Louisiana Transportation Research Center

Technical Assistance Report 18-04TA-P

Submerged Road Characteristics and Distresses on LA 493, Natchitoches Parish, State Project Number H.011071

by

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TECHNICAL REPORT STANDARD PAGE

1. Report No. **FHWA/LA.17/18-04TA-P**	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle **Submerged Road Characteristics and Distresses on LA 493, Natchitoches Parish, State Project Number H.011071**	**5. Report Date** May 2019 6. Performing Organization Code	
7. Author(s) Kevin Gaspard, P.E., and Zhongjie Zhang, Ph.D., P.E	**8. Performing Organization Report No.**	
9. Performing Organization Name and Address Louisiana Transportation Research Center 4101 Gourrier Ave. Baton Rouge, LA 70808	**10. Work Unit No.** **11. Contract or Grant No.**	
12. Sponsoring Agency Name and Address Louisiana Department of Transportation and Development P.O. Box 94245 Baton Rouge, LA 70804-9245	**13. Type of Report and Period Covered** Technical Assistance Report August to November 2017 **14. Sponsoring Agency Code**	

15. Supplementary Notes

Conducted in Cooperation with the U.S. Department of Transportation, Federal Highway Administration

Executive summary

The Louisiana Transportation Research Center (LTRC) is conducting a research project to determine the pavement and embankment distress mechanisms associated with normal seasonal variation changes in the subgrade soil and base course moisture content in areas with and without trees. Approximately two months after the newly constructed asphaltic concrete roadway was fully opened to traffic, it was submerged for several months (January 2016 to March 2016) due to a heavy rainfall event. Since that time, it was submerged twice more from February 2017 to April 2017 and July 2017 to August 2017. Submergence events created higher subgrade soil and base course layer saturation events beyond the "normal" seasonal variation in those layers based upon LTRC's knowledge. Because of that, the original experiment was adjusted to accommodate the submergence events.

The damage to the pavement structure in the six test sites caused by the submergence events could now be catalogued on a newly constructed pavement during the time period of December 2015 to July 2018. A cross-section survey was conducted in December 2015 approximately one month prior to the first submergence event (January 2016). Subsequent cross-section surveys were conducted. The test sites were assessed with LTRC's roadway surface profiler and imaging system on June 2017 and June 2018. Information from the profiler and imaging system provided information on the roughness of the roadway as measured by the International Roughness Index (IRI), roadway surface profile, roadway surface rutting, and roadway surface cracks. With these parameters inferences were made on the damage caused by the submergence events.

Cross-section surveys clearly demonstrated the elevation increases and differential movements across the pavement surface caused by the submergence event(s). The increase in elevation at the center line of the roadway ranged from 2.44 mm to 44.50 mm. With the exception of cross-section Site 1A, cross-section points right and left of the centerline all increased with no adjacent point having the same magnitude of increase within each cross-section. This in and of itself will cause damage to the entire roadway section (pavement and soil cement base course). The differential movements in the cross-sections occurred to varying degrees at the different test sites as observed on subsequent cross-section surveys. Movements of differing proportions throughout the service life of the pavement will adversely affect its performance and reduce its service life.

The data gathered from the profiler and imagining system also provided evidence of damage caused by submerging the newly constructed pavement. On the June 2017 assessment, the maximum IRI was 141.8 and the minimum was 84.7 for both travel lanes in the test sites. At that time the pavement had been in service for approximately 19 months of which it was submerged for 3 months. When the new roadway was fully opened to traffic, it is reasonable to assume that the roadway had no surface cracks or rutting and that the IRI would have been less than or equal to 75 in./mile, which is DOTD's IRI requirement for this type of newly constructed roadway. With that being the case, IRI values as high as 141.8 greatly exceeds the IRI values that should have been present on a low volume roadway at this point in its service life. On the June 2018 assessment, the IRI values ranged from 176.5 to 75.2. There was a slight increase in roughness between the 2018 and 2017 assessment period which was to be expected. The high variability in IRI magnitudes observed in the test site locations which were a total length of 4,702 ft. indicate that significant differences in the longitudinal profile existed. Plots of the longitudinal profile confirmed this. The rutting data also pointed towards damage in the roadway structure. There was a high variability in rutting amongst the test sites. Rutting values as high as 42.8 mm were measured.

Regarding roadway surface cracking, only longitudinal cracks were observed on the test sites. The observed longitudinal cracks in the test sites ranged from 3 ft. to 1,003 ft. and 16 ft. to 1,017 ft., respectively, on the June 2017 and 2018 assessments. The amounts of longitudinal cracks observed indicated that (1) most of the sites had excessive longitudinal cracking for the time that they were in service, (2) the longitudinal cracking observed is consistent with volumetric changes occurring in the subgrade, and (3) it is logical to infer that the submergence events were responsible for both the magnitude and premature emergence of these longitudinal cracks.

17. Key Words		**18. Distribution Statement** **Unrestricted. This document is available through the National Technical Information Service, Springfield, VA 21161.**	
19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	21. No. of Pages	22. Price

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conducted for

Louisiana Department of Transportation and Development
Louisiana Transportation Research Center

May 2019

EXECUTIVE SUMMARY

The Louisiana Transportation Research Center (LTRC) conducted a research project to determine the pavement and embankment distress mechanisms associated with normal seasonal variation changes in the subgrade soil and base course moisture content in areas with and without trees. Approximately two months after the newly constructed asphaltic concrete roadway was fully opened to traffic, it was submerged for several months (January 2016 to March 2016) due to a heavy rainfall event. Since that time, it was submerged twice more from February 2017 to April 2017 and July 2017 to August 2017. Submergence events created higher subgrade soil and base course layer saturation events beyond the "normal" seasonal variation in those layers based upon LTRC's knowledge. Because of that, the original experiment was adjusted to accommodate the submergence events.

The damage to the pavement structure in the six test sites caused by the submergence events could now be catalogued on a newly constructed pavement during the time period of December 2015 to July 2018. A cross-section survey was conducted in December 2015 approximately one month prior to the first submergence event (January 2016). Subsequent cross-section surveys were conducted. The test sites were assessed with LTRC's roadway surface profiler and imaging system on June 2017 and June 2018. Information from the profiler and imaging system provided information on the roughness of the roadway as measured by the International Roughness Index (IRI), roadway surface profile, roadway surface rutting, and roadway surface cracks. With these parameters, inferences were made on the damage caused by the submergence events.

Cross-section surveys clearly demonstrated the elevation increases and differential movements across the pavement surface caused by the submergence event(s). The increase in elevation at the center line of the roadway ranged from 2.44 mm to 44.50 mm. With the exception of cross-section Site 1A, cross-section points right and left of the centerline all increased with no adjacent point having the same magnitude of increase within each cross-section. This in and of itself will cause damage to the entire roadway section (pavement and soil cement base course). The differential movements in the cross-sections occurred to varying degrees at the different test sites as observed on subsequent cross-section surveys. Movements of differing proportions throughout the service life of the pavement will adversely affect its performance and reduce its service life.

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that time, the pavement had been in service for approximately 19 months of which it was submerged for 3 months. When the new roadway was fully opened to traffic, it is reasonable to assume that the roadway had no surface cracks or rutting and that the IRI would have been less than or equal to 75 in./mile, which is DOTD's IRI requirement for this type of newly constructed roadway. With that being the case, IRI values as high as 141.8 greatly exceeds the IRI values that should have been present on a low volume roadway at this point in its service life. On the June 2018 assessment, the IRI values ranged from 176.5 to 75.2. There was a slight increase in roughness between the 2018 and 2017 assessment period, which was to be expected. The high variability in IRI magnitudes observed in the test site locations, which were a total length of 4,702 ft., indicate that significant differences in the longitudinal profile existed. Plots of the longitudinal profile confirmed this. The rutting data also pointed towards damage in the roadway structure. There was a high variability in rutting amongst the test sites. Rutting values as high as 1.685 in. were measured.

Regarding roadway surface cracking, only longitudinal cracks were observed on the test sites. The observed longitudinal cracks in the test sites ranged from 3 ft. to 1,003 ft. and 16 ft. to 1,017 ft., respectively, on the June 2017 and 2018 assessments. The amounts of longitudinal cracks observed indicated that (1) most of the sites had excessive longitudinal cracking for the time that they were in service, (2) the longitudinal cracking observed is consistent with volumetric changes occurring in the subgrade, and (3) it is logical to infer that the submergence events were responsible for both the magnitude and premature emergence of these longitudinal cracks.

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INTRODUCTION

The Louisiana Transportation Research Center (LTRC) conducted a research project to determine the pavement and embankment distress mechanisms associated with normal seasonal variation changes in the soil moisture content especially when trees are present. The project is entitled "Prevention of Extensive Desiccation Cracking on Rural Highways."

The original major objectives were:

1. Measure the vertical profile changes of the pavement surface due to the seasonal expansion and swelling of the embankment where trees were present.
2. Measure the seasonal volumetric moisture changes in the soil layers.
3. Measure the seasonal soil suction changes in the soil layers.
4. Measure the vertical tilt of the embankment slope.
5. Construct test sections and evaluate their performance based on distresses typically measured by the Louisiana Department of Transportation and Development's (DOTD) Pavement Management System (PMS).

The experiment designed by LTRC was based on assessing the "normal seasonal variation properties" of the pavement layers for LA 493. Appendix 1 contains the title sheet for the plans under which the project was constructed. Unfortunately, approximately two months after the roadway was fully opened to traffic, it was submerged for several months (January 2016 to March 2016) due to a heavy rainfall event. Since that time, it was submerged twice more: February 2017 to April 2017 and July 2017 to August 2017. Submergence events created higher soil saturation events beyond the "normal" seasonal variation in the soil and base course layers based upon LTRC's knowledge. Therefore, the original experiment had to be adjusted to accommodate the submergence events.

The damage to the pavement structure caused by the submergence events could now be catalogued on a newly constructed pavement during the time period of December 2015 to the writing of this report. A cross-section survey was conducted in December 2015 approximately one month prior to the first submergence event (January 2016). Subsequent cross-section surveys were conducted and the results from the cross-section surveys will be presented later in this report.

Pavement Distresses and Soil Physics

Pavement surface and embankment distresses due to seasonal moisture variation in the base course, subgrade, foreslope, ditches, and backslope are both a national and international issue existing since the first hard surfaced pavements were constructed *[1-8]*. Clay soils, which are prevalent in some regions of Louisiana, can be particularly vulnerable to changes in moisture content, shrinking during drying (desiccation) and swelling during wetting (absorption). In some instances, soils with high silt contents may also exhibit volume changes and desiccation cracking. Volume changes and/or tension cracks can be accelerated or increased when trees are present, since they extract water from the soil, which in turn increases the suction stresses in the soil as well as the magnitude of moisture content changes due to the seasonal wetting and drying the embankment soil and base course.

In Louisiana, it is LTRC's opinion that a proportion of longitudinal cracks, meandering cracks, subsidence, and heaving in the pavement layers have occurred as a result of seasonal volume changes in the roadway embankment. In some instances, trees are present which further adds to the distresses previously mentioned as presented in Figures 1 and 2. Distresses and volume changes have and will continue to lead to pavement service life reduction, costly maintenance repairs, and complaints from the public.

Figure 1
Longitudinal cracks: LA 1200: CSLM 2.348

Figure 2
Multiple Longitudinal cracks: LA 494: CSLM 1.864

Pavement surface distresses resulting from seasonal soil moisture content variation can be attributed to four major factors as well as their interactions:

a. Transverse and longitudinal volumetric change differential (due to wetting and drying) in the embankment, base course, and adjacent natural ground
b. Desiccation cracking
c. Dynamic settlement due to soil densification caused by soil suction stresses
d. Slope failures

Volumetric changes in the subgrade and/or base course differ in the travel lane(s) in that the volume change at the center line of the pavement differs significantly from the volume change at the pavement edge. Near the pavement edge, movement may be significant enough to cause damage as presented in Figure 3. Such a volumetric differential can manifest either as single or multiple longitudinal crack(s) beginning approximately 1 to 3 ft. from the pavement edge due to pavement bending (heave and subsidence) as presented in Figures 1, 2, and 3 *[7-11]*. As a result of continual bending, alligator cracking patterns have been known to occur in the asphaltic (AC) surface as presented in Figure 4. The volume change also occurs longitudinally along the travel lane(s) which can lead to bumps and depressions in the pavement. This in turn contributes to decreased ride quality due to the changes in the roadway profile.

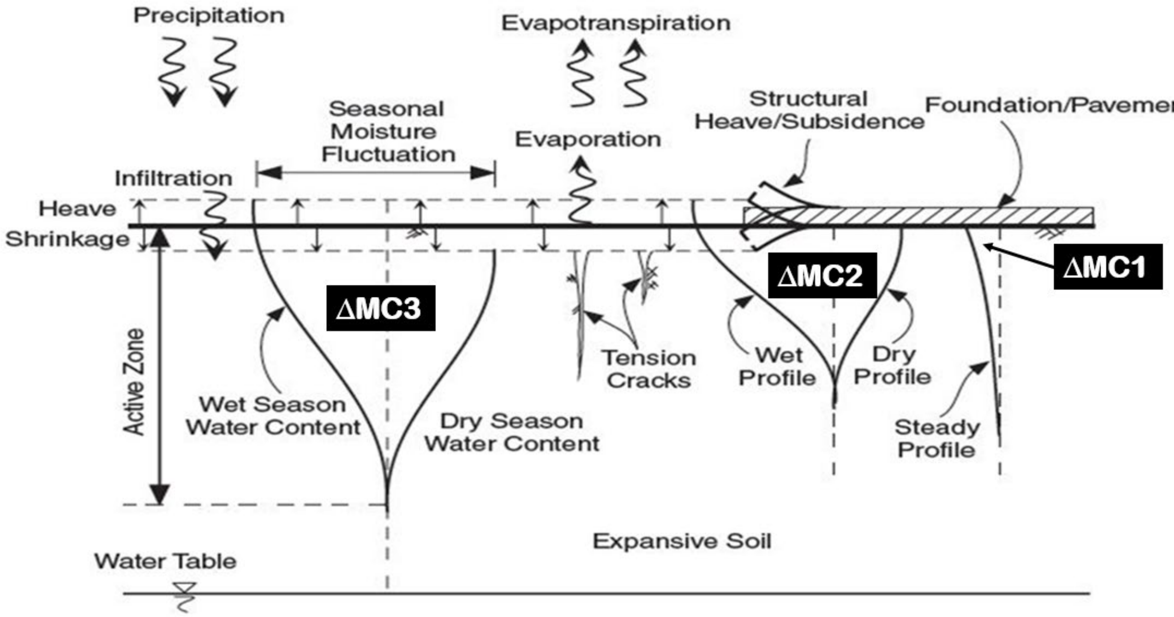

Figure 3
Heave and shrinkage profiles: Source Lu *[6]*

Figure 4
Alligator cracking in AC surface

Longitudinal cracks in the pavement may also be caused by desiccation in the expansive clay. When the soil suction stresses induced by desiccation coupled with net normal stress exceed the tensile strength of the soil, a crack will form as shown in Figure 3 *[4-6]*. When this occurs beneath the pavement, it is possible for the crack to propagate through the pavement structure as presented in Figures 1 to 3.

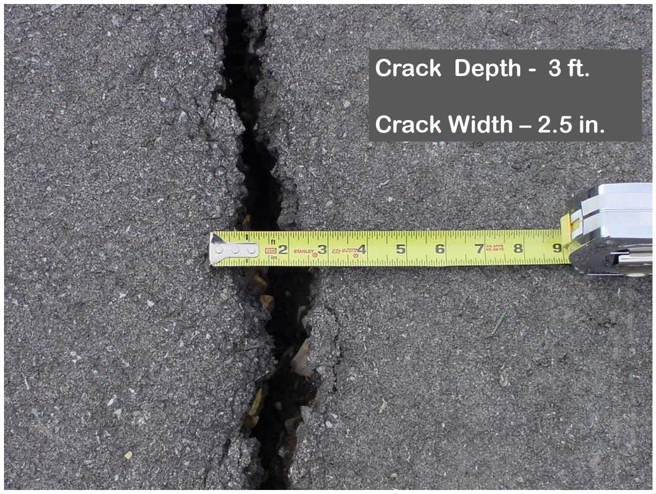

Figure 5
Parish Road: St. Martin Parish

While it is possible for desiccation to be completely driven by evaporation alone, the presence of flora accelerates the process through transpiration. Transpiration is the passage of water through a plant or tree from its roots through its vascular system to the atmosphere by way of the leaves *[1, 12-14]*. The transpiration period for trees typically begins during the spring and peaks during the summer months, which adds to the desiccation caused by evaporation. The process of evaporation and transpiration together is called evapotranspiration *[1]*.

When the yearly rainfall is insufficient to return the active zone (the depth of soil layer(s) impacted by evapotranspiration) to its field capacity (equilibrium saturation), a zone of permanent of desiccation is created as presented in Figure 6 *[1-3, 12, 13]*. If permanent desiccation occurs either near the pavement edge or beneath it, permanent settlement (dynamic settlement) at that location may be the culprit of both multiple longitudinal cracks and subsidence as shown in Figures 1, 2, 6, 7, and 8 *[12]*.

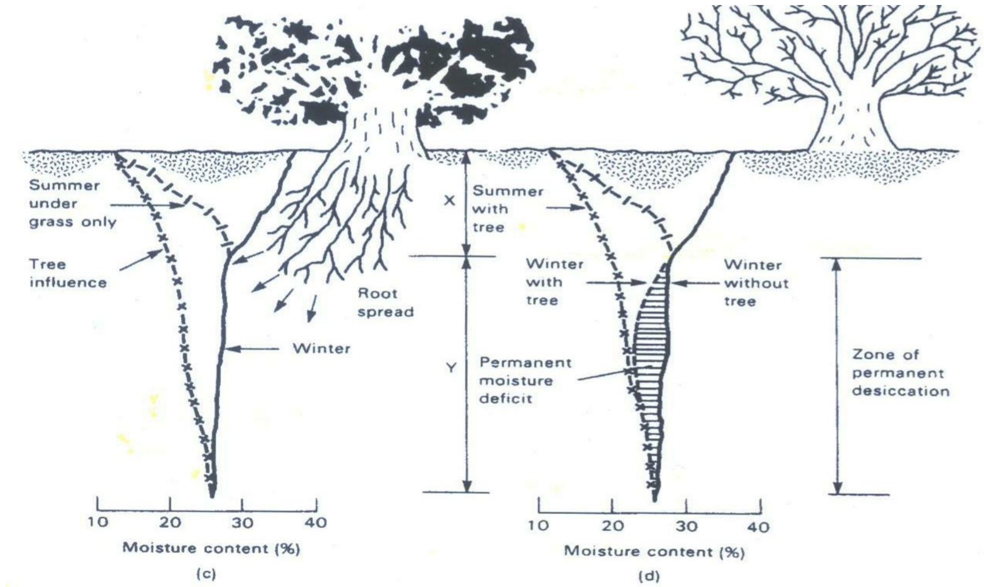

Figure 6
Permanent desiccation: Source: Roberts *[13]*

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Figure 7
Multiple longitudinal cracks and subsidence: West Parker near LTRC

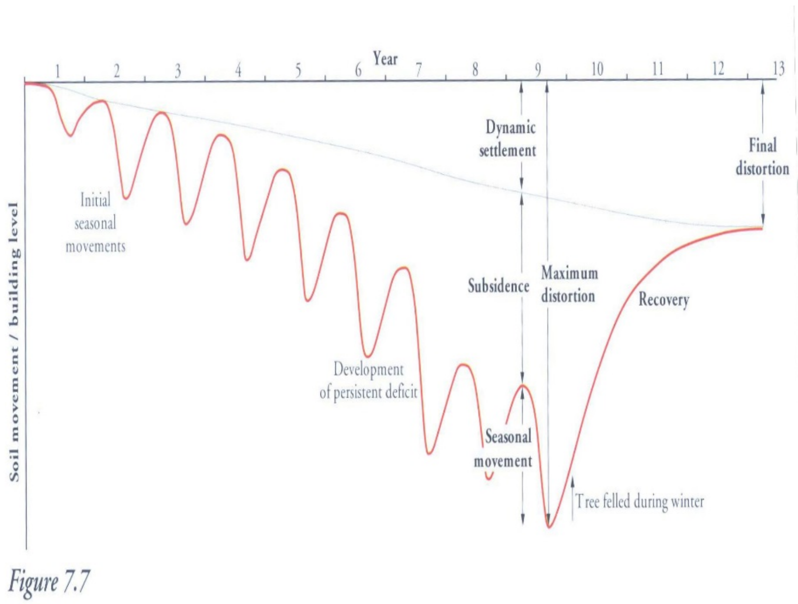

Figure 8
Dynamic settlement: Source Biddle *[12]*

Slope failures may also occur due to seasonal moisture variation. If tension cracks develop in the embankment slope during desiccation, a failure plane may develop. Tension cracks create direct paths for water infiltration, which can saturate the embankment reducing its shear strength which can lead to failure. Cracks as deep as 3 ft. and as wide as 2.5 in. have been measured by LTRC as presented in Figure 5. These cracks are probably due to a combination of distress mechanisms such as volumetric changes, desiccation cracking, and slope failures.

