concrete pavement and overlaying it with 0.15 m (6 in) of hot-mix asphalt (HMA). It is well known that rubblization will not be effective if attempted over wet and weak subsurface layers. Therefore, mobile LiDAR was utilized to collect surface geometry to determine how roadside drainage could be improved and also to determine how and where a longitudinal underdrain should be placed. In plan view, the underdrain should be placed longitudinally along the joint between the mainlanes and shoulder, ensuring that water under the traveled way is captured and moved out. In order to move the water out, underdrain lateral lines must be constructed to convey the water from the longitudinal line to the roadside.

Many design constraints exist within this project. First, the area in question is in a speed zone transition leaving town. The speed limit increases within the project limits to 75 mph. At this speed limit, the frontslope off of the mainlane shoulder must remain as flat as possible. The flowline of the ditch must be lowered below the bottom of the pavement structure and have positive drainage. The cut required in the ditch must not compromise slope steepness. In order to obtain the required cut and maintain a flat frontslope off of the mainlanes, it would be easiest to move the flowline of the ditch horizontally toward the frontage road. Unfortunately, this cannot be done without creating too steep of a frontage road frontslope. The existing frontslope along the northbound frontage road is as steep as 4.2H:1V with a prolonged slope (~230 ft) of steeper than 5H:1V, all measured with LiDAR data. Using LiDAR data, it is known that the height of the frontslope is between 14 ft and 15 ft and steepening it creates slope stability.
concerns. During project level analysis, the frontage road frontslope is kept as flat as possible, with flatter than 3.5H:1V desirable.

**PROJECT LEVEL ANALYSIS AND DESIGN**

For the project level analysis, 10 data collection runs were performed on January 4, 2016. Each run was collected at approximately 45 mph. Of the 10 runs, three are predominately used for project level analysis. The primary area of interest discussed in this study is a section along the northbound lanes, near a ramp merge point with a shallow, flat ditch along the roadside. Figure 4 is an image of this location.

![Figure 4: Project Level Location](image)

The following design questions are addressed using data collected with mobile LiDAR:

1. What are the limits of the drainage issue along the outside edge of pavement?
2. How shallow is the outside ditch in relation to the pavement structure?
3. What cut is required in the ditch flowline to achieve positive drainage while insuring both mainlane and frontage road frontslopes do not exceed design tolerance?
4. What are the anticipated frontslopes on the mainlanes and frontage road after rubblization and overlay?
5. With these cuts, where are the flowline daylight points?
6. How does the ditch flowline coordinate with the underdrain flowline to insure water is moved out from under the mainlanes?
7. What is the fall and suggested spacing for the underdrain laterals?

LiDAR data was collected using a mobile light detecting and ranging LiDAR systems (MLS) manufactured by Roadscanners Oy of Finland. Data processing occurred in Road Doctor 3 software, also manufactured by Roadscanners. During processing, the data grid was built on 2 ft transverse and longitudinal increments. A 2ft x 2ft data grid builds a matrix consisting of 2 ft longitudinal data as the row descriptor and 2 ft parallel lines as the column descriptor. The
The internal structure of the matrix consists of relative elevation data. In summary, cross sections are cut on 2 ft increments traveling longitudinally down the roadway and profile lines (i.e. lines parallel to the profile of US 75) are cut every 2 ft moving transversely across the area of interest. Additionally, raw reflection data was used to determine the location of lane striping and the edge of pavement.

The area of interest is displayed using LiDAR reflection data in the following figure.

**FIGURE 5** Project Plan View Displayed with Reflection Data

All dimensions in Figure 5 are in meters. The reflection data clearly illustrates the pavement striping. The ramp completes its merge near the 915 m location in the longitudinal direction. The extent of the hill between the mainlanes and frontage road is also clear from approximately 800 m to almost 1000 m. Concrete patches are also easily visible in the reflection data.

In order to answer the design questions above, the existing highpoint of the ditch must be found and the future highpoint of the ditch must be determined. This highpoint will dictate the limits of the drainage problem. Using LiDAR data, it is known that the existing ditch highpoint is located near 810 m. The flowline at this point is higher than the bottom of the pavement structure. From the highpoint, the existing ditch flows to the north with an approximate slope of 0.6%. The flatness of the slope keeps the flowline above the bottom of the pavement structure for over 200 m (650 ft).