Submergence

The pavement distress and soil physics phenomenon previously described were intended to illustrate what happens during normal seasonal wetting and drying events. Submergence of the roadway serves to exacerbate the swelling and shrinking of expansive soils by fully saturating (100%) the soil and base course.

For example, assume that that the volumetric moisture content (VMC) beneath the pavement (ΔMC1) normally ranges from 70 to 90%, and the VMC at the edge of the pavement (ΔMC2) normally ranges from 40 to 70% while the VMC at a location away from the pavement (ΔMC3) (natural ground) ranges from 20 to 60% seasonally; see Figure 3.

After a submergence event, it is possible and probable for the soil to fully saturate (VMC = 100%) at ΔMC1, ΔMC2, and ΔMC3. Once the flood waters recede and the roadway, embankment, and natural ground become exposed to the atmosphere and sunlight, evaporation will occur. If it is in the spring and summer, evaporation will be even greater where trees are present due the transpiration of the trees and other flora. So instead of ΔMC1, ΔMC2, and ΔMC3 ranging from their normal VMC maximums of 90%, 70%, and 60%, they now range respectively from 100% to 70%, 100% to 40%, and 100% to 20%. Such changes in the VMC in an expansive soil will increase the magnitude of its swell, thus, leading to a larger range of ground movement due to swell. Furthermore, as evaporation and transportation remove water from the ground and beneath the pavement surface, shrinkage will occur leading to subsidence in the ground. However, under this circumstance, the range between swelling and shrinking is greater than the normal range witnessed for this area under normal seasonal variation. Such a range in movement can damage the pavement leading to premature failures and cracking with subsequent service life reductions. Figure 9 presents the general relationship of void ratio (e) versus VMC for an expansive soil. As the soil varies in its mineralogical composition, so will the relationship between void ratio and VMC. Through formulas, the volume change and subsequent change in height or ground movement can be calculated.

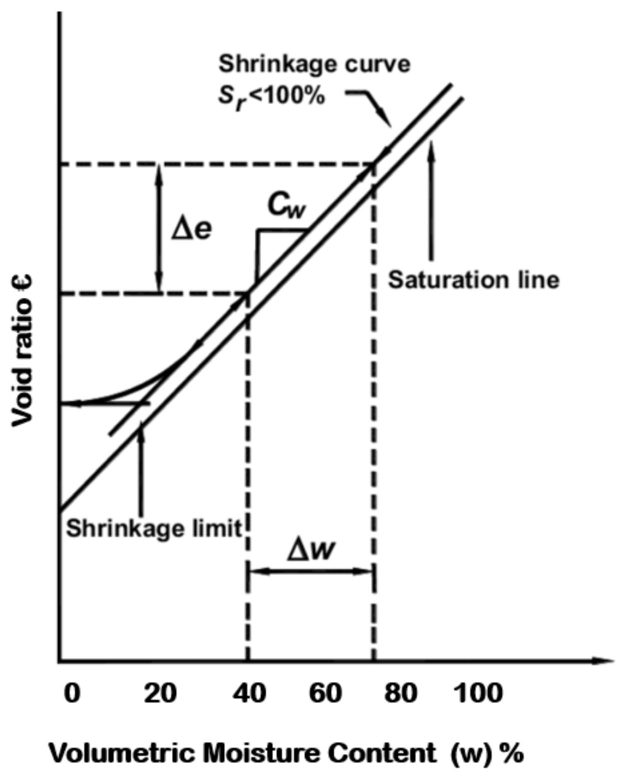

Figure 9
Volumetric moisture content versus void ratio

METHODOLOGY

Experiment Design

The location selected for the test sites was LA 493 in Natchitoches Parish. It is a low-volume road with an average daily traffic of 330 with 12 percent trucks. Test site treatments varied in thickness and type as presented in Table 1. They were initially designed to discover the effectiveness of the treatments on mitigating pavement distresses caused by "normal" seasonal volumetric changes in expansive clays when trees are located at the right- of-way line as presented in Figure 10. Figures for the typical section for each test site can be found in Appendix 2.

Table 1
Experimental test sites

Test Site Number	Notes	Additional Treatments	Stations			Typical Section Layers (in.)								
			From	To	Length (ft.)	AC	AST	SC	Stone	Geogrid	Geosynthetic Fabric	Sand Layer	Select Material	Lime Treated
1A	No Trees		10+00	12+00	200	3.5	Yes	8.5	No	No	Yes	12	3.5	No
1			12+00	18+00	600	3.5	Yes	8.5	No	No	Yes	12	3.5	No
2			18+00	25+00	700	3.5	No	8.5	4	No	Yes	No	12	12
3		Paved Foreslope of Embankment	25+00	32+00	700	3.5	Yes	8.5	No	No	Yes	No	12	12
4		Sand Basin in Ditch Bottom	33+02	41+02	800	3.5	Yes	8.5	No	No	Yes	No	12	12
5	Control Section Without Grid		41+02	49+02	800	3.5	Yes	8.5	No	No	Yes	No	12	12
6	Control Section With Grid		49+02	57+02	800	3.5	Yes	8.5	No	Yes	Yes	No	12	12

Legend: AC- asphaltic concrete; AST- asphalt surface treatment on soil cement; SC- soil cement base course; Stone- crushed stone base course interlayer; Select Material- soil that meets DOTD's usable soil criteria; Lime Treated - subgrade soil that was treated with lime.

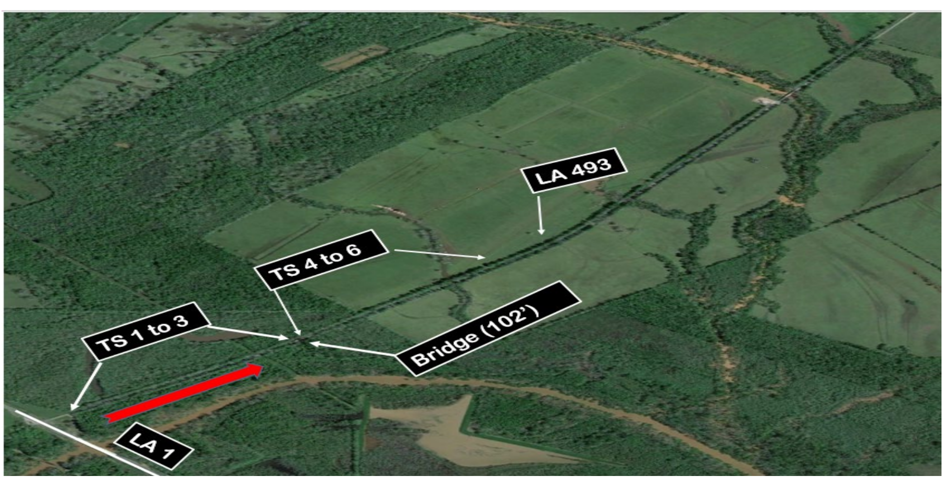

Figure 10
Aerial view of LA 493 test section locations

Three submergence events occurred after both lanes of the roadway were open to traffic in December 2015. The first submergence event occurred from approximately January 2016 to March 2016. Subsequent submergence events occurred on February 2017 to April 2017 and July 2017 to August 2017. These events negated the original intent previously discussed; but, LTRC was able to develop a new experiment in which the effects of submergence could be investigated on the test sections constructed on this project which will be discussed later.

Soil Classifications

During construction on this project, soil samples were taken in the test section locations as presented in Table 2. The results of the soil classification tests indicated that the untreated soil in the subgrade were clays with AASHTO classification types of either A-7(6) or A-7(5). Clays with liquid limits (LL) greater than 70 have severe swelling/shrinkage potential *[1-5]*. Rows in Table 2 with lime listed in them refer to the lime treated subgrade layer. The select material used on the project met DOTD's usable soil criteria and classified as an A-6(4) while the sand used on the project classified as an A-3. The column labeled in-place moisture content refers to the gravimetric moisture content present in the soil when they were collected from the field.

Table 2
Soil classifications

Test section & layer	AASHTO Type	USCS Type	In-place moisture content	Atterberg Limits %			Organic Content
			%	LL	PL	PI	%
Site 1 Subgrade	A-7(6)	CH	**26.5**	79	27	52	2
Site 3 Subgrade	A-7(6)	CH	25.1	76	25	51	1
Site 3 Lime	A-7(5)	CH	25.6	67	30	37	1
Site 4 Subgrade	A-7(5)	CH	14.0	64	24	40	1
Site 4 Lime	A-7(6)	CL	18.3	42	28	14	1
Site 5 Subgrade	A-7(5)	CH	17.1	57	20	37	2
Site 5 Lime	A-4 (0)	SM	17.9	40	35	5	1
Select Material	A-6 (4)	CL	20.7	35	21	14	1
Sand	A-3 (0)	SW	4.7	22	22	0	0

Cross-section Survey Locations and Dates

LTRC conducted cross-section surveys in each of the test site at the locations and dates presented in Tables 3 and 4. Two locations were surveyed in Test Site 1 because the first portion of the site (Station 10+00 to approximately Station 12+00) had no trees adjacent to the right-of-way and the second portion (Station 12+00 to Station 18+00) did. At the time of the first cross-section survey date (12/7/2015), the roadway had been open to traffic for approximately 1 month and then flooded from approximately January 2016 to March 2016. The level used for the cross-section survey was a Trimble "DINI" digital level and readings were recorded at a vertical accuracy of 0.3048 mm. The bench mark used for the survey was the bridge concrete rail at approximately Station 32+50, left of the centerline.

Table 3
Cross-section locations

Test Site	Cross-section survey	Location (Station)	Trees Present
1	1A	10+75	No
	1	14+00	Yes
2	2	21+44	Yes
3	3	29+19	Yes
4	4	37+14	Yes
5	5	45+21	Yes
6	6	53+08	Yes

Table 4
Cross-section survey dates

Cross-section survey dates
12/7/2015
4/25/2016
6/16/2016
9/20/2016
12/6/2016
4/25/2017
7/13/2017
9/15/2017
12/6/2017
3/15/2018

Roadway Profiling and Imaging

LTRC's roadway profiler and imaging vehicle, hereafter referred to as profiler, was used to assess the roadway surface in the test section locations. LTRC's profiler is unique in that it measures the roadway surface profile in the left wheel path (LWP), right wheel path (RWP) and in the center of the lane (CLP). From the profile measurements, the International Roughness Index (IRI) is calculated. On typical roadways, both the LWP and RWP IRI measurements will be generally higher than the CLP IRI measurements. This is because the vehicle tires generally do not make contact with the center of the lane. In most cases, the IRI measurements from the RWP will be greater than the LWP. If the CLP IRI measurements exceed either or both of the LWP and RWP measurements, then it is probably caused by something other than normal traffic loadings such as volumetric changes in the subgrade. The imaging system was used to measure and locate cracks in the asphaltic concrete roadway surface. This provides insights into the types of distress mechanisms occurring in the pavement structure.

Due to mechanical issues, inclement weather, and submergence events, the test sections were assessed on two occasions: June 2017 and June 2018. The service life of the pavements were approximately 18 months (June 2017) and 30 months (June 2018) at the time of those assessments. The roadway had been submerged twice at the June 2017 date and once more by June 2018 so the effects of submergence can be measured. Unfortunately, no assessments had taken place prior to the January 2016 to March 2016 and February 2017 to April 2017 submergence events. However, it is reasonable to assume that no distress cracks or rutting were present prior to the first submergence event and the smoothness of the road International Roughness Index (IRI) would have conformed to DOTD's requirement of less than 75 in./mile for new roadways of this functional class.

DISCUSSION OF RESULTS

Cross-section Survey

LTRC conducted cross-section surveys at the points on the roadways AC surface shown on Figure 11. Doing so provided insight on the magnitude of movement translating to the surface of the roadway due to submergence. Measurements, vertical and horizontal, were converted and are presented in metric units (mm) for convenience purposes. As previously presented in Table 3, cross-section surveys were conducted at seven locations in six test sites at the 10 dates presented in Table 4.

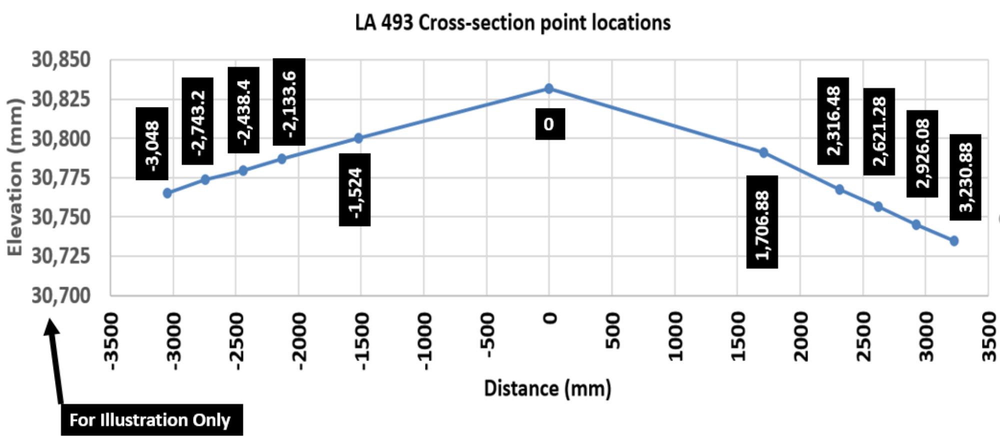

Figure 11
LA 493 cross-section point locations

Site 1A Cross-section Results

Tables 5-6 and Figures 12-13 present the cross-section results. Table 5 provides the elevations (mm) of each cross-section point as well as the dates on which they were taken for informational purposes. Table 6 presents the results of the change in elevation for each cross-section point from the initial preflooded event (12/7/2015). For example, the measured elevation of the center line point (0) on 12/7/2015 was 30831.74 mm and was 30834.18 on 4/25/2016, as presented in Table 5. The difference between the two (30834.18-30831.74) equals 2.44 mm, as presented in Table 6. The same computations were performed for each cross-section point at each date and a similar logic was followed for the remaining cross-section locations in the test sites. For clarity purposes, the first row in Table 6 is for 12/7/2015 with all the values in that row being equal to zero.

This location has the highest elevations of the test sections and is also the only one where trees were not present adjacent to the roadway right-of-way. As such it provides some interesting information regarding the effects of trees on embankment volumetric changes during flooding events.

The measured differences in elevation changes between Site 1A (no trees) and Site 1 (trees) on 4/25/2016, which was after the first flooding event. The hypothesis that trees create a zone of permanent desiccation as presented in Figure 6 was authenticated by the survey measurements presented in Tables 5 through 8 and Figures 12 through 15. The subgrade soil type in both sections 1A and 1 was a clay with an AASHTO designation of A-7(6), refer to Table 2. However, the increase in elevation at the centerline (0), was 2.44 mm in section 1A and 12.50 mm in section 1 according to the survey measurement on 4/25/2016. The probable reason for this difference was that the in-place moisture content at site l was lower than the in-place moisture content at Site 1A prior to the submergence event. Therefore, after the submergence event, there was a greater moisture content increase at Site 1 than Site 1A which in turn translates into a greater volume change in the embankment at Site 1 than Site 1A. The differences in the elevation increase (12.50 mm versus 2.44 mm) has far reaching implications in that (1) submergence of roadways where trees are present will be more damaged than roadways without trees, and (2) roadways will be damaged by submergence especially if expansive clays are present due to volume changes. The effects of saturation on the strength or load carrying capacity of submergence has already been demonstration by others and will not be discussed in this report *[15-22]*.

Further interesting observations from the survey measurements from Site 1A were that some points showed elevation increases while others showed elevation decreases across the roadway cross-section. One plausible explanation is that because of differential movement in the subgrade, semi-rigidity of the soil cement base course, and partial rigidity of the AC layer, an upward movement at one location may cause a downward movement at the adjacent location. A detailed finite element analysis, which is beyond the scope of this report, could validate this. This phenomenon though does fortify the notion that differential movements are occurring at roadway surface and those movements will induce stress into the AC layer which will eventually if not immediately lead to damage. In fact, careful examination of the values in Table 6 and Figures 12-13 reveal the obvious movements of each point as well as the differences of movement of each point over the course of the cross-section surveys (12/7/2015 to 3/15/2018) as well as the effect of submergence.

Table 5

Cross-section data for Site 1A

Survey Date	Distance (mm)											Elevations of cross-section points (mm)
	-3048	-2743.2	-2438.4	-2133.6	-1524	0	1706.88	2316.48	2621.28	2926.08	3230.88	
12/7/2015	30764.99	30773.83	30779.62	30786.93	30800.04	30831.74	30790.90	30767.43	30756.76	30745.18	30734.51	
4/25/2016	30763.77	30774.13	30777.48	30784.80	30804.31	30834.18	30790.59	30768.04	30756.45	30746.40	30732.07	
6/16/2016	30760.00	30767.00	30774.00	30781.00	30796.00	30829.00	30786.00	30764.00	30754.00	30742.00	30728.00	
9/20/2016	30759.00	30765.00	30772.00	30779.00	30795.00	30828.00	30786.00	30764.00	30754.00	30743.00	30729.00	
12/6/2016	30755.00	30762.00	30768.00	30774.00	30790.00	30824.00	30781.00	30759.00	30749.00	30738.00	30723.00	
4/25/2017	30757.00	30764.00	30770.00	30776.00	30792.00	30826.00	30783.00	30762.00	30751.00	30740.00	30726.00	
7/13/2017	30757.00	30764.00	30771.00	30777.00	30792.00	30826.00	30783.00	30762.00	30752.00	30740.00	30727.00	
9/15/2017	30764.00	30771.00	30778.00	30785.00	30800.00	30834.00	30789.00	30768.00	30758.00	30746.00	30732.00	
12/6/2017	30759.00	30766.00	30772.00	30779.00	30796.00	30829.00	30785.00	30763.00	30753.00	30742.00	30728.00	
3/15/2018	30762.00	30769.00	30776.00	30783.00	30799.00	30832.00	30789.00	30766.00	30755.00	30744.00	30730.00	

Table 6

Changes in cross-section elevations from 12/7/2015 for Site 1A

Survey dates	Distance (mm)											Change in Elevation (mm) from 12/7/2015.
	-3048	-2743.2	-2438.4	-2133.6	-1524	0	1706.88	2316.48	2621.28	2926.08	3230.88	
12/7/2015	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
4/25/2016	-1.22	0.30	-2.13	-2.13	4.27	2.44	-0.30	0.61	-0.30	1.22	-2.44	
6/16/2016	-4.99	-6.83	-5.62	-5.93	-4.04	-2.74	-4.90	-3.43	-2.76	-3.18	-6.51	
9/20/2016	-5.99	-8.83	-7.62	-7.93	-5.04	-3.74	-4.90	-3.43	-2.76	-2.18	-5.51	
12/6/2016	-9.99	-11.83	-11.62	-12.93	-10.04	-7.74	-9.90	-8.43	-7.76	-7.18	-11.51	
4/25/2017	-7.99	-9.83	-9.62	-10.93	-8.04	-5.74	-7.90	-5.43	-5.76	-5.18	-8.51	
7/13/2017	-7.99	-9.83	-8.62	-9.93	-8.04	-5.74	-7.90	-5.43	-4.76	-5.18	-7.51	
9/15/2017	-0.99	-2.83	-1.62	-1.93	-0.04	2.26	-1.90	0.57	1.24	0.82	-2.51	
12/6/2017	-5.99	-7.83	-7.62	-7.93	-4.04	-2.74	-5.90	-4.43	-3.76	-3.18	-6.51	
3/15/2018	-2.99	-4.83	-3.62	-3.93	-1.04	0.26	-1.90	-1.43	-1.76	-1.18	-4.51	

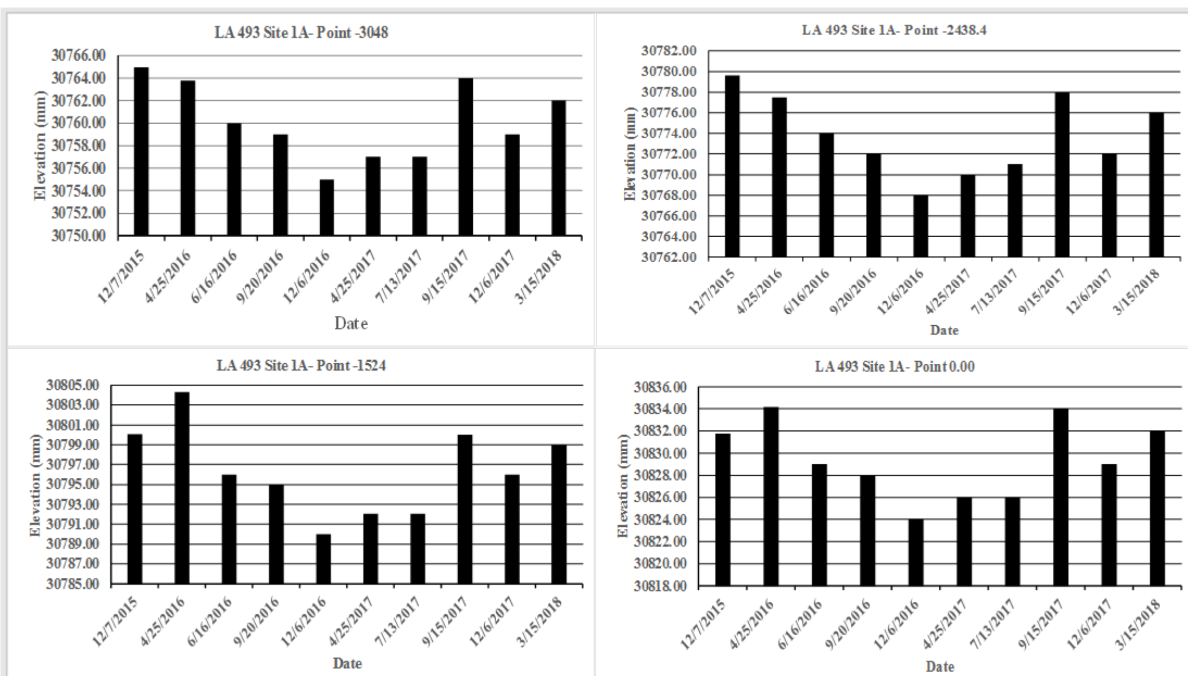

Figure 12

Charts of cross-section points for Site 1A (point -3048.00 to point 0.00)

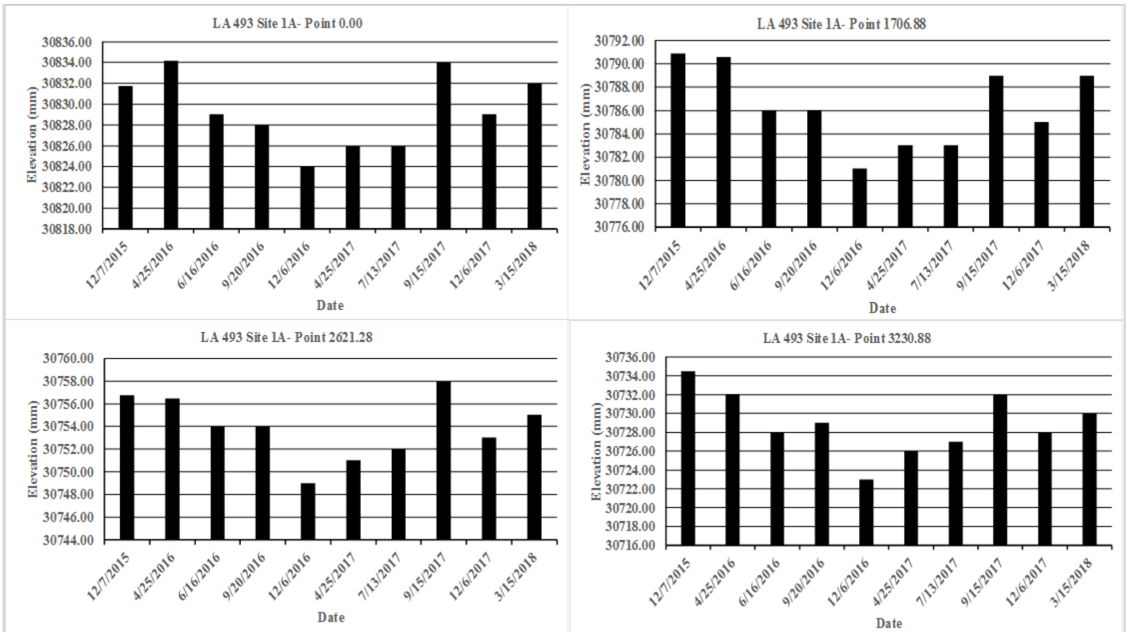

Figure 13

Charts of cross-section points for Site 1A (point 0.00 to point 3230.88)

Site 1 Cross-section Results

Tables 7-8 and Figures 14-15 present the results for the cross-section surveys. For this cross-section, no data is reported for the point 3230.88 because the edge of the road where this point was originally taken was damaged by heavy machinery. The elevation of the cross-section points (4/25/2016) all increased after the first flooding event with elevation increases ranging from 19.20 mm to 10.97 mm. As with section 1A, no adjacent point increased with a similar magnitude indicating that bending stresses were induced into the AC pavement and underlying layers. The trend toward increasing elevations continued until 12/6/2016 at which time the centerline (0) and left side of the roadway (- distances) reduced in magnitude while there was a general increase in magnitude on the right side (+ distances) of the roadway. The reasons for these differences between the left side and right side of the roadway is unknown. However, the reasons for the decreases in elevation (shrinking) can be explained because no flooding occurred between the 4/25/2016 and 12/6/2016. This trend generally reversed (increasing elevations) in the period between 4/25/2017 and 3/15/2018 which is probably the result of the two flooding events February 2017 to April 2017 and July 2017 to August 2017. It should be noted that on 3/15/2018, the AC surface was 59.51 mm (2.34 in.) higher than the time of the first cross-sectional survey on 12/7/2015 and that no point measured on the cross-section had the same magnitude.

Table 7
Cross-section data for Site 1

Survey Dates	Distance (mm)									
	-3048	-2743.2	-2438.4	-2133.6	-1524	0	1706.88	2316.48	2621.28	2926.08
12/7/2015	30078.88	30086.20	30091.08	30095.34	30104.49	30143.81	30111.80	30094.73	30089.86	30082.54
4/25/2016	30091.38	30100.83	30106.62	30113.94	30123.69	30156.30	30122.77	30110.28	30105.71	30099.61
6/16/2016	30094.00	30101.00	30106.00	30114.00	30125.00	30157.00	30122.00	30110.00	30105.00	30100.00
9/20/2016	30094.00	30102.00	30106.00	30114.00	30126.00	30158.00	30122.00	30111.00	30105.00	30099.00
12/6/2016	30075.00	30084.00	30089.00	30096.00	30109.00	30154.00	30134.00	30123.00	30117.00	30109.00
4/25/2017	30091.00	30098.00	30104.00	30112.00	30124.00	30156.00	30120.00	30108.00	30102.00	30098.00
7/13/2017	30099.00	30105.00	30113.00	30126.00	30158.00	30123.00	30110.00	30105.00	30099.00	30094.00
9/15/2017	30104.00	30109.00	30117.00	30128.00	30164.00	30128.00	30116.00	30110.00	30104.00	30099.00
12/6/2017	30099.00	30105.00	30113.00	30126.00	30160.00	30124.00	30112.00	30106.00	30100.00	30095.00
3/15/2018	30104.00	30110.00	30118.00	30130.00	30164.00	30129.00	30117.00	30111.00	30106.00	30100.00

Elevation of cross-section points (mm)

Table 8
Changes in cross-section elevations from 12/7/2015 for Site 1

Survey Date	Distance (mm)									
	-3048	-2743.2	-2438.4	-2133.6	-1524	0	1706.88	2316.48	2621.28	2926.08
12/7/2015	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4/25/2016	12.50	14.63	15.54	18.59	19.20	12.50	10.97	15.54	15.85	17.07
6/16/2016	15.12	14.80	14.92	18.66	20.51	13.19	10.20	15.27	15.14	17.46
9/20/2016	15.12	15.80	14.93	18.66	21.51	14.20	10.20	16.27	15.14	16.46
12/6/2016	-3.88	-2.20	-2.07	0.66	4.51	10.20	22.20	28.27	27.14	26.46
4/25/2017	12.12	11.80	12.93	16.66	19.51	12.20	8.20	13.27	12.14	15.46
7/13/2017	20.12	18.80	21.93	30.66	53.51	-20.80	-1.80	10.27	9.14	11.46
9/15/2017	25.12	22.80	25.93	32.66	59.51	-15.80	4.20	15.27	14.14	16.46
12/6/2017	20.12	18.80	21.93	30.66	55.51	-19.80	0.20	11.27	10.14	12.46
3/15/2018	25.12	23.80	26.93	34.66	59.51	-14.80	5.20	16.27	16.14	17.46

Change in Elevation (mm) from 12/7/2015.

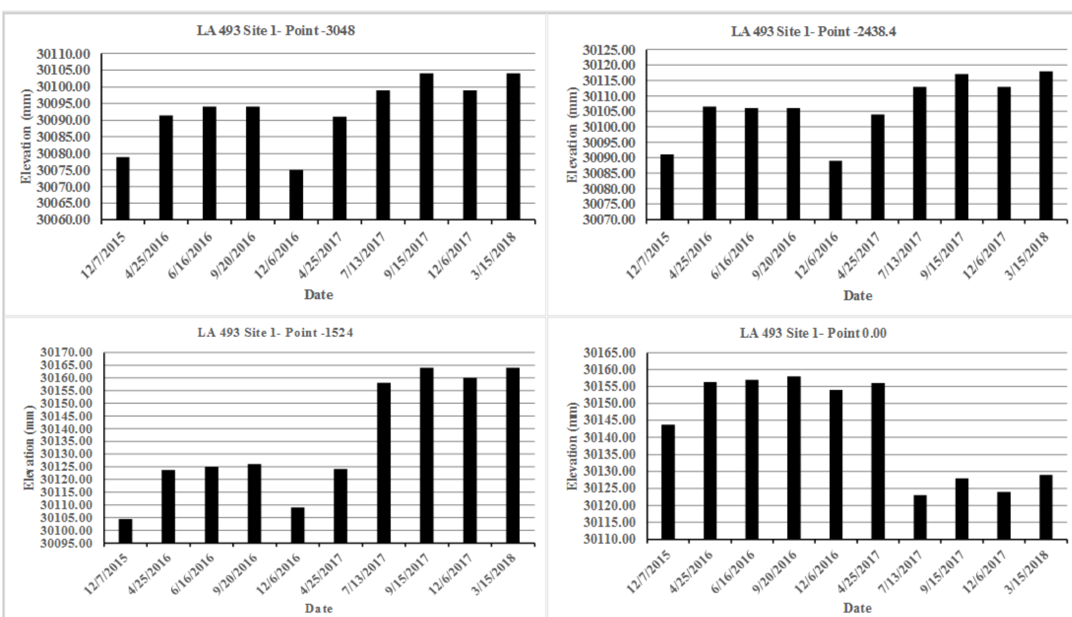

Figure 14
Charts of cross-section points for Site 1 (point -3048.00 to point 0.00)

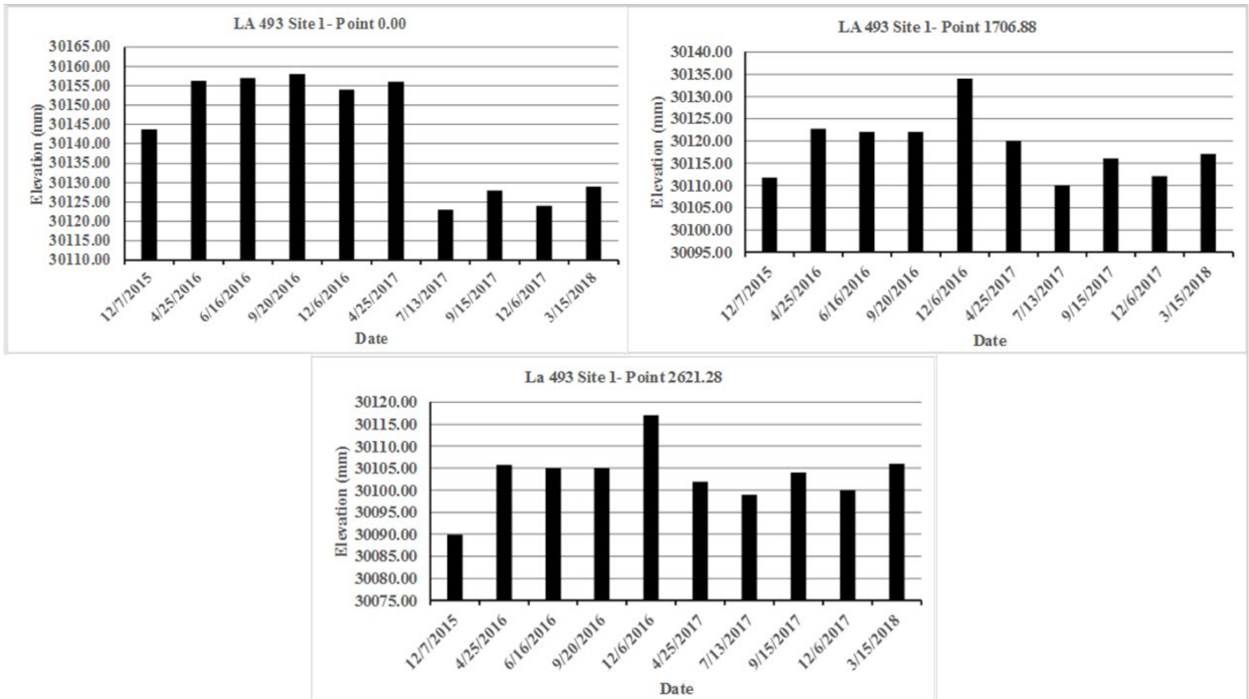

Figure 15
Charts of cross-section points for Site 1 (point 0.00 to 2621.28)

Site 2 Cross-section Results

Tables 9-10 and Figures 16-17 presents the results for Site 2. As with the previous sites, there was an increase in elevation (17.07 mm) at the centerline on 4/25/2016. The magnitude of elevation increase ranged from 30.78 mm to 10.67 mm with the right side of the roadway having a higher magnitude of increase than the left. No point on the roadway had the same magnitude of increase giving further credence to stresses being induced in the roadway by submergence.

There was a general trend in decreasing elevations from 4/25/2016 to 12/6/2016. From there elevations generally increased at varying rates due to the flooding events in February 2017 to April 2017 and July 2017 to August 2017. The elevation at the centerline (0) was 29.06 mm higher than it was on 12/7/2015. The elevation increases on the left side of the roadway were less than on the right side of the roadway with the elevation increase being as high as 45.07 mm. This trend was opposite at Site 1. What this does point to, however, is that volumetric changes in the embankment were highly variable.

Table 9

Cross-section data for Site 2

Survey Date	Distance (mm)										
	-3048.00	-2743.20	-2438.40	-2133.60	-1524.00	0.00	1706.88	2316.48	2621.28	2926.08	3230.88
12/7/2015	30144.72	30150.51	30151.73	30158.44	30168.80	30202.94	30173.98	30160.87	30153.25	30146.24	30138.93
4/25/2016	30155.39	30165.14	30169.71	30173.68	30184.04	30220.01	30193.79	30179.16	30177.94	30174.29	30169.71
6/16/2016	30161.00	30168.00	30173.00	30177.00	30189.00	30224.00	30201.00	30190.00	30185.00	30182.00	30178.00
9/20/2016	30157.00	30165.00	30169.00	30174.00	30186.00	30222.00	30199.00	30185.00	30179.00	30175.00	30170.00
12/6/2016	30156.00	30164.00	30168.00	30173.00	30185.00	30221.00	30198.00	30183.00	30176.00	30171.00	30163.00
4/25/2017	30157.00	30164.00	30169.00	30173.00	30184.00	30222.00	30200.00	30187.00	30181.00	30178.00	30173.00
7/13/2017	30158.00	30166.00	30170.00	30175.00	30188.00	30225.00	30203.00	30189.00	30183.00	30179.00	30174.00
9/15/2017	30162.00	30170.00	30174.00	30179.00	30192.00	30229.00	30206.00	30192.00	30185.00	30182.00	30176.00
12/6/2017	30158.00	30166.00	30170.00	30175.00	30188.00	30226.00	30204.00	30189.00	30183.00	30179.00	30173.00
3/15/2018	30164.00	30172.00	30176.00	30181.00	30194.00	30232.00	30212.00	30198.00	30192.00	30189.00	30184.00

Elevations of cross-section points (mm)

Table 10

Changes in cross-section elevations from 12/7/2015 for Site 2

Survey Dates	Distances (mm)										
	-3048	-2743.2	-2438.4	-2133.6	-1524	0	1706.88	2316.48	2621.28	2926.08	3230.88
12/7/2015	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4/25/2016	10.67	14.63	17.98	15.24	15.24	17.07	19.81	18.29	24.69	28.04	30.78
6/16/2016	16.28	17.49	21.27	18.56	20.20	21.06	27.02	29.13	31.75	35.76	39.07
9/20/2016	12.28	14.49	17.27	15.56	17.20	19.06	25.02	24.13	25.75	28.76	31.07
12/6/2016	11.28	13.49	16.27	14.56	16.20	18.06	24.02	22.13	22.75	24.76	24.07
4/25/2017	12.28	13.49	17.27	14.56	15.20	19.06	26.02	26.13	27.75	31.76	34.07
7/13/2017	13.28	15.49	18.27	16.56	19.20	22.06	29.02	28.13	29.75	32.76	35.07
9/15/2017	17.28	19.49	22.27	20.56	23.20	26.06	32.02	31.13	31.75	35.76	37.07
12/6/2017	13.28	15.49	18.27	16.56	19.20	23.06	30.02	28.13	29.75	32.76	34.07
3/15/2018	19.28	21.49	24.27	22.56	25.20	29.06	38.02	37.13	38.75	42.76	45.07

Change in Elevation (mm) from 12/7/2015.

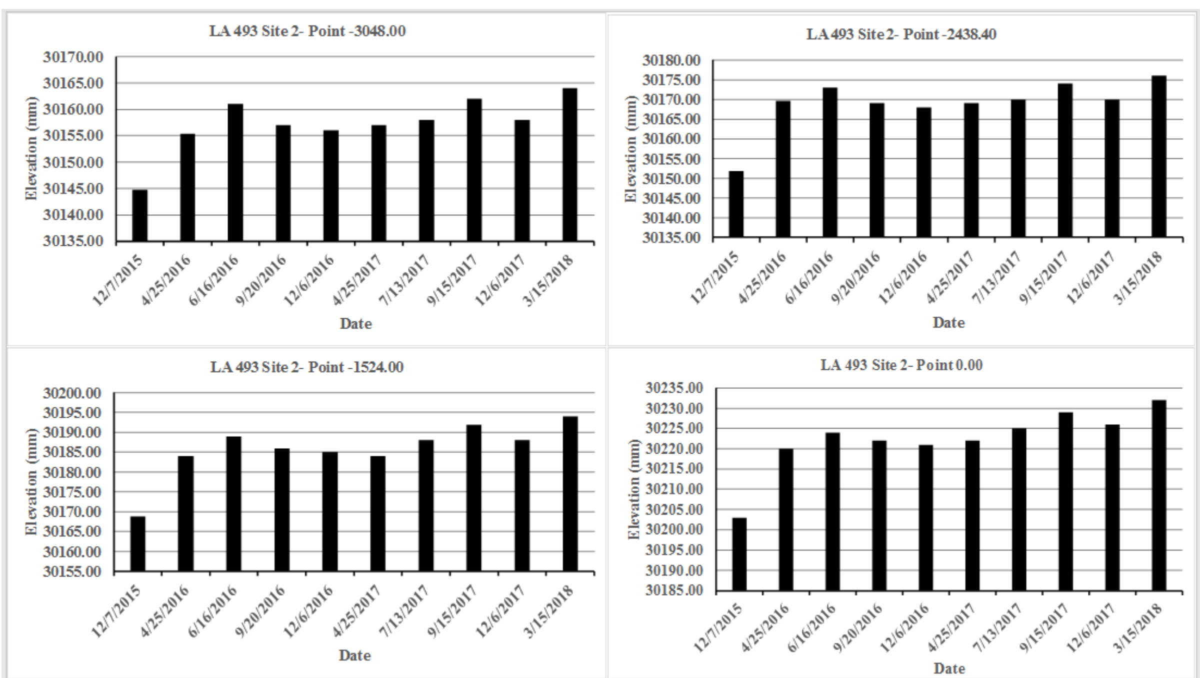

Figure 16

Charts of cross-section points for Site 2 (point -3048.00 to point 0.00)

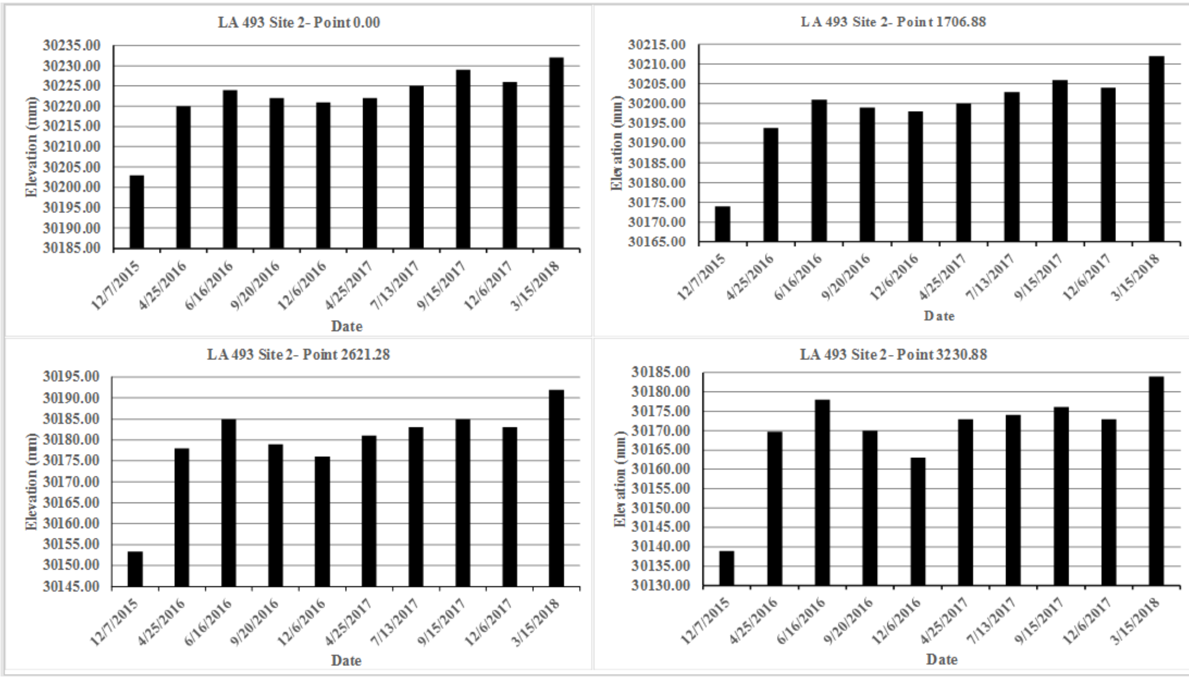

Figure 17
Charts of cross-section points for Site 2 (point 0.00 to point 3230.88)

Site 3 Cross-section Results
Tables 11-12 and Figures 18-19 present the results for Site 3. As with the previous sites, there was an increase in elevation at the centerline on 4/25/2016 and its magnitude was 37.80 mm. The magnitude of elevation increase ranged from 44.20 mm to 24.38 mm with the left side of the roadway having a higher magnitude of increase than the right. The points on the roadway had differing magnitudes of elevation increases.