In order to visualize the problem and potential solution, Figure 6 displays the current bottom of pavement structure elevation compared with the existing ditch flowline elevation and the proposed ditch flowline elevation. These elevations were generated from LiDAR collected data. The longitudinal reference in Figure 6 matches that in Figure 5 and travels parallel to the northbound mainlane centerline. Existing conditions are built upon LiDAR data which collects a
measurement each time it encounters a target object. This can make the data look noisy, but it provides significantly more information to develop a preliminary design than traditional techniques.

![FIGURE 6 Existing and Proposed Elevations](image)

The current flowline of the ditch is at or near the bottom of the pavement structure elevation from the 800 m mark to approximately 1025 m. The highpoint of the existing ditch near 810 m is also clear in Figure 6. The proposed highpoint is moved to 850 m. This location was fixed after multiple iterations for design. During the multiple iterations, a balance between future frontslope steepness, depth of cut within the pavement, longitudinal slope of the underdrain, and transverse slope of the lateral pipes was sought. The elevation of the highpoint was also set to 0.15 m (6 in) below the bottom of the pavement structure. This value was selected so that a 0.15 m (6 in) underdrain pipe could be installed below the existing pavement structure. From this point, moving both north and south, the goal is to lower the flowline of the ditch to provide adequate outfall slope for the underdrain. In order to lower the flowline to the bottom of the pavement structure, a cut of 0.24 m (0.78 ft) is required. The new frontslope adjacent to the mainlanes will be 8.27H:1V. From this point, the ditch should be graded at 1.5% fall to the south. Following the existing horizontal flowline of the ditch, daylight should be achieved approximately 110 m (360 ft) to the south. Using the existing ditch alignment, daylight should occur approximately 15.5 m (50.5 ft) from the edge of the ramp, measuring perpendicular
to the mainlanes. Moving back to the highpoint, the ditch should be graded to drain to the north
at 1.5% for 30.5 m (100 ft). At this point, the cut should be approximately 0.51 m (1.68 ft),
creating a frontslope approximately 5.3:1 after final pavement construction. After grading at
1.5% for 30.5 m (100 ft), the grade of the ditch should be flattened to 1% to the north and held
for another 30.5 m (100 ft). At this point, the cut is likely to be just above 0.61 m (2 ft), creating
a 4.8H:1V frontslope. Again, the flowline slope should be flattened to 0.5% to the north and
held for 59 m (195 ft) where the cut will be approximately 0.43 m (1.4 ft) and the frontslope will
be 6.4H:1V. Finally, at this point, the flowline should be steepened to 2.4% to the north and held
until daylight. Daylight is expected to occur an additional 79.25 m (260 ft) to the north. As with
drainage to the south, drainage to the north should follow the existing horizontal offset of the
flowline.

Figure 6 and the associated descriptions answer the first five questions raised in the
preceding section. The questions, with answers, are relisted below:

1. What are the limits of the drainage issue along the outside edge of pavement? Using
   the existing horizontal flowline offset, daylight is expected near 740 m and 1050 m.
   The amount of ditch grading required is expected to be approximately 310 m (1015
   ft).

2. How shallow is the outside ditch in relation to the pavement structure? The existing
   flowline is above the bottom of the pavement structure for over 225 m (735 ft).

3. What cut is required in the ditch flowline to achieve positive drainage while insuring
   both mainlane and frontage road frontslopes do not exceed design tolerance? The
cuts and frontslopes are variable. Table 1 displays cut information provided to the
TxDOT district and ultimately to a ditch grading contractor. This cut information
formed the basis for actual field construction. These cuts were developed completely
from LiDAR data. Figure 7 displays the expected future frontslope.

4. What are the anticipated frontslopes on the mainlanes and frontage roads after
   rubblization and overlay? Figure 7 provides information on the expected frontslope
for the mainlanes and frontage road. The mainlane slopes represent the anticipated
slope after overlay.