There was a general trend of continual elevation increases on the left side of the roadway and elevation decreases on the right side of the roadway up to 12/6/2016. Elevation increases in general were measured for the remainder of the cross-sectional surveys. The maximum elevation increase was 63.47 mm with the minimum increase being 46.51 mm. The right side of the roadway had higher elevation increase magnitudes than the left side; once again demonstrating the high variability of volumetric changes.

Table 11
Cross-section data for Site 3

Survey Dates	Distance (mm)											Elevations of cross-section points (mm)
	-3048.00	-2743.20	-2438.40	-2133.60	-1524.00	0.00	1706.88	2316.48	2621.28	2926.08	3230.88	
12/7/2015	30025.85	30035.60	30041.70	30047.49	30059.07	30110.28	30107.53	30107.53	30107.23	30105.40	30104.18	
4/25/2016	30059.99	30069.13	30076.44	30091.68		30148.07	30144.42	30137.40	30132.83	30130.70	30128.57	
6/16/2016	30056.00	30064.00	30071.00	30078.00	30094.00	30152.00	30150.00	30137.00	30134.00	30133.00	30127.00	
9/20/2016	30059.00	30069.00	30073.00	30080.00	30096.00	30157.00	30156.00	30146.00	30140.00	30136.00	30129.00	
12/6/2016	30077.00	30084.00	30090.00	30097.00	30111.00	30155.00	30136.00	30123.00	30119.00	30112.00	30107.00	
4/25/2017	30069.00	30079.00	30078.00	30085.00	30100.00	30160.00	30161.00	30150.00	30148.00	30143.00	30138.00	
7/13/2017	30073.00	30077.00	30083.00	30089.00	30103.00	30162.00	30164.00	30156.00	30154.00	30150.00	30145.00	
9/15/2017	30077.00	30080.00	30086.00	30091.00	30105.00	30165.00	30168.00	30161.00	30162.00	30158.00	30154.00	
12/6/2017	30073.00	30084.00	30084.00	30089.00	30102.00	30162.00	30165.00	30160.00	30159.00	30161.00	30155.00	
3/15/2018	30079.00	30084.00	30089.00	30094.00	30108.00	30167.00	30171.00	30168.00	30169.00	30168.00	30165.00	

Table 12
Changes in cross-section elevations from 12/7/2015 for Site 3

Survey Dates	Distances (mm)											Change in Elevation (mm) from 12/7/2015.
	-3048	**-2743.2**	**-2438.4**	**-2133.6**	**-1524**	**0**	**1706.88**	**2316.48**	**2621.28**	**2926.08**	**3230.88**	
12/7/2015	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
4/25/2016	34.14	33.53	34.75	44.20		37.80	36.88	29.87	25.60	25.30	24.38	
6/16/2016	30.15	28.40	29.30	30.51	34.93	41.72	42.47	29.47	26.77	27.60	22.82	
9/20/2016	33.15	33.40	31.30	32.51	36.93	46.72	48.47	38.47	32.77	30.60	24.82	
12/6/2016	51.15	48.40	48.30	49.51	51.93	44.72	28.47	15.47	11.77	6.60	2.82	
4/25/2017	43.15	43.40	36.30	37.51	40.93	49.72	53.47	42.47	40.77	37.60	33.82	
7/13/2017	47.15	41.40	41.30	41.51	43.93	51.72	56.47	48.47	46.77	44.60	40.82	
9/15/2017	51.15	44.40	44.30	43.51	45.93	54.72	60.47	53.47	54.77	52.60	49.82	
12/6/2017	47.15	48.40	42.30	41.51	42.93	51.72	57.47	52.47	51.77	55.60	50.82	
3/15/2018	53.15	48.40	47.30	46.51	48.93	56.72	63.47	60.47	61.77	62.60	60.82	

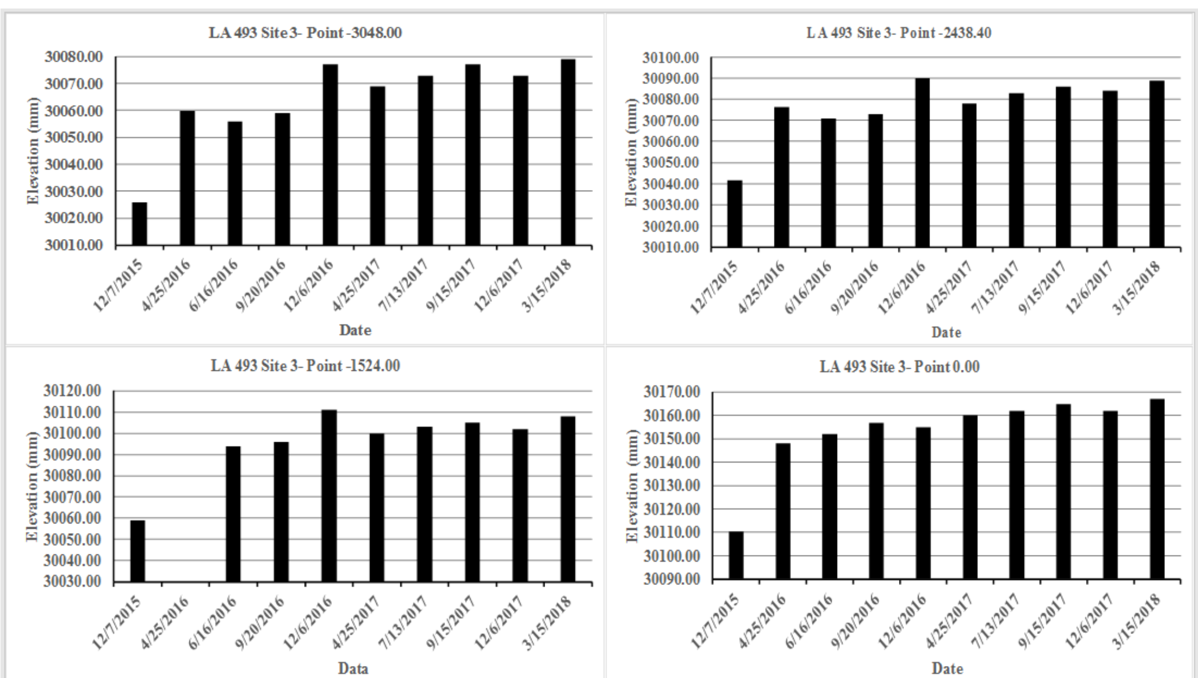

Figure 18
Charts of cross-section points for Site 3 (point -3048.00 to point 0.00)

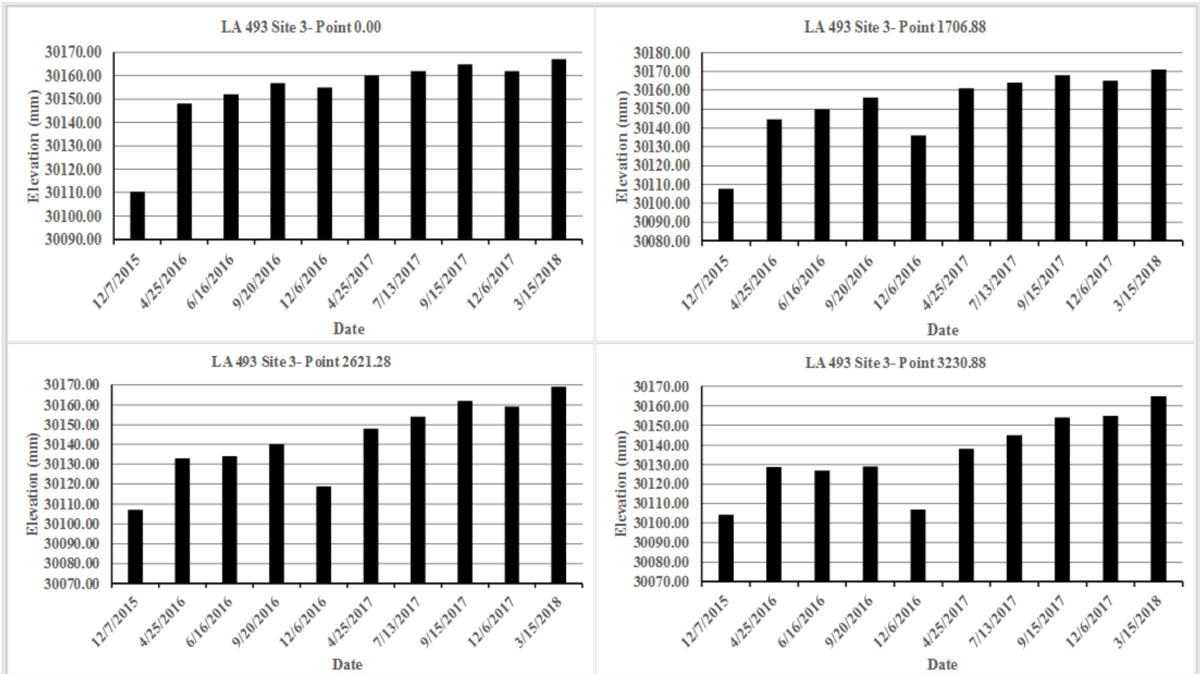

Figure 19

Charts of cross-section points for Site 3 (point 0.00 to 3230.88)

Site 4 Cross-section Results

Tables 13-14 and Figures 20-21 present the results for Site 4. As with the previous sites, there was an increase in elevation at the centerline on 4/25/2016 and its magnitude was 44.50 mm. The magnitude of elevation increase ranged from 44.5 mm to 31.09 mm with the right side of the roadway having a higher magnitude of increase than the left. The points on the roadway had differing magnitudes of elevation increases.

Unlike the previous sites, the cross-sections maintained a fairly consistent elevation from 4/25/2016 to 12/6/2016. From there a consistent increase in elevation for the cross-section was measured. At 3/15/2018 the maximum elevation increase was 55.42 mm with the right side of the roadway having higher elevation increases than the left.

Table 13
Cross-section data for Site 4

Survey dates	Distance (mm)										
	-3048.00	-2743.20	-2438.40	-2133.60	-1524.00	0.00	1706.88	2316.48	2621.28	2926.08	3230.88
12/7/2015	30262.07	30266.03	30272.13	30278.83	30289.50	30326.08	30288.59	30277.31	30270.91	30262.68	30255.97
4/25/2016	30293.16	30299.56	30307.18	30313.88	30330.04	30370.58	30329.12	30315.10	30307.18	30298.95	30290.41
6/16/2016	30297.00	30302.00	30310.00	30317.00	30332.00	30372.00	30332.00	30319.00	30310.00	30302.00	30294.00
9/20/2016	30298.00	30303.00	30311.00	30317.00	30331.00	30371.00	30331.00	30317.00	30308.00	30301.00	30294.00
12/6/2016	30300.00	30305.00	30312.00	30318.00	30333.00	30372.00	30331.00	30317.00	30307.00	30299.00	30290.00
4/25/2017	30304.00	30310.00	30317.00	30322.00	30336.00	30374.00	30335.00	30323.00	30314.00	30307.00	30298.00
7/13/2017	30305.00	30310.00	30318.00	30323.00	30336.00	30375.00	30337.00	30324.00	30316.00	30309.00	30301.00
9/15/2017	30308.00	30313.00	30320.00	30326.00	30339.00	30377.00	30339.00	30326.00	30319.00	30311.00	30302.00
12/6/2017	30307.00	30312.00	30318.00	30324.00	30337.00	30375.00	30337.00	30324.00	30316.00	30308.00	30299.00
3/15/2018	30312.00	30317.00	30323.00	30328.00	30341.00	30380.00	30344.00	30331.00	30325.00	30318.00	30310.00

Elevations of cross-section points (mm)

Table 14
Changes in cross-section elevations from 12/7/2015 for Site 4

Survey Dates	Distance (mm)										
	-3048	-2743.2	-2438.4	-2133.6	-1524	0	1706.88	2316.48	2621.28	2926.08	3230.88
12/7/2015	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4/25/2016	31.09	33.53	35.05	35.05	40.54	44.50	40.54	37.80	36.27	36.27	34.44
6/16/2016	34.93	35.97	37.87	38.17	42.50	45.92	43.41	41.69	39.09	39.32	38.03
9/20/2016	35.93	36.97	38.87	38.17	41.50	44.92	42.42	39.69	37.09	38.32	38.03
12/6/2016	37.93	38.97	39.87	39.17	43.50	45.92	42.42	39.69	36.09	36.32	34.03
4/25/2017	41.93	43.97	44.87	43.17	46.50	47.92	46.42	45.69	43.09	44.32	42.03
7/13/2017	42.93	43.97	45.87	44.17	46.50	48.92	48.42	46.69	45.09	46.32	45.03
9/15/2017	45.93	46.97	47.87	47.17	49.50	50.92	50.42	48.69	48.09	48.32	46.03
12/6/2017	44.93	45.97	45.87	45.17	47.50	48.92	48.42	46.69	45.09	45.32	43.03
3/15/2018	49.93	50.97	50.87	49.17	51.50	53.92	55.42	53.69	54.09	55.32	54.03

Change in Elevation (mm) from 12/7/2015.

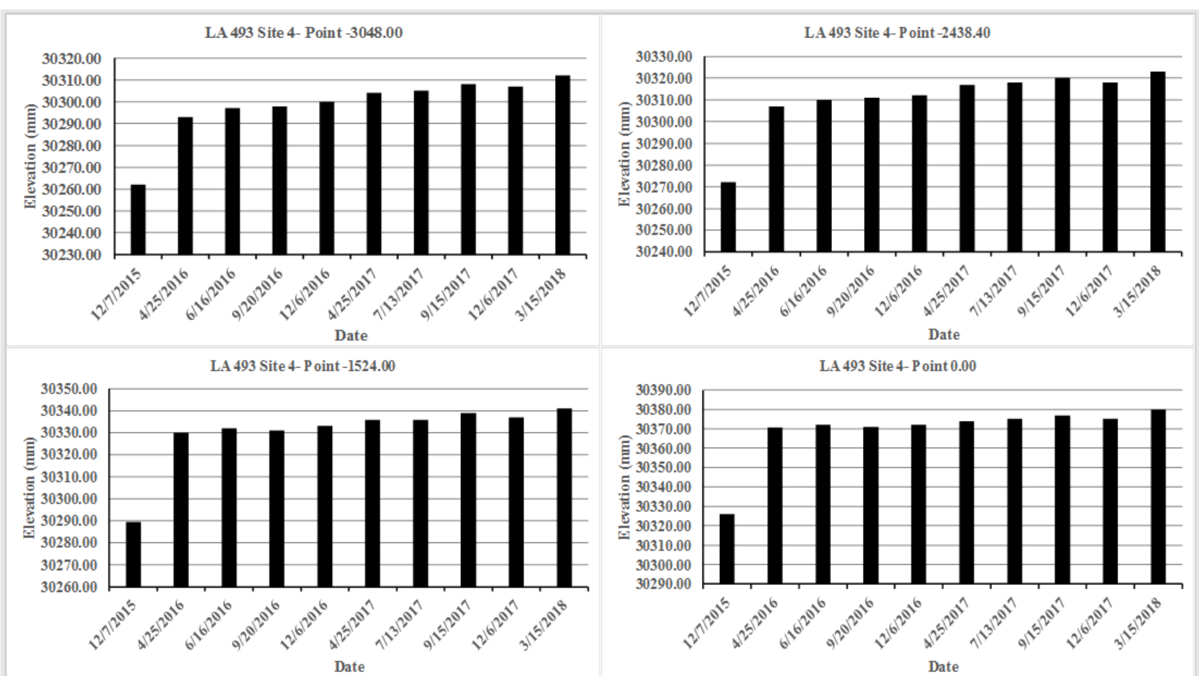

Figure 20

Charts of cross-section points for Site 4 (point -3048.00 to point 0.00)

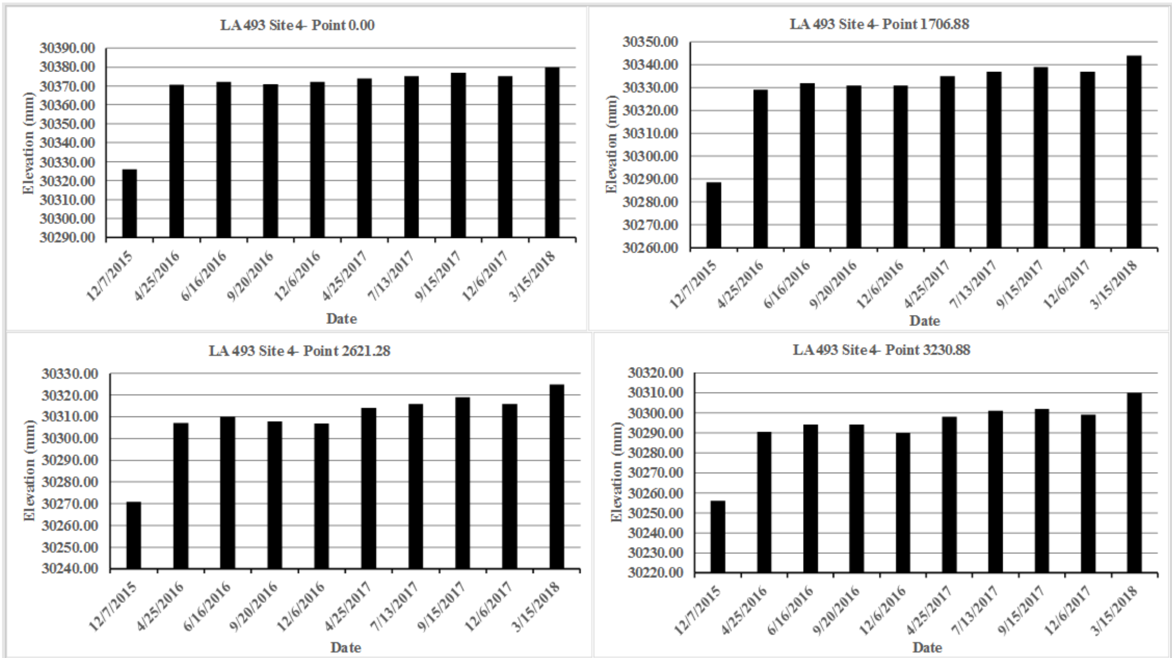

Figure 21
Charts of cross-section points Site 4 (point 0.00 to 3230.88

Site 5 Cross-section Results

Tables 15-16 and Figures 22-23 present the results for Site 5. As with the previous sites, there was an increase in elevation at the centerline on 4/25/2016 and its magnitude was 34.44 mm. The magnitude of elevation increase ranged from 34.44 mm to 23.47 mm with the right side of the roadway having a higher magnitude of increase than the left. The points on the roadway had differing magnitudes of elevation increases.

Similar to Site 4 and, unlike the previous sites, the cross-sections maintained a fairly consistent elevation from 4/25/2016 to 12/6/2016. From there, a generally consistent increase in elevation for the cross-section was measured. At 3/15/2018, the maximum elevation increase was 45.01 mm with the right side of the roadway having higher elevation increases than the left.

Table 15
Cross-section data for Site 5

Survey date	Distance (mm)										
	-3048.00	-2743.20	-2438.40	-2133.60	-1524.00	0.00	1706.88	2316.48	2621.28	2926.08	3230.88
12/7/2015	30121.25	30124.30	30128.57	30133.14	30142.28	30180.99	30148.07	30132.53	30125.21	30120.64	30115.15
4/25/2016	30145.33	30147.77	30153.25	30159.66	30172.76	30215.43	30175.50	30159.66	30152.95	30146.24	30141.37
6/16/2016	30147.00	30149.00	30155.00	30161.00	30174.00	30216.00	30178.00	30162.00	30155.00	30149.00	30144.00
9/20/2016	30147.00	30149.00	30154.00	30160.00	30173.00	30214.00	30177.00	30162.00	30155.00	30149.00	30144.00
12/6/2016	30149.00	30151.00	30155.00	30162.00	30175.00	30216.00	30179.00	30163.00	30157.00	30150.00	30144.00
4/25/2017	30151.00	30153.00	30158.00	30164.00	30177.00	30218.00	30181.00	30166.00	30160.00	30154.00	30149.00
7/13/2017	30154.00	30156.00	30161.00	30166.00	30179.00	30220.00	30184.00	30169.00	30163.00	30157.00	30151.00
9/15/2017	30155.00	30158.00	30161.00	30168.00	30178.00	30222.00	30186.00	30171.00	30164.00	30159.00	30154.00
12/6/2017	30152.00	30153.00	30158.00	30164.00	30178.00	30218.00	30183.00	30168.00	30161.00	30156.00	30151.00
3/15/2018	30160.00	30162.00	30166.00	30171.00	30185.00	30226.00	30192.00	30177.00	30171.00	30165.00	30160.00

Elevations of cross-section points (mm)

Table 16
Changes in cross-section elevations from 12/7/2015 for Site 5

Survey Date	Distance (mm)										
	-3048	-2743.2	-2438.4	-2133.6	-1524	0	1706.88	2316.48	2621.28	2926.08	3230.88
12/7/2015	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4/25/2016	24.08	23.47	24.69	26.52	30.48	34.44	27.43	27.13	27.74	25.60	26.21
6/16/2016	25.75	24.70	26.43	27.86	31.72	35.01	29.93	29.47	29.79	28.36	28.85
9/20/2016	25.75	24.70	25.44	26.86	30.72	33.01	28.93	29.47	29.79	28.36	28.85
12/6/2016	27.75	26.70	26.44	28.86	32.72	35.01	30.93	30.47	31.79	29.36	28.85
4/25/2017	29.75	28.70	29.44	30.86	34.72	37.01	32.93	33.47	34.79	33.36	33.85
7/13/2017	32.75	31.70	32.44	32.86	36.72	39.01	35.93	36.47	37.79	36.36	35.85
9/15/2017	33.75	33.70	32.44	34.86	35.72	41.01	37.93	38.47	38.79	38.36	38.85
12/6/2017	30.75	28.70	29.44	30.86	35.72	37.01	34.93	35.47	35.79	35.36	35.85
3/15/2018	38.75	37.70	37.44	37.86	42.72	45.01	43.93	44.47	45.79	44.36	44.85

Change in Elevation (mm) from 12/7/2015.

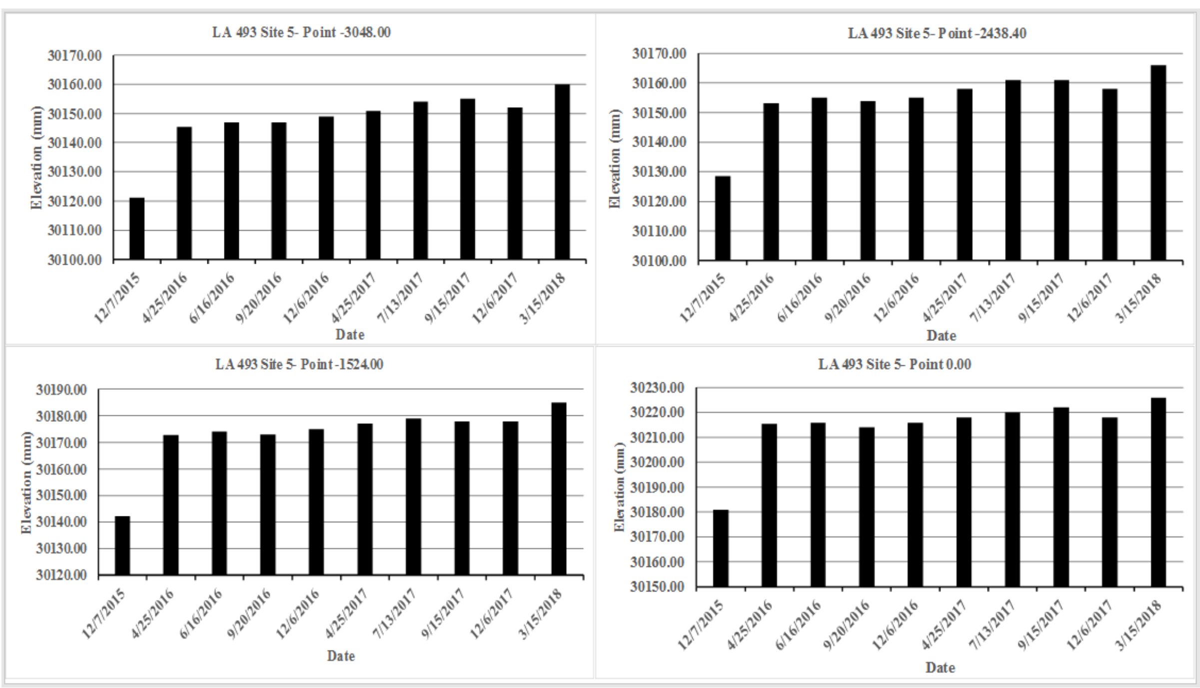

Figure 22
Charts of cross-section points for Site 5 (point -3048.00 to point 0.00)

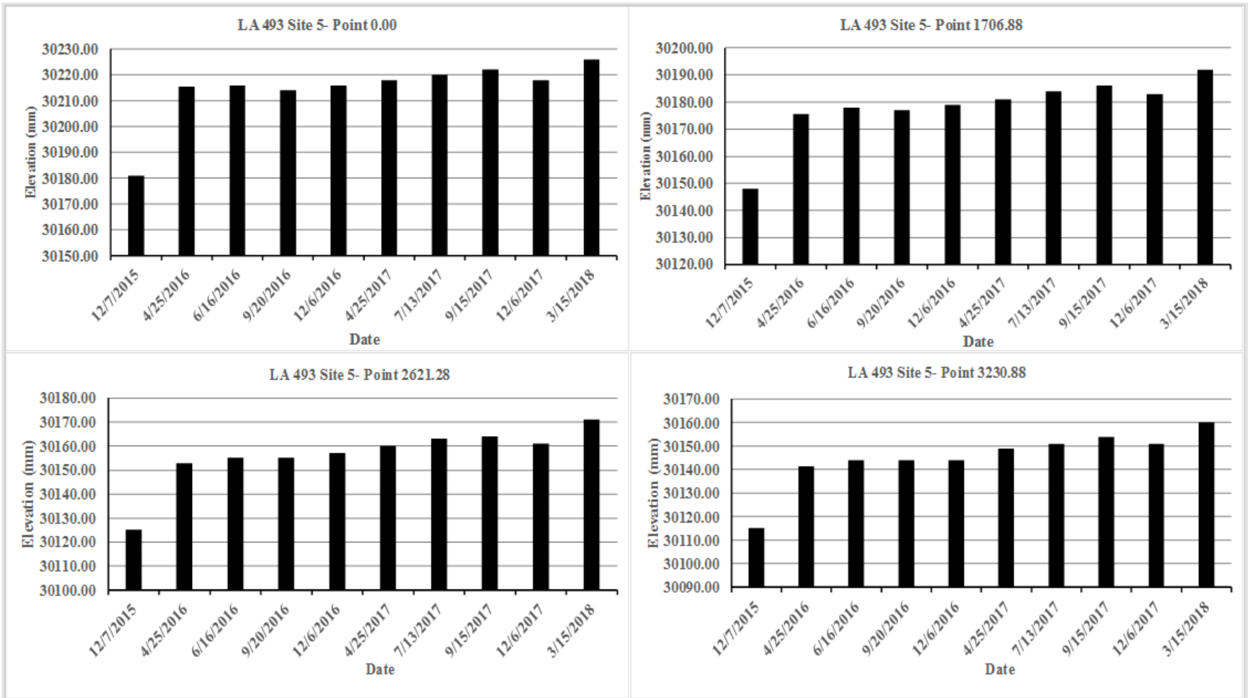

Figure 23

Charts of cross-section points for Site 5 (point 0.00 to point 3230.88)

Site 6 Cross-section Results

Tables 17-18 and Figures 24-25 present the results for Site 6. As with the previous sites, there was an increase in elevation at the centerline on 4/25/2016 and its magnitude was 18.59 mm. The magnitude of elevation increase ranged from 23.47 mm to 16.15 mm with the left side of the roadway having a higher magnitude of increase than the left. The points on the roadway had differing magnitudes of elevation increases.

The cross-sections maintained a fairly consistent elevation from 4/25/2016 to 12/6/2016. From there a general consistent increase in elevation for the cross-section was measured. At 3/15/2018 the maximum elevation increase was 47.46 mm with the left side of the roadway having higher elevation increases than the right.

Table 17

Cross-section data for Site 6

Survey dates	Distance (mm)											Elevations of cross-section points (mm)
	-3048.00	**-2743.20**	**-2438.40**	**-2133.60**	**-1524.00**	**0.00**	**1706.88**	**2316.48**	**2621.28**	**2926.08**	**3230.88**	
12/7/2015	30317.54	30323.33	30329.12	30334.31	30344.36	30385.82	30357.17	30342.84	30333.70	30330.04	30323.33	
4/25/2016	30341.01	30346.19	30350.46	30355.34	30363.87	30404.41	30377.28	30362.04	30354.73	30350.46	30339.49	
6/16/2016	30345.00	30349.00	30353.00	30358.00	30366.00	30407.00	30380.00	30365.00	30358.00	30352.00	30346.00	
9/20/2016	30347.00	30351.00	30353.00	30357.00	30365.00	30407.00	30376.00	30365.00	30360.00	30354.00	30347.00	
12/6/2016	30349.00	30353.00	30356.00	30360.00	30368.00	30409.00	30380.00	30368.00	30363.00	30355.00	30346.00	
4/25/2017	30355.00	30359.00	30361.00	30365.00	30373.00	30414.00	30387.00	30375.00	30370.00	30364.00	30357.00	
7/13/2017	30356.00	30360.00	30362.00	30366.00	30373.00	30415.00	30388.00	30376.00	30371.00	30366.00	30358.00	
9/15/2017	30360.00	30363.00	30365.00	30368.00	30376.00	30417.00	30390.00	30380.00	30375.00	30369.00	30360.00	
12/6/2017	30359.00	30362.00	30364.00	30367.00	30375.00	30416.00	30390.00	30379.00	30374.00	30366.00	30356.00	
3/15/2018	30365.00	30368.00	30368.00	30372.00	30379.00	30420.00	30394.00	30383.00	30379.00	30374.00	30366.00	

Table 18

Changes in cross-section elevations from 12/7/2015 for Site 6

Survey Date	Distance (mm)											Change in Elevation (mm) from 12/7/2015.
	-3048	**-2743.2**	**-2438.4**	**-2133.6**	**-1524**	**0**	**1706.88**	**2316.48**	**2621.28**	**2926.08**	**3230.88**	
12/7/2015	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
4/25/2016	23.47	22.86	21.34	21.03	19.51	18.59	20.12	19.20	21.03	20.42	16.15	
6/16/2016	27.46	25.67	23.88	23.69	21.64	21.18	22.83	22.16	24.30	21.96	22.67	
9/20/2016	29.46	27.67	23.88	22.70	20.64	21.18	18.84	22.16	26.30	23.96	23.67	
12/6/2016	31.46	29.67	26.88	25.70	23.64	23.18	22.84	25.16	29.30	24.96	22.67	
4/25/2017	37.46	35.67	31.88	30.70	28.64	28.18	29.84	32.16	36.30	33.96	33.67	
7/13/2017	38.46	36.67	32.88	31.70	28.64	29.18	30.84	33.16	37.30	35.96	34.67	
9/15/2017	42.46	39.67	35.88	33.70	31.64	31.18	32.84	37.16	41.30	38.96	36.67	
12/6/2017	41.46	38.67	34.88	32.70	30.64	30.18	32.84	36.16	40.30	35.96	32.67	
3/15/2018	47.46	44.67	38.88	37.70	34.64	34.18	36.84	40.16	45.30	43.96	42.67	

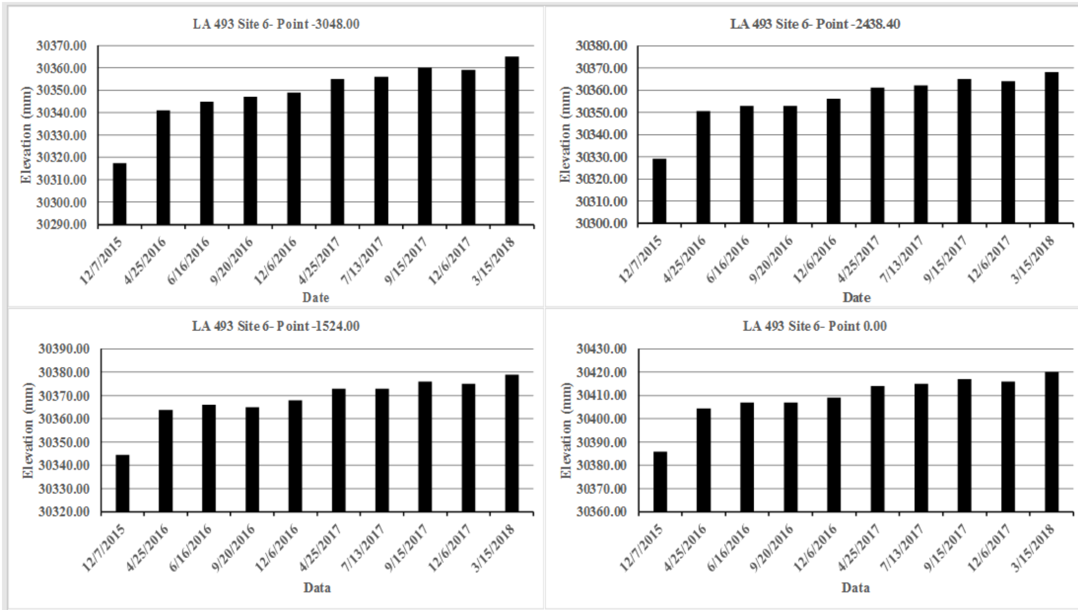

Figure 24

Charts of cross-section points for Site 6 (point -3048.00 to point 0.00)

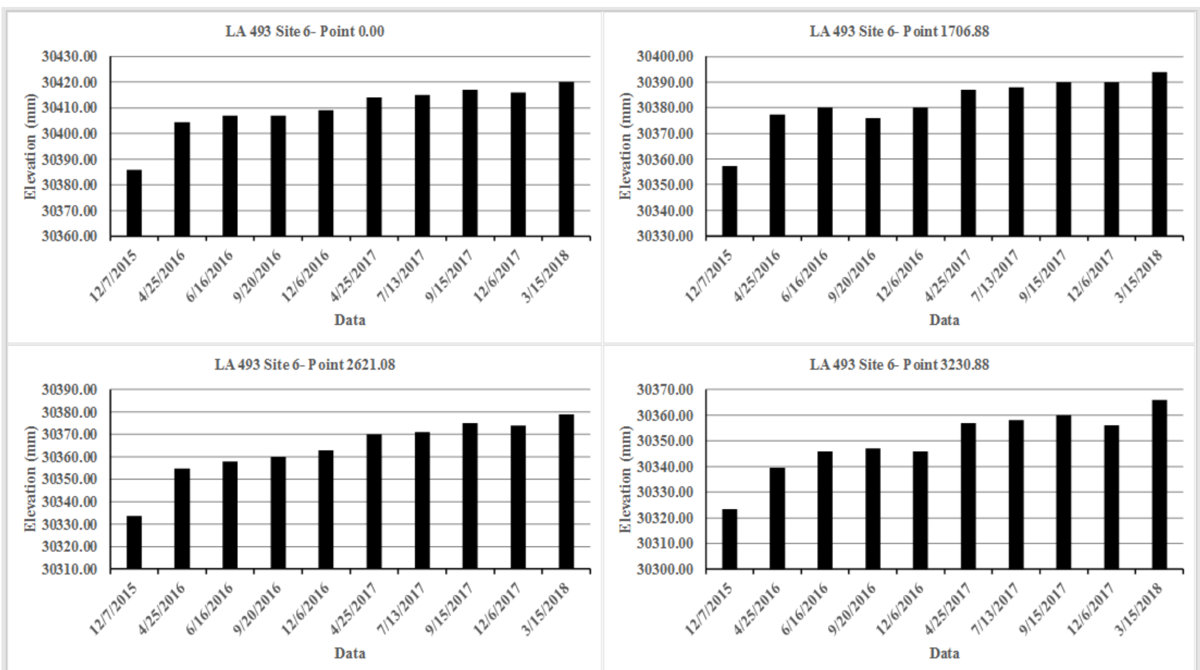

Figure 25

Charts of cross-section points for Site 6 (point 0.00 to point 3230.88)

Roadway Surface Profile Information

Roadway Surface Smoothness (EB)

The IRI measurements for the six sites are presented in Figures 26 and 27. Regarding the EB direction assessment, there was only approximately 300 ft. on roadway available for the vehicle to begin its assessment. Because of that, the profile data may not represent the conditions of the roadway surface for Site 1. The profile measurements on the remaining sites (2-6) should not have been affected. IRI values for all sites exceeded 75 on the June 2017 collection date indicating that the roadway is rougher than it should be for the amount to time that it has been in service.

Regarding Site 1, both the LWP and RWP had higher IRI values than the CLP on both collection dates (June 2017 and June 2018). The IRI values in June 2018 were higher than the June 2017 values and is typical.

For Site 2, the CLP IRI values were higher than both the LWP and RWP for both collection dates. The IRI values for the June 2018 collection date was higher than the June 2017 collection date which is typical.

On Site 3, the IRI value for the RWP was higher than the CLP and LWP for both collection dates and the CLP was higher than the LWP on both collection dates. While it is typical for the RWP to be higher than both the CLP and LWP, it is not typical for the CLP to be higher that the LWP.

The IRI values for the LWP, CLP, and RWP were similar for the June 2017 collection date and somewhat similar on the June 2018 collection date on Site 4. There was no significant difference in IRI values between June 2017 and June 2018.

Site 5 IRI values for the LWP were higher than both the CLP and RWP for the June 2017 collection date. On the June 2018 collection date the CLP IRI values were higher than the LWP and RWP. The IRI for the RWP value increased more than the CLP and LWP for the June 2018 collection date. The IRI values for the June 2018 collection date were larger than the June 2017 collection date.

For Site 6, the IRI values for the LWP and RWP were higher than the CLP for the June 2017 collection date. On the June 2018 collection date, the LWP and CLP had similar IRI values and both were less than the RWP. The IRI values for the June 2018 collection date were larger than the June 2017 collection date.

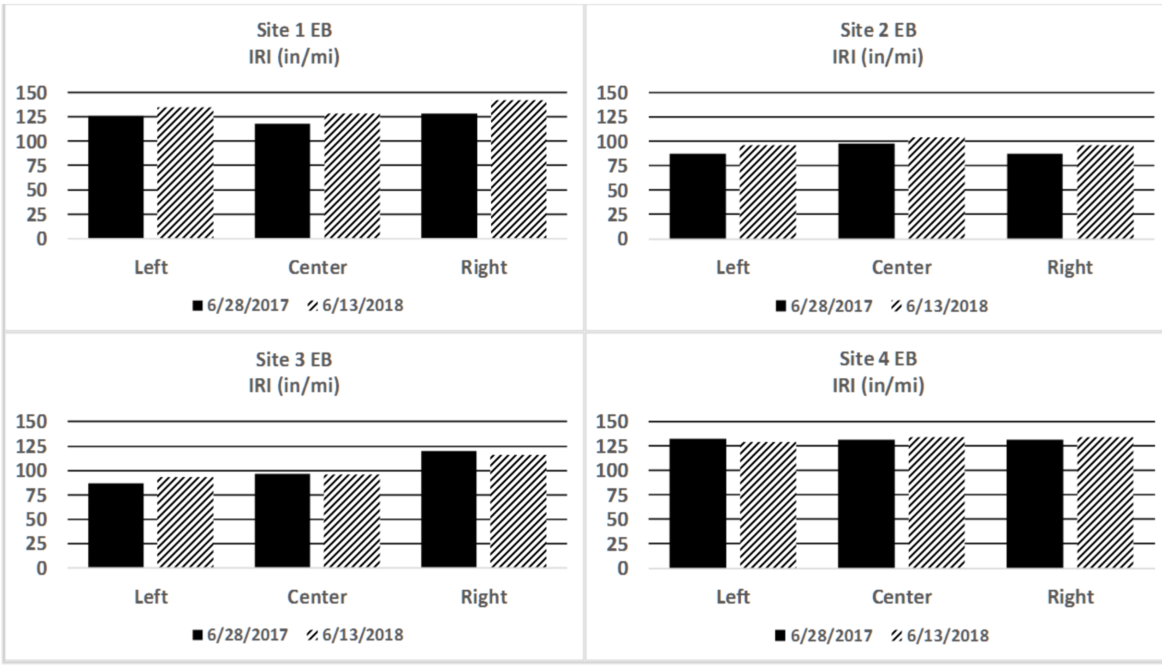

Figure 26
EB IRI for Sites 1 to 4

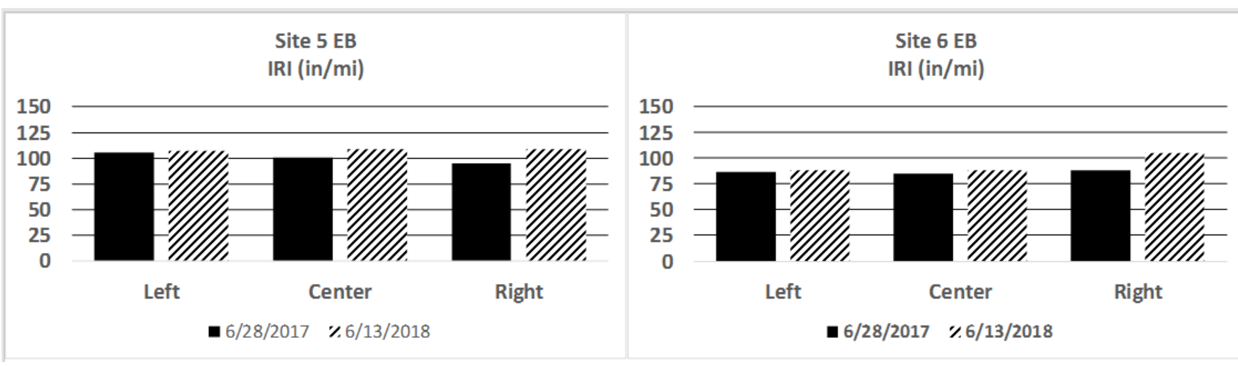

Figure 27
EB IRI for Sites 5 to 6

Roadway Surface Smoothness (WB)

The IRI measurements for the six sites are presented in Figures 28 and 29. Similar to the EB direction, IRI values for all sites exceeded 75 on the June 2017 collection date indicating that the roadway is rougher than it should be for the amount to time that it has been in service. On some sections the IRI decreased between June 2018 and June 2017 collection dates. This is an unusual event and may be due to profile changes, but the reason for this is unknown.