5. With these cuts, where are the flowline daylight points? These points are listed in the
answer to question 1, where the limits of construction are defined.
### TABLE 1 Designed Ditch Cuts and Slopes

<table>
<thead>
<tr>
<th>Location (m)</th>
<th>Approx. FL Offset (m)</th>
<th>Depth of cut (m)</th>
<th>Ditch Flowline Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>-110</td>
<td>15.4</td>
<td>0</td>
<td>-1.50%</td>
</tr>
<tr>
<td>-91</td>
<td>14.1</td>
<td>0.144</td>
<td>-1.50%</td>
</tr>
<tr>
<td>-76</td>
<td>14.5</td>
<td>0.56</td>
<td>-1.50%</td>
</tr>
<tr>
<td>-61</td>
<td>12.7</td>
<td>1.12</td>
<td>-1.50%</td>
</tr>
<tr>
<td>-46</td>
<td>7.1</td>
<td>0.973</td>
<td>-1.50%</td>
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<td>-31</td>
<td>7.3</td>
<td>0.774</td>
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<tr>
<td>-16</td>
<td>5.7</td>
<td>0.547</td>
<td>-1.50%</td>
</tr>
<tr>
<td>Highpoint</td>
<td>4.6</td>
<td>0.239</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>4.6</td>
<td>0.42</td>
<td>-1.50%</td>
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<tr>
<td>31</td>
<td>4.6</td>
<td>0.513</td>
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</tr>
<tr>
<td>46</td>
<td>4.9</td>
<td>0.629</td>
<td>-1.00%</td>
</tr>
<tr>
<td>61</td>
<td>4.9</td>
<td>0.646</td>
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<td>5.5</td>
<td>0.626</td>
<td>-0.50%</td>
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<td>137</td>
<td>6.1</td>
<td>0.726</td>
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<td>152</td>
<td>7.3</td>
<td>1.03</td>
<td>-2.40%</td>
</tr>
<tr>
<td>167</td>
<td>11.6</td>
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<td>182</td>
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<td>0.868</td>
<td>-2.40%</td>
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<tr>
<td>197</td>
<td>24.4</td>
<td>0.251</td>
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</tr>
<tr>
<td>200</td>
<td>24.4</td>
<td>0</td>
<td>-2.40%</td>
</tr>
</tbody>
</table>
Figure 7 indicates frontage frontslopes remain at or near 4H:1V except for a short section between 900 m and 950 m. Even within this section the frontage frontslope maximum steepness is 3.78H:1V, a steepness, assuaging slope stability concerns. Mainlane frontslopes will become steeper than 6H:1V, specifically in the area where the current ditch is shallow and closest to the edge of pavement. For the most part, final mainlane frontslope steepness, that is after rubblization and overlay, will be near 5H:1V. The use of LiDAR in this design presents engineers with the unique ability to completely understand the frontslopes and how different techniques may affect those slopes. Ultimately, a more informed design decision is made.

While solving the roadside drainage issue is integral, it will only be effective if it is done in a way that provides positive drainage to the underdrain system. Mobile LiDAR measurements provide accurate surface data on US 75. The surface of US 75, within the area of interest, has 0.5 percent fall toward the north. With a flat profile grade, minimizing the cut to the underdrain flowline becomes challenging. Using a 0.15 m (6 in) diameter underdrain pipe, the minimum cut from the pavement surface is 0.56 m (22 in). This cut is required to get below the pavement structure of 0.41 m (16 in) and account for the 0.15 m (6 in) diameter pipe. Figure 8 displays two underdrain options, along with the preliminary longitudinal underdrain design provided to TxDOT.

Option 1 in Figure 8 sets the underdrain highpoint at the ditch flowline highpoint and provides two percent fall in each direction. With this option, by the 1050 m mark, the cut below
the pavement surface exceeds 3 m (9.8 ft). Option 2 moves the underdrain highpoint to the 740 m location and places the flowline at the minimum cut of 0.56 m. One percent fall is provided to the north to 1050 m. Even with a flatter flowline slope, the cut at 1050 m exceeds 2 m (6.6 ft). Using the LiDAR data for design, it is clear that the longitudinal underdrain must be placed with a very flat flowline slope. Through multiple iterations, a design was provided placing the underdrain highpoint at 740 m with the minimum cut of 0.56 m. The design underdrain passes through the 850 m mark with a flowline elevation equal to the new roadside ditch flowline elevation. This flat-spot is overcome by designing lateral underdrain lines to have adequate fall on each side of the flat-spot.