The IRI value for the RWP was higher than the CLP with the LWP being less than the CLP for Site 1 on the June 2017 collection date. For the June 2018 collection date, the IRI values in the LWP were higher than the CLP while the IRI values in the RWP were less than the other wheel paths. All the IRI values in the June 2018 collection date were less than the June 2017 which is counterintuitive. The reason for this is unknown.

On Site 2, the IRI values for the LWP was higher than the CLP while the IRI on the RWP was lower. On June 2018, the IRI values for the RWP and CLP were similar and the LWP values were less than them. At this Site the IRI value for the LWP on June 2018 was less than June 2017. The reason for this is unknown.

At Site 3, all the IRI values for the June 2018 collection date were greater than the June 2017 collection date. The RWP and LWP IRI values were greater that CLP values on June 2017 and a similar trend existed in 2018.

Regarding Site 4, the IRI value in the RWP was greater than the CLP, and both were greater than the LWP on June 2017. On the other collection date, June 2018 the trend was similar and all values increased from the June 2017 collection date.

The IRI values at Site 5 were much higher than the other sites. The IRI values for the RWP was higher than the CLP and both were higher than the LWP on the June 2017 collection date. There was a similar trend on the June 2018 collection date. The IRI value for the RWP on the June 2018 collection date was similar to the June 2017 date. The CLP and LWP IRI values decreased between the June 2018 and June 2017 collection date.

On Site 6, the IRI value on the RWP was greater than the CLP and both were greater than the LWP on the June 2017 collection date. The trend was similar in the June 2018 collection date and all the IRI values increased.

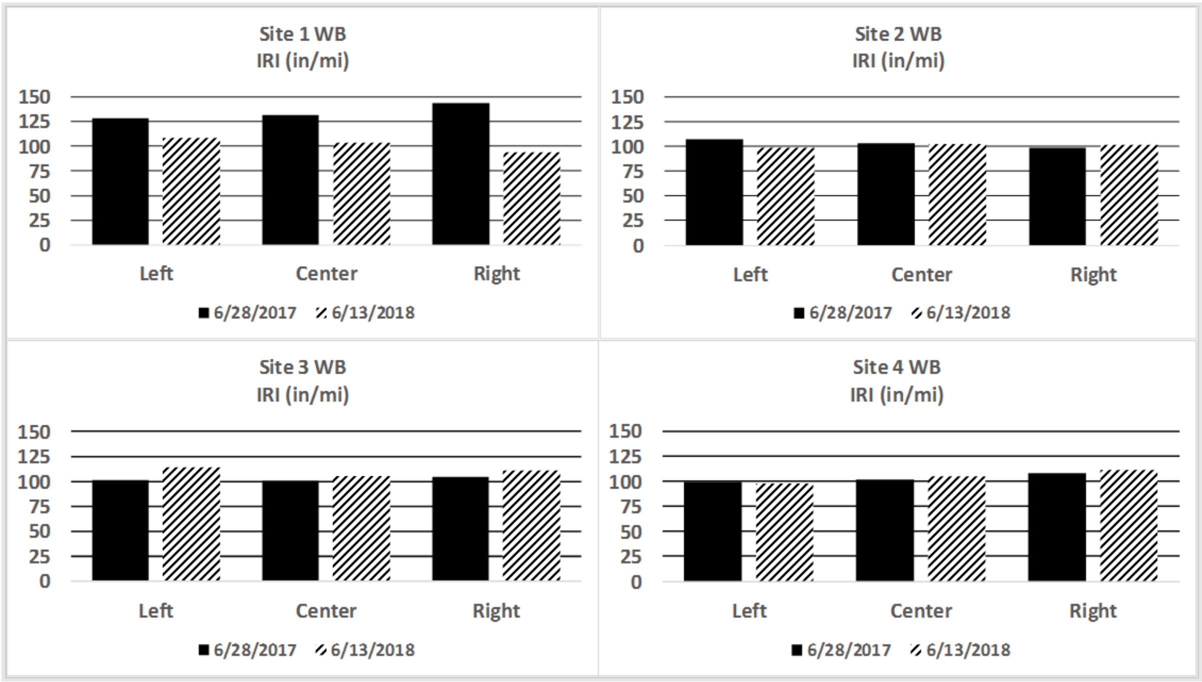

Figure 28
WB IRI for Sites 1 to 4

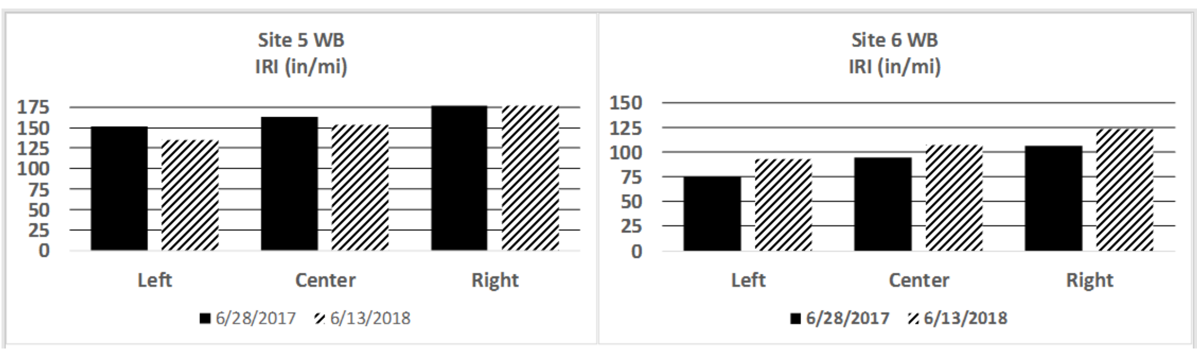

Figure 29
WB IRI for Sites 5 to 6

Roadway Surface Longitudinal Profile

Figures 30 to 33 presents the longitudinal profiles for the LWP, CLP, and RWP for Sites 1 and 2 for the EB roadway. The remainder of longitudinal profile figures for both the EB and WB roadway are located in Appendix 3. The longitudinal profiles for the June 2017 and June 2018 collection dates are presented in the Figures. Examining the Figures indicates that there were changes in the profile at the two collection dates. While it is typical for the profiles to change over time due to traffic loading, it is important to keep in mind that no traffic was on the roadways during the three submergence events of January 2016 to March 2016, February 2017 to

April 2017, and July 2017 to August 2017. It is probable that the changes in profile shapes were primarily due to volumetric changes in the subgrade.

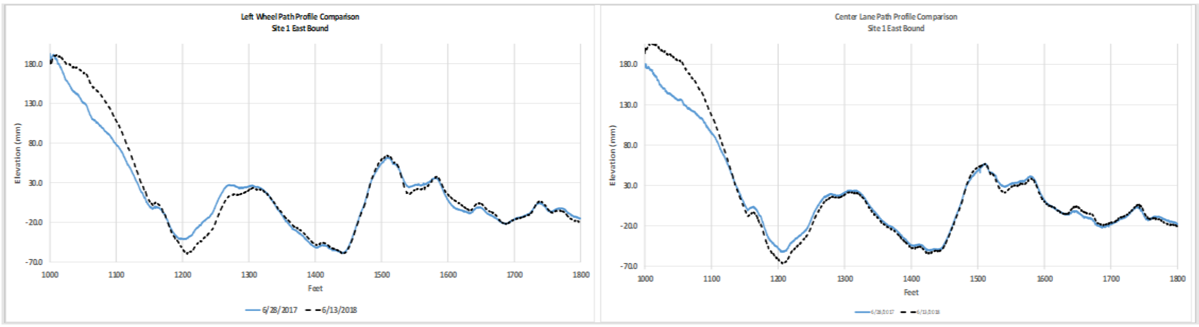

Figure 30

Site 1 EB longitudinal profile for left wheel path and center of lane

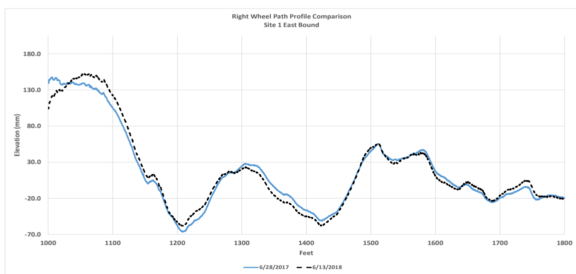

Figure 31

Site 1 EB longitudinal profile for right wheel path

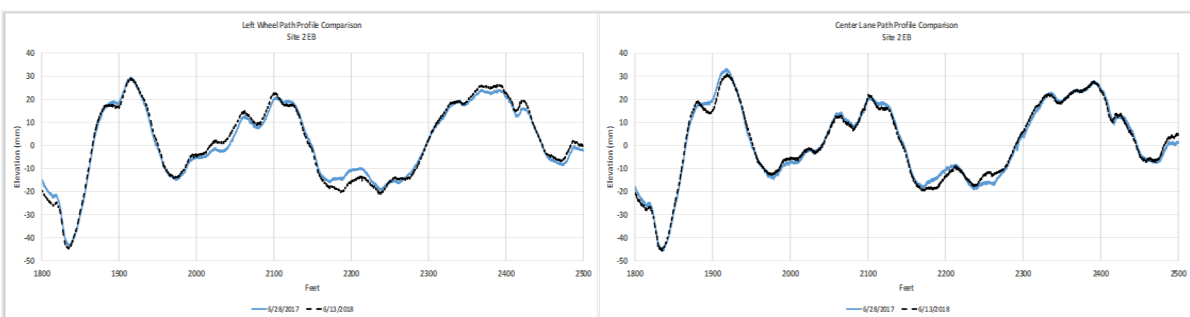

Figure 32

Site 2 EB longitudinal profile for left wheel path and center of lane

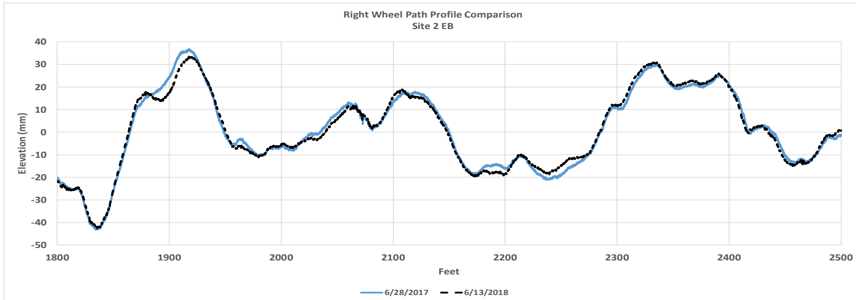

Figure 33
Site 2 EB longitudinal profile for right wheel path

Roadway Surface Distresses

Roadway Surface Rutting (EB)

Figures 34 and 35 present the rutting measurements for Sites 1 to 6 on the assessment dates of June 2017 and June 2018. DOTD considers rutting greater than 0.5 in. to be significant and in need of mitigation. The average rutting depths for each site were very minor but there were significant maximum rutting depths at some locations within each Site. It is probable that the significant rutting at some locations were due to weakening of the pavement structure due to volumetric changes in the embankment as well as depressions caused by movements in the embankment. For Site 1, the maximum rutting in the RWP was 0.386 in. in June 2017 and 0.74 in. in June 2018 indicating that rutting in those locations are increasing. Site 2 showed a similar pattern with the maximum rutting in the RWP being 0.713 in. in June 2017 and 0.205 in. on June 2018. The reason for the decrease in the maximum rutting between June 2017 and June 2018 is unknown. The maximum rutting values for Site 3 in the RWP were 0.382 in. on June 2017 and 0.232 in. on June 2018. Site 4 had maximum rutting values in the RWP of 0.953 in. on June 2017 and 0.28 in. on June 2018. As with Site 2, the authors are uncertain of the decrease in maximum rutting between June 2017 and June 2018. The maximum rutting values in the RWP for Site 5 were 0.673 in. and 1.2 in. on June 2017 and June 2018, respectively. This site had the highest maximum rut depth in the EB direction. Site 6 had maximum rutting values in the RWP of 0.953 in. and 1.5 in. on June 2017 and June 2018, respectively.

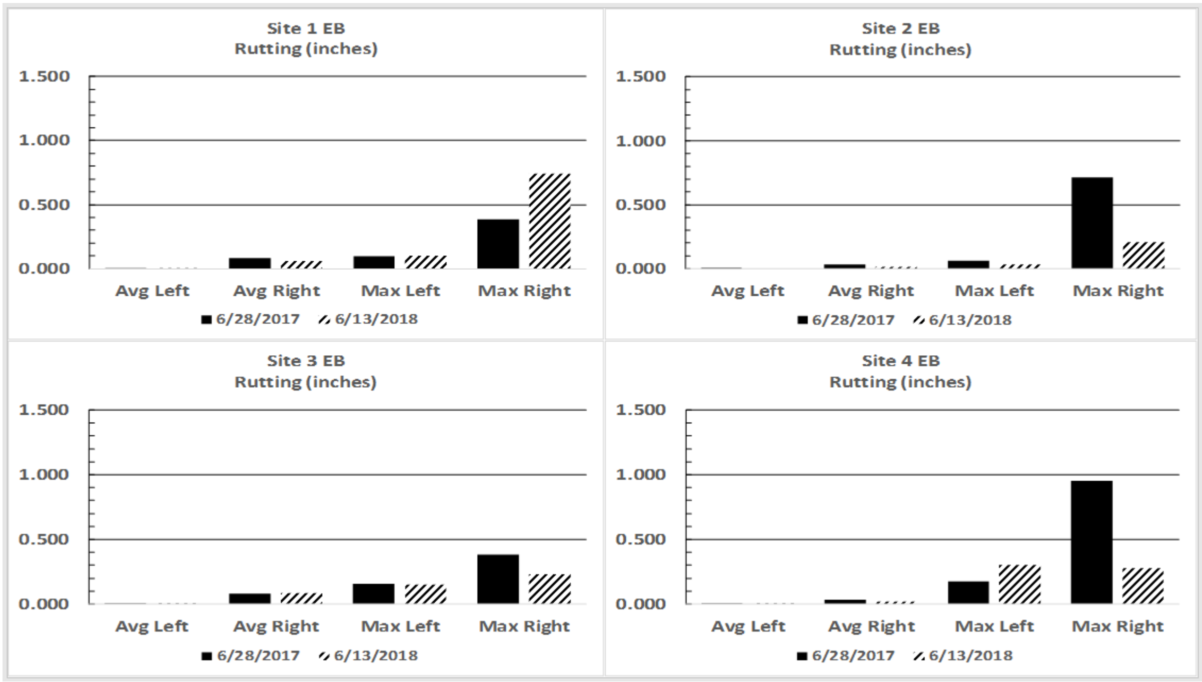

Figure 34
EB rutting for Sites 1 to 4

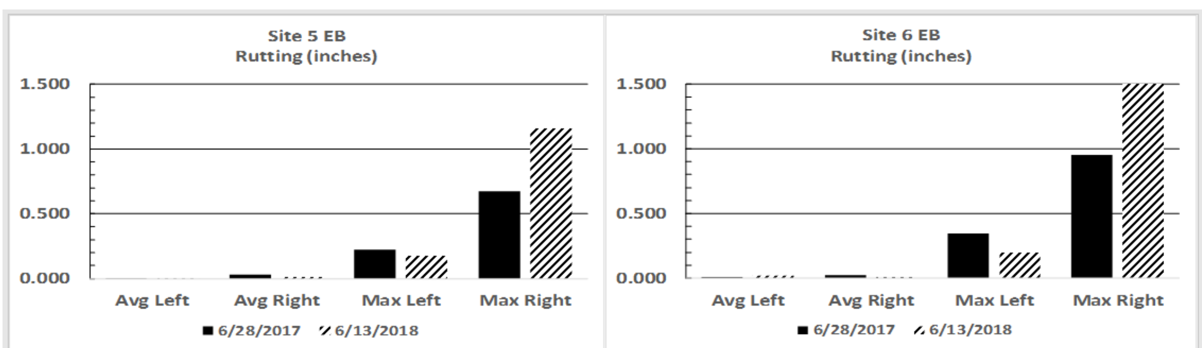

Figure 35
EB rutting for Sites 5 and 6

Roadway Surface Rutting (WB)

Figures 36 and 37 present the rutting measurements for Sites 1 to 6 on the assessment dates of June 2017 and June 2018. The average rutting depths for each site were minor but there were significant maximum rutting depths at some locations within each Site. On Site 1, the maximum rutting depth in the RWP was 0.276 in. and 0.858 in. on June 2017 and June 2018 respectively. Site 2 had maximum rutting depths in the RWP of 0.807 in. on June 2017 and 0.122 in. on June 2018. The reason for the decrease in the rutting depths between June 2017 and June 2018 is unknown but may be due to volumetric changes in the embankment. The maximum rutting depth in the RWP for Site 3 was 0.268 in. and 0.850 in. on June 2017 and June 2018 respectively. Site 4 had maximum rutting depths on the RWP of 1.236 in. and 0.929 in. on June

2017 and June 2018, respectively. Regarding Site 5, the maximum rutting depth in the RWP in June 2017 was 0.824 in. and on June 2018 it was 0.965 in. On Site 6, the maximum rutting depth on the RWP was 1.118 in. on June 2017 and 0.118 in. in June 2018.

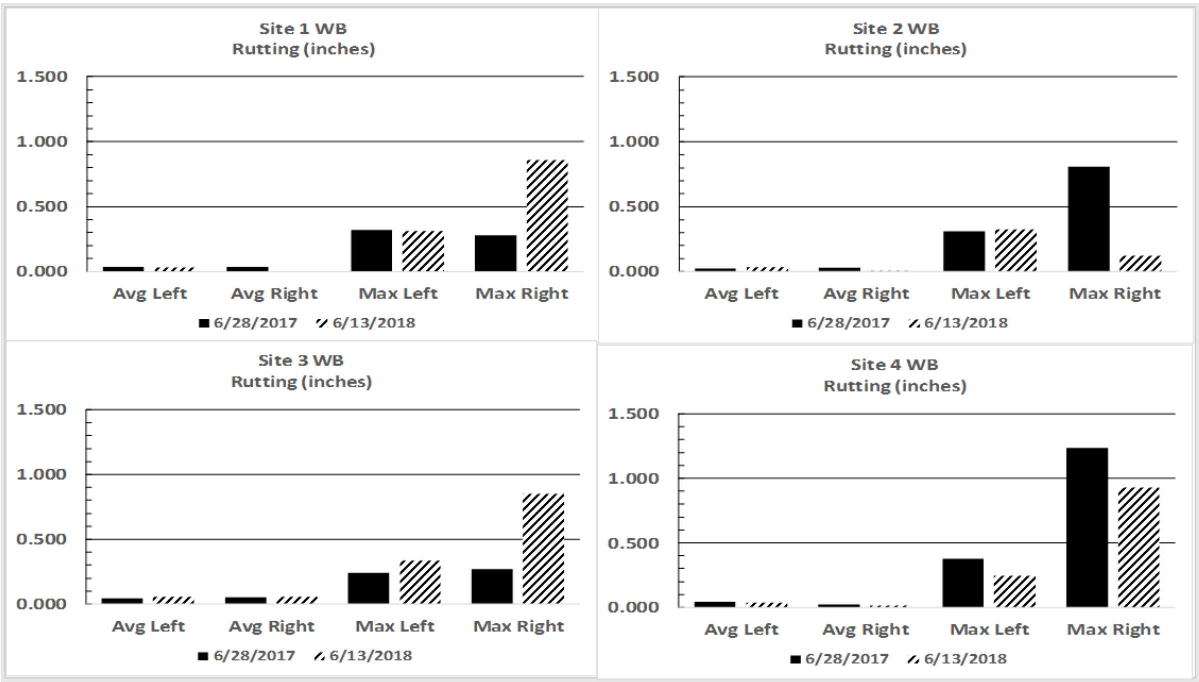

Figure 36
WB rutting for Sites 1 to 4

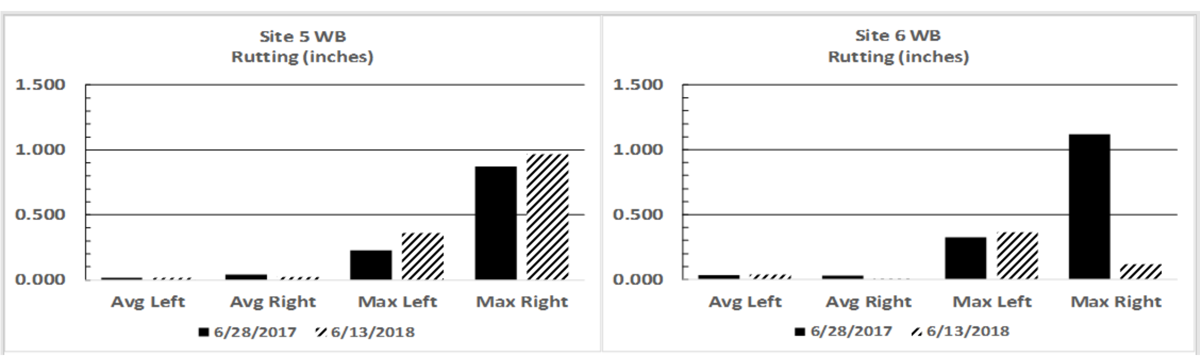

Figure 37
WB rutting for Sites 5 and 6

Roadway Surface Cracking

The test sites were assessed with LTRC's profiling and imaging vehicle in June 2017 and June 2018. Table 19 and 20 presents the cracking that were visible for each test site. Test Site 1 was divided into 1A, the area where no trees were present and 1, the area where trees were present.

The only cracking visible were longitudinal cracks, abbreviated as LNCR in the tables. Longitudinal cracks on roadways with pavement layers similar to this one are generally a sign of issues with movement (shrinking, swelling, or both) in the subgrade.

Table 19
EB pavement cracking data

Test Site (EB)	From	To	Test site length (ft.)	June 2017 LNCR (ft.)	June 2018 LNCR (ft.)
1A	10+00	12+00	200	21	19
1	12+00	18+00	600	154	170
2	18+00	25+00	700	303	273
3	25+00	32+00	700	452	506
4	33+02	41+02	800	546	717
5	41+02	49+02	800	1003	1017
6	49+02	57+02	800	739	754

Table 20
WB pavement cracking data

Test Site (WB)	From	To	Test site length (ft.)	June 2017 LNCR (ft.)	June 2018 LNCR (ft.)
1A	10+00	12+00	200	3	16
1	12+00	18+00	600	71	110
2	18+00	25+00	700	211	317
3	25+00	32+00	700	296	326
4	33+02	41+02	800	64	100
5	41+02	49+02	800	827	992
6	49+02	57+02	800	426	449

It is important to note that longitudinal cracks were present at all Sites in June 2017, approximately 18 months after the first submergence event (January 2016 to March 2016). According to LTRC survey staff, there were no observed cracks of any kind on the roadway at the time of the first cross-section survey in December 2015.

Comparing Site 1A to 1 for both the EB and WB directions, it is obvious that more longitudinal cracks were present in Site 1. This provides evidence for the hypothesis that an area with no trees will have less distresses than an area with trees with all else being equal. There were more observed cracks on the June 2018 assessment than the June 2017 assessment. Site 1A had the least amount of longitudinal cracks than the other sections for both the June 2017 and 2018 assessment. With the exception of the WB lane on Site 4 and both lanes on Site 1A, Site 1 ranked second in terms of least amount of longitudinal cracks. It is LTRCs opinion that Sites 1 and 1A had less longitudinal cracks due to the ground movement mitigation effects of the 2 ft. thick sand interlayer, refer to Appendix 2 for details of the typical section.

In the EB direction for Site 2, there were similar amounts of longitudinal cracks in the June 2018 assessment that the June 2017 assessment while there were increased amounts of longitudinal cracks in the WB direction between the June 2017 and 2018 assessments. There were similar amounts of longitudinal cracks in the EB lane and WB lanes.

For Site 3, there were increased amounts of longitudinal cracks in the EB lane for the June 2017 and 2018 assessments while the WB lane had similar amounts of longitudinal cracks for both the June 2017 and 2018 assessments. The WB lanes had less amounts of longitudinal cracks than the EB lanes.

Regarding Site 4, there were more longitudinal cracks on the June 2018 assessment than 2017 assessment on the EB lane and the same was true on the WB lane. However, there were significantly less longitudinal cracks on the WB lane than the EB lane. In fact, the longitudinal cracking on this Site was similar to the WB lane on Site 1. LTRC is uncertain why there were significantly less longitudinal cracks at this location and this warrants further investigation.

Site 5 had the most longitudinal cracks on both the EB and WB lanes in all assessments. On the EB lane, the longitudinal cracks were similar between the June 2017 and 2018 assessments while the WB lane had more longitudinal cracks on the June 2018 assessment than the June 2017 assessment.

The amount of longitudinal cracks on the EB lane for Site 6 were similar between both the June 2017 and 2018 assessments and the same was true for the WB lane. The WB lane had less longitudinal cracks than the EB lanes.

CONCLUSIONS

LTRC has conducted a comprehensive research study that provides strong evidence of damage to roadways caused by submergence. The evidence supporting the submergence damage comes from two major sources. The first is from a rod and level cross-section survey taken approximately one month prior to the first submergence event and subsequent cross-section surveys taken after the first, second, and third submergence events. The second source comes from pavement assessments with LTRC's roadway surface profiler and imaging vehicle. Data presented in this report included roadway surface smoothness in terms of IRI, roadway surface longitudinal profile, roadway surface rutting, and roadway surface crack distresses.

The cross-section survey clearly demonstrated the differential movement of the roadway surface caused by the flooding events. The first cross-section survey occurred approximately one month (December 2015) after the newly constructed roadway was fully opened to traffic. Approximately one month (January 2016) after the first cross-section survey, the roadway submerged for approximately 3 months (January 2016 to March 2016). The next cross-section survey occurred in April 2016. The cross-section surveys clearly demonstrated the elevation increases caused by the submergence event. The increase in elevation at the center line of the roadway ranged from 2.44 mm to 44.50 mm. With the exception of cross-section Site 1A, cross-section points right and left of the centerline all increased with no adjacent point having the same magnitude of increase within each cross-section. This in and of itself will cause damage to the entire roadway section (pavement and soil cement base course). Cross-section 1A is unique amongst the sites in that it was the only location where trees were not present adjacent to the right-of-way. When compared to the other cross-section sites, it is clearly evident the effect that trees have on the subgrade in that much more significant elevation changes occurred in those sections after the first flooding event. The differential movements in the cross-sections occurred to varying degrees at the different test sites as observed on subsequent cross-section surveys. The sites with the sand interlayers (1A and 1) had the least magnitude of movements. Movements of differing proportions throughout the service life of the pavement will adversely affect its performance and reduce its service life.

The data gathered from the profiler and imagining system also provided evidence of damage caused by submerging the newly constructed pavement. On the June 2017 assessment the maximum IRI was 141.8 and the minimum was 84.7 for both travel lanes in the test sites. At that time the pavement had been in service for approximately 19 months of which it was submerged for 3 months. When the new roadway was fully opened to traffic, it is reasonable to assume that the roadway had no surface cracks or rutting and that the IRI would have been less than or equal to 75 in./mile which is DOTD’s IRI requirement for this type of newly constructed roadway. With that being the case, IRI values as high as 141.8 greatly exceeds the IRI values that should have been present on a low volume roadway at this point in its service life. On the June 2018 assessment, the IRI values ranged from 176.5 to 75.2. There was a slight increase in roughness between the 2018 and 2017 assessment period which was to be expected. The high variability in IRI magnitudes observed in the test site locations which were a total length of 4,702 ft. indicate that significant differences in the longitudinal profile existed. Plots of the longitudinal profile confirmed this. The rutting data also pointed towards damage in the roadway structure. There was a high variability in rutting amongst the test sites. Rutting values as high as 1.685 in. were measured.

Regarding roadway surface cracking, only longitudinal cracks were observed on the test sites. Site 1A had the least amount of longitudinal cracks amongst the test sites. This corresponds to LTRC’s observance that sites with trees generally have more distresses than sites without trees. The observed longitudinal cracks in the test sites ranged from 3 ft. to 1,003 ft. and 16 ft. to 1,017 ft., respectively, on the June 2017 and 2018 assessments. The amounts of longitudinal cracks observed indicated that (1) most of the sites had excessive longitudinal cracking for the time that they were in service, (2) the longitudinal cracking observed is consistent with volumetric changes occurring in the subgrade, and (3) it is logical to infer that the submergence events were responsible for both the magnitude and premature emergence of these longitudinal cracks.