The description above makes it clear that the lateral underdrain lines will be required to move the water out from under the pavement structure. The longitudinal underdrain flowline designed in Figure 8 was done to create a flat-spot at the ditch highpoint, but allow for lateral pipes with at least two percent fall within 15.24 m (50 ft) of the flat-spot. Potential design slopes for lateral underdrain pipes are shown in Figure 9. Lateral outfall pipes should be placed at spacings to meet many design considerations. A primary consideration is moving the water out in a relatively flat area. Additionally, lateral spacing should be close enough to allow for periodic clean-out of the longitudinal pipe. Figure 9 allows engineers to adjust lateral spacing with an understanding of how steep the flowlines can become. The flat-spot is clearly visible at

![FIGURE 8 Longitudinal Underdrain Path Options](image-url)
850 m, but within 10 m (33 ft) on either side, lateral lines can be placed with two percent fall. The longitudinal underdrain at this location has 0.25 percent fall to the north. The initial underdrain design provided to TxDOT recommends placing lateral lines at 30 m (100 ft) spacings to ensure water is efficiently moved out from under the pavement with lateral lines.

FIGURE 9 Potential Lateral Underdrain Pipe Slopes

Figure 9 and the description associated with it help to answer the final two design questions.

6. How does the ditch flowline coordinate with the underdrain flowline to insure water is moved out from under the mainlanes? Figure 8 and Figure 9 illustrate the answer to this question. In summary, the new flowline of the ditch is low enough to provide adequate water outfall from the underdrain flowline which is necessarily flat to avoid excessive cut within the pavement. The roadside is regraded in such a way to continue to move water away from the pavement.

7. What is the fall and suggested spacing for the underdrain laterals? Figure 9 provides information on percent fall potential for lateral lines. The critical point is near the 850 m location where the ditch flowline and underdrain flowline are designed at the same elevation. The ditch is graded to begin to provide lateral fall as quickly as possible without increasing the cut too much to exceed front slope design constraints.
Table 2 is a small portion of a design table provided to TxDOT. This table combines ditch, longitudinal, and lateral underdrain information. Arrows within the table indicate additional data is available within the master table.

**TABLE 2 Flowline Design Table**

<table>
<thead>
<tr>
<th>Location (m)</th>
<th>Design Ditch FL Elev. (m)</th>
<th>Ditch FL Long. Slope (%)</th>
<th>UD FL Elev. (m)</th>
<th>UD Long. Slope (%)</th>
<th>Offset from UD to Ditch (m)</th>
<th>UD Lateral Slope (%)</th>
<th>New Mainlane Front-slope (#H:1V)</th>
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**CONCLUSIONS AND FUTURE WORK**

Mobile LiDAR provides a safe and effective means to capture vast amounts of accurate surface geometric data. The study described in this article demonstrates how LiDAR data can be used to develop a preliminary design for the improvement of roadside drainage and installation of underdrain. This design is vital to the implementation of a permanent rehabilitation strategy for a portion of US 75 in northern Texas. The location in the case study proved challenging because of a shallow and flat ditch near the mainlanes. The flowline offset of this ditch was controlled by slope stability concerns of the frontslope along the frontage road and mainlane frontslope steepness.

Data collected using mobile LiDAR provided the information to develop a preliminary design that will improve roadside drainage by lowering the ditch flowline below the bottom of...
the pavement structure. A grading plan is developed to ensure longitudinal fall of the new ditch. The design of the ditch works in coordination with the design of an underdrain system to be constructed at the joint between the mainlanes and shoulder. LiDAR provides the data to design the underdrain by controlling the depth of cut below the pavement surface while ensuring adequate lateral fall between the longitudinal underdrain and the ditch flowline. A flat profile grade along US 75 controlled the allowable fall in the longitudinal pipe to a substantially flat design. Working through the design flowline of the ditch and coordinating it with the design flowline of the longitudinal pipe, underdrain lateral pipes were designed to be equipped with at least two percent fall except in a small window near the ditch highpoint.

Cut data and preliminary design information was provided to the governing TxDOT district. Several weeks after ditch grading, TxDOT personnel indicated the ditch was still dry, empirically performing better than prior to the ditch cleaning. Future work includes investigating the use of post-construction LiDAR data for quality assurance purposes.

Opportunities exist for future research in this area, including a) the use of mobile LiDAR at the network level to identify roadway and roadside sections with potential drainage issues, leading to proactive (rather than reactive) maintenance work, and b) improvements to LiDAR data processing and analysis capabilities to facilitate the use of this technology in drainage design at the production level within the industry.

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REFERENCES