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APPENDIX 1

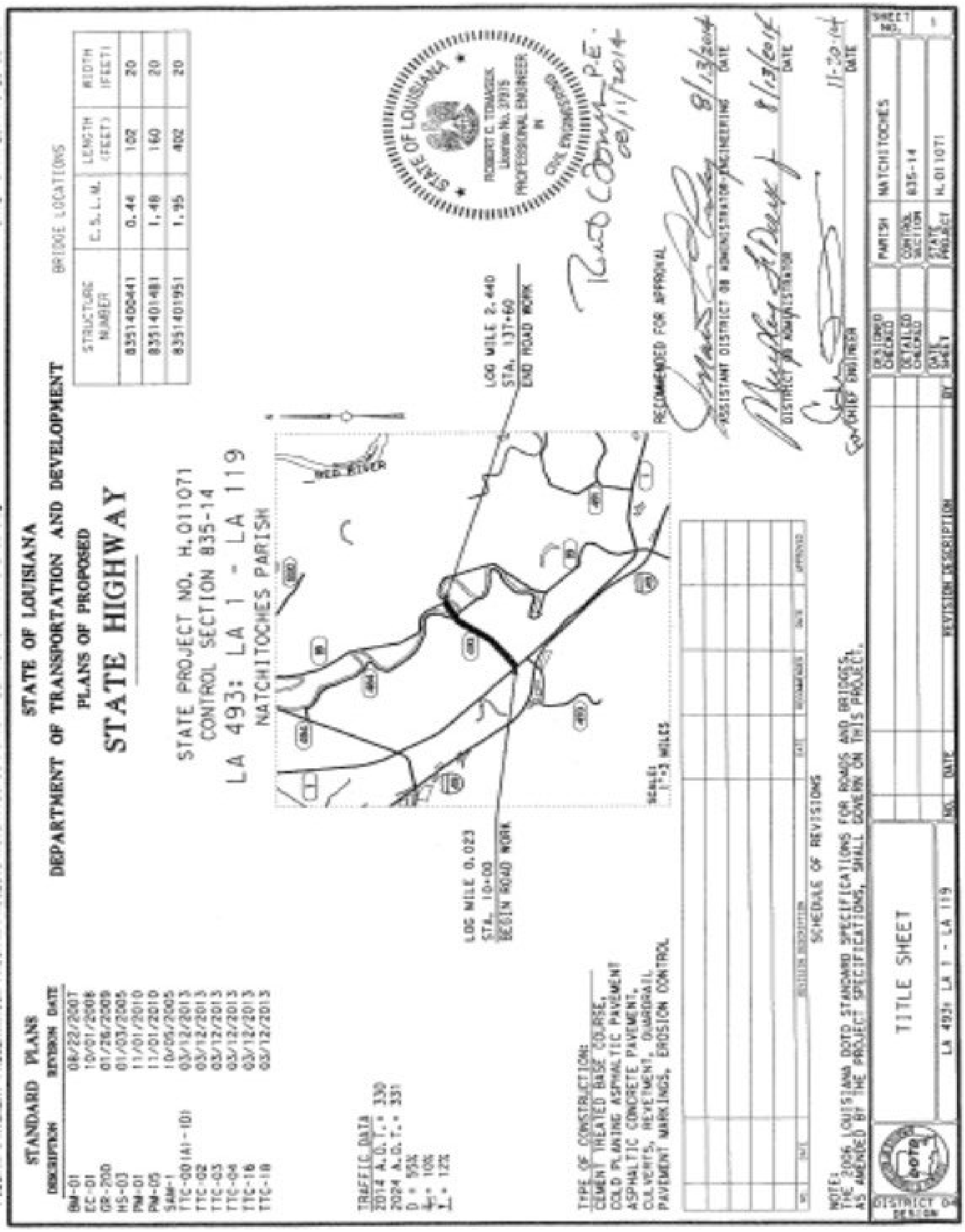


Figure 38
Project title sheet

APPENDIX 2

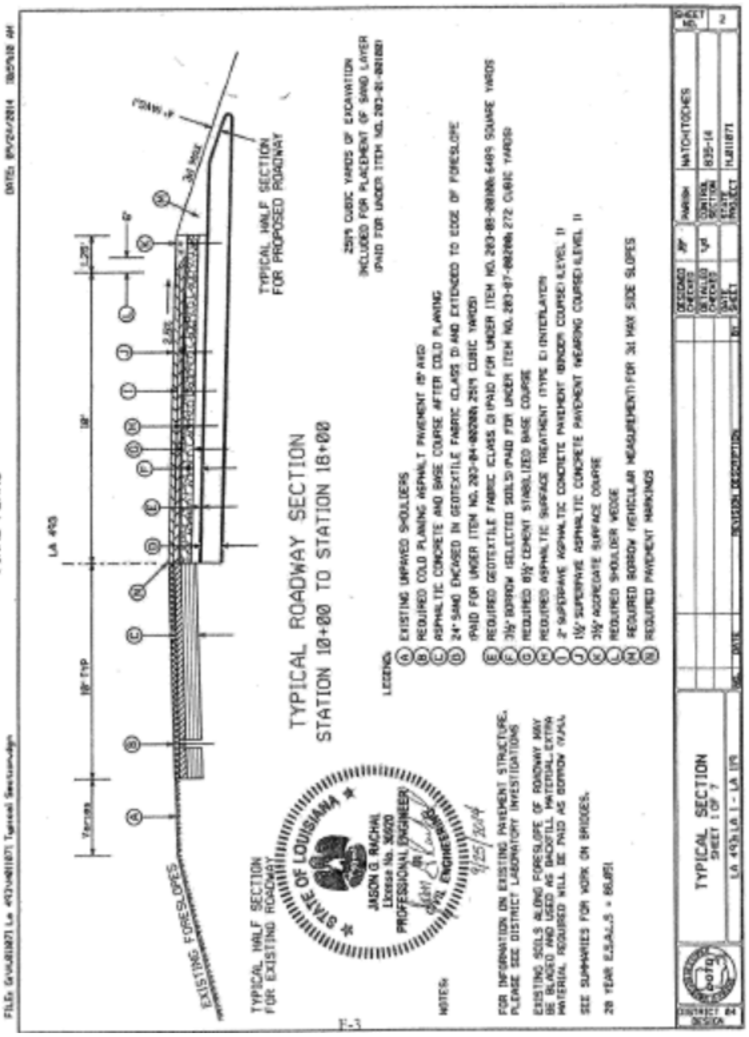


Figure 39
Test Site 1

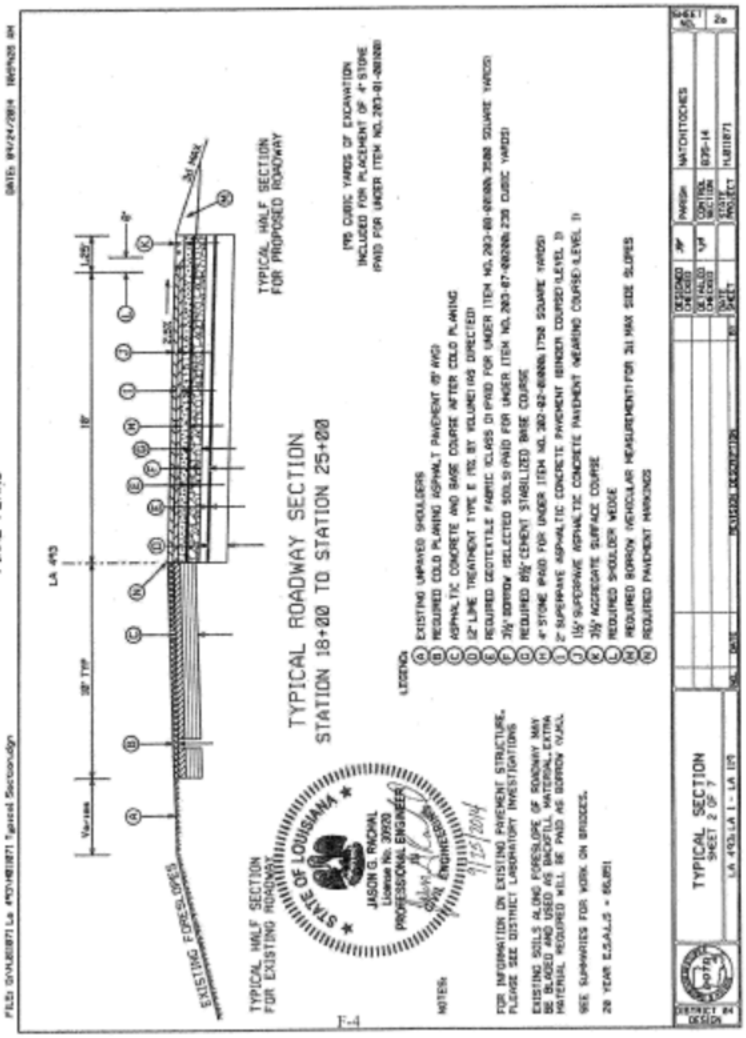


Figure 40
Test Site 2

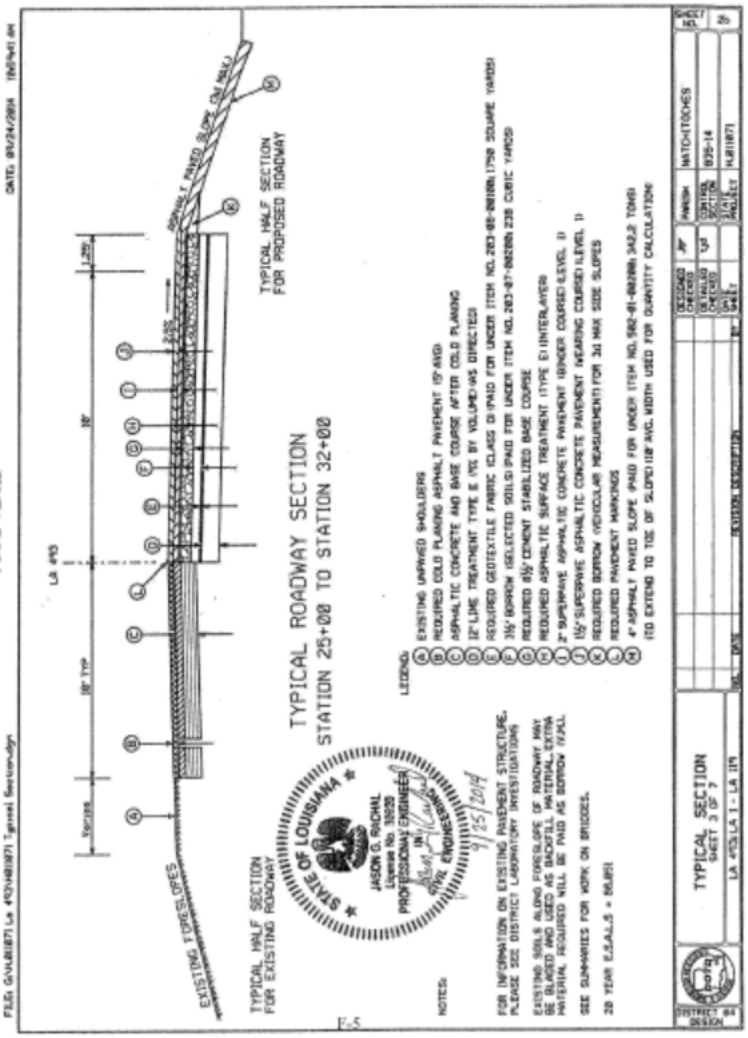


Figure 41
Test Site 3

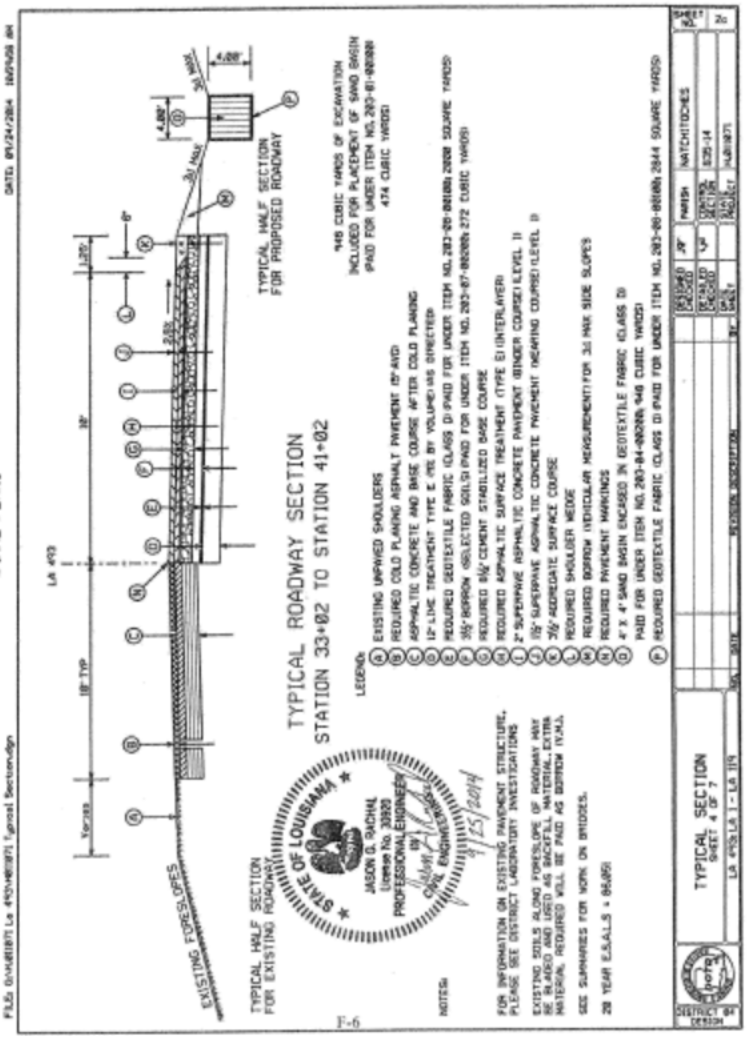
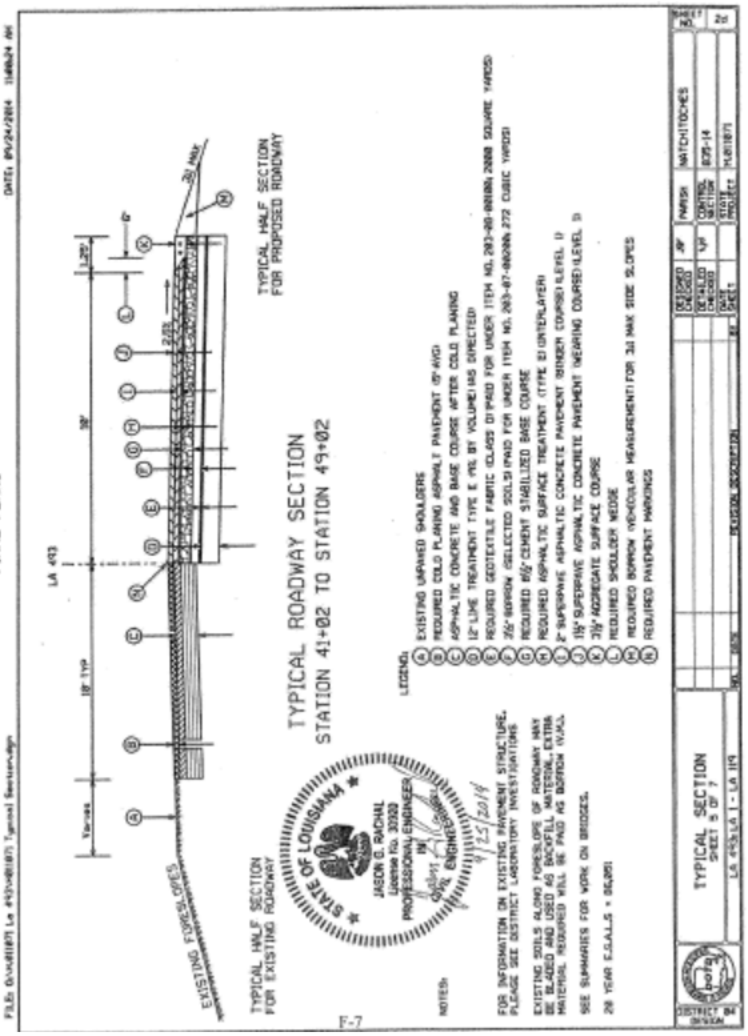


Figure 42

Test Site 4



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Test Site 5

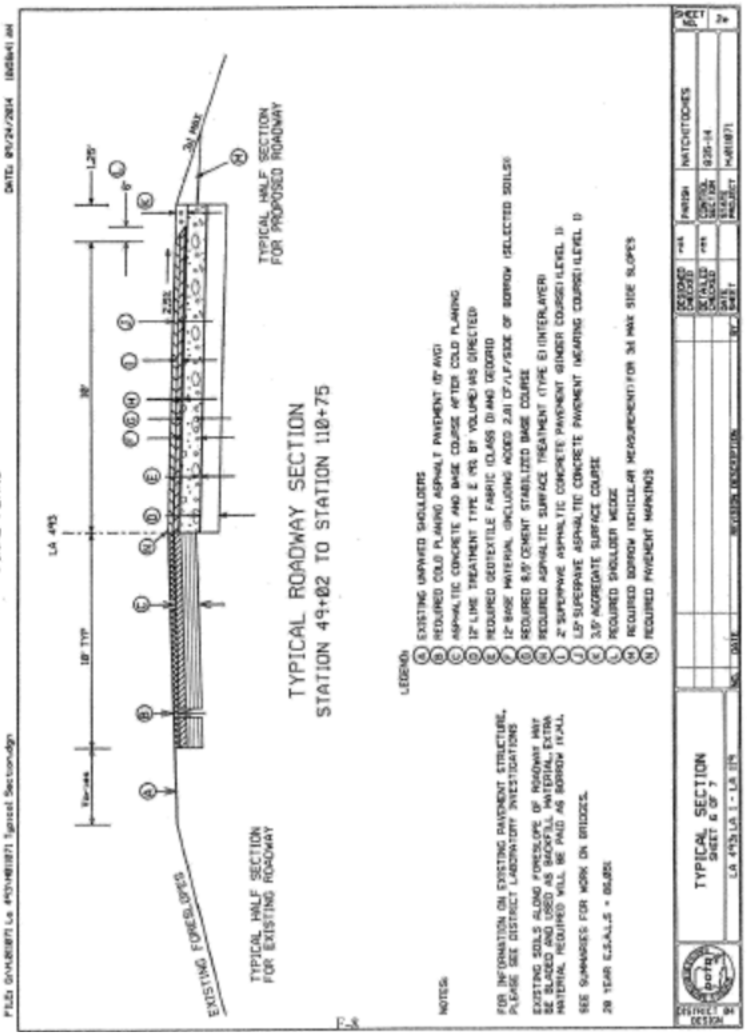

Figure 44

Test Site 6

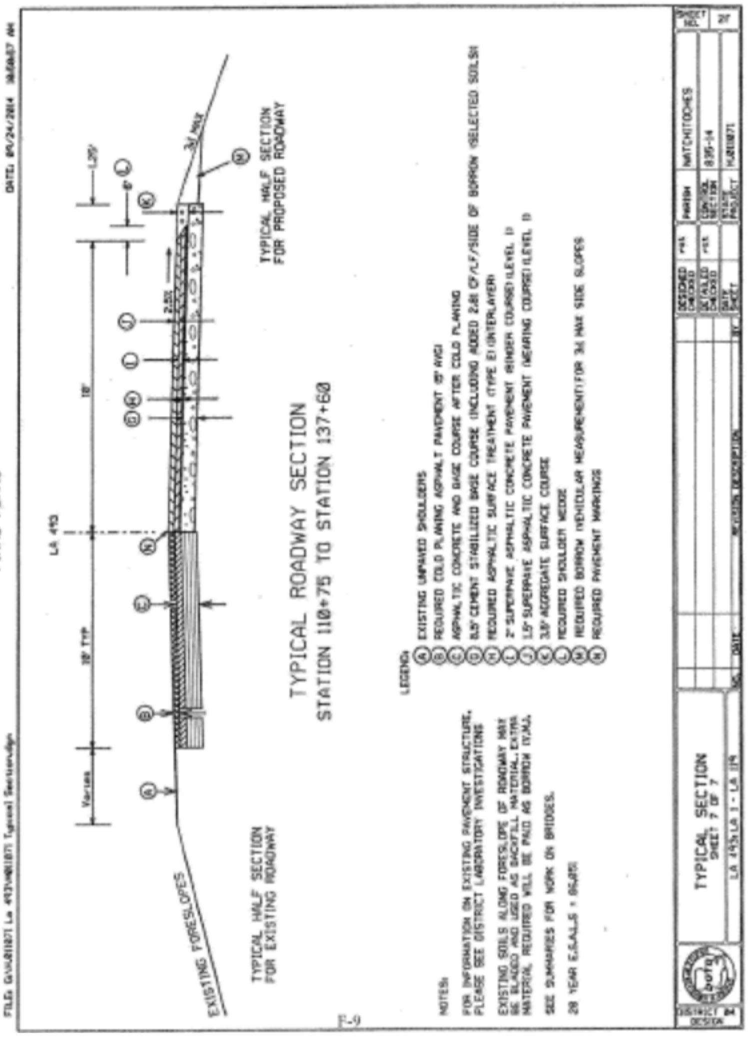

Figure 45

Typical section outside of Test sites

APPENDIX 3

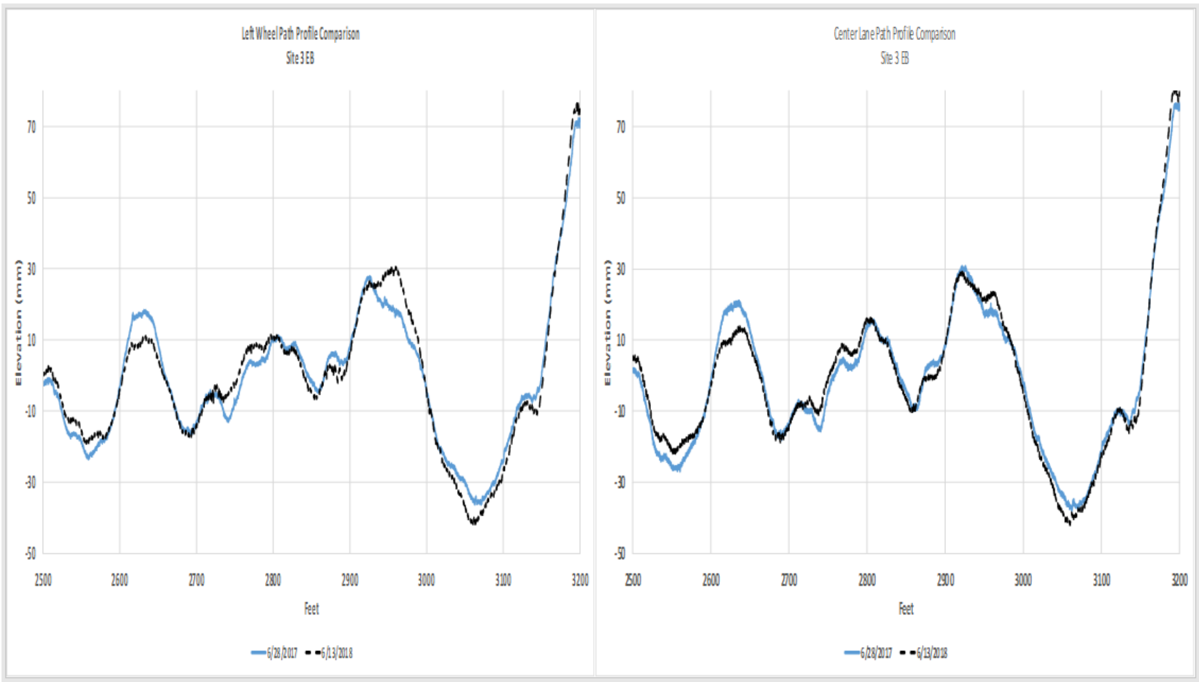

Figure 46
Site 3 EB longitudinal profile for left wheel path and center of lane

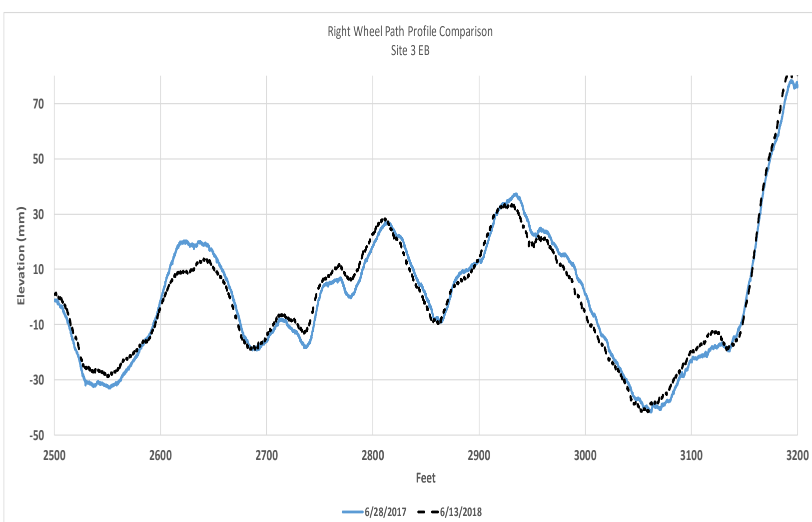

Figure 47
Site 3 EB longitudinal profile for right wheel path

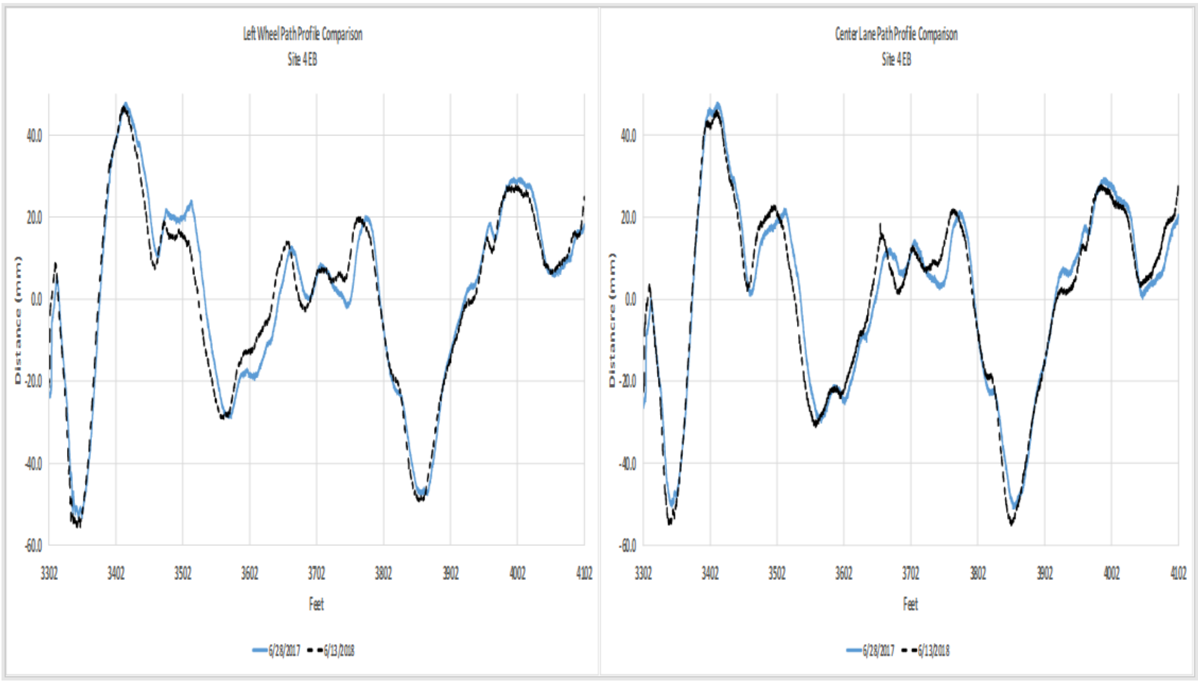

Figure 48

Site 4 EB longitudinal profile for left wheel path and center of lane

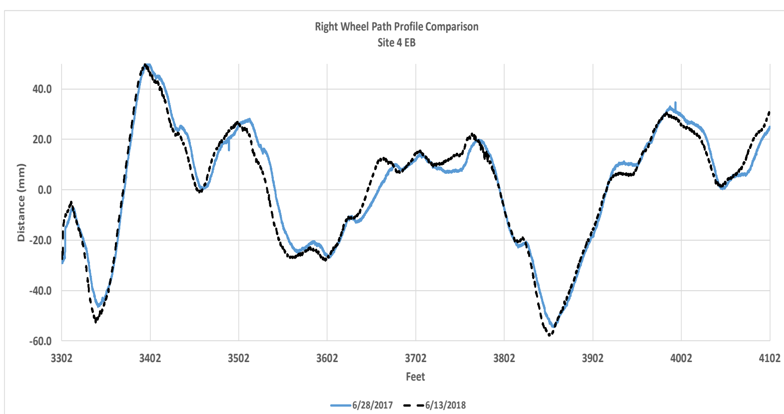

Figure 49

Site 4 EB longitudinal profile for right wheel path

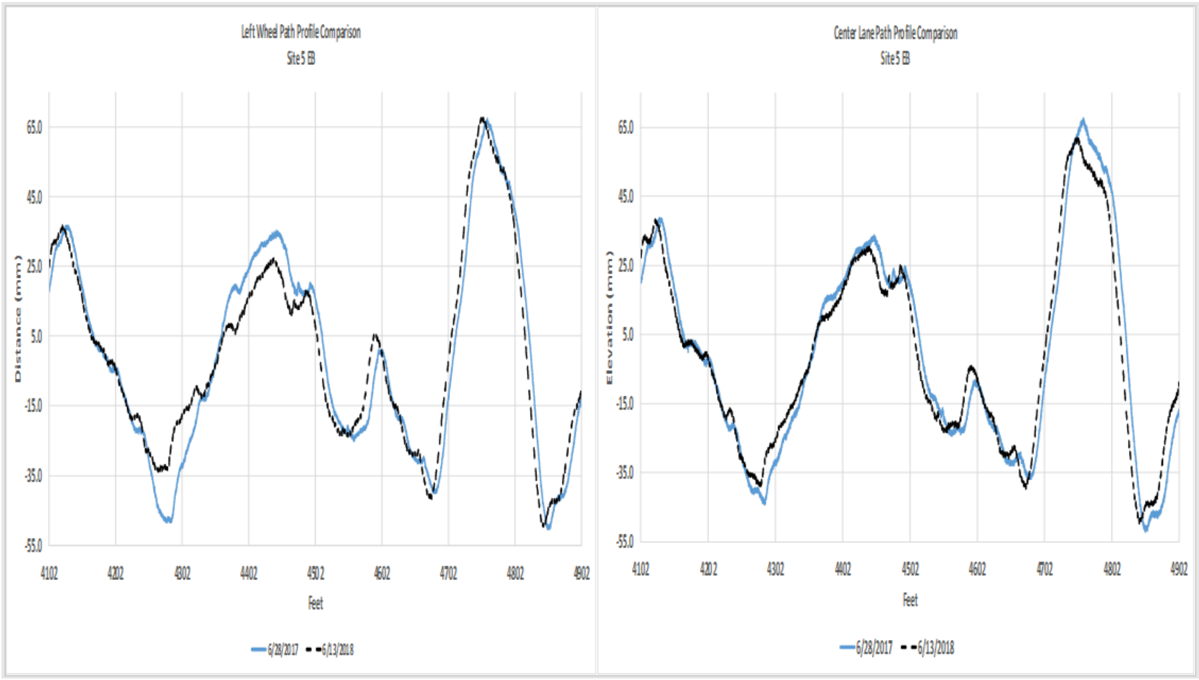

Figure 50
Site 5 EB longitudinal profile for left wheel path and center of lane

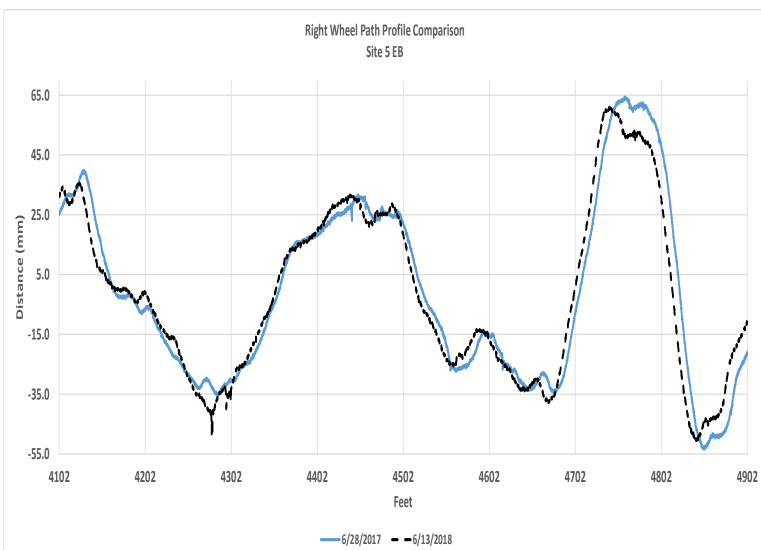

Figure 51
Site 5 EB longitudinal profile for right wheel path

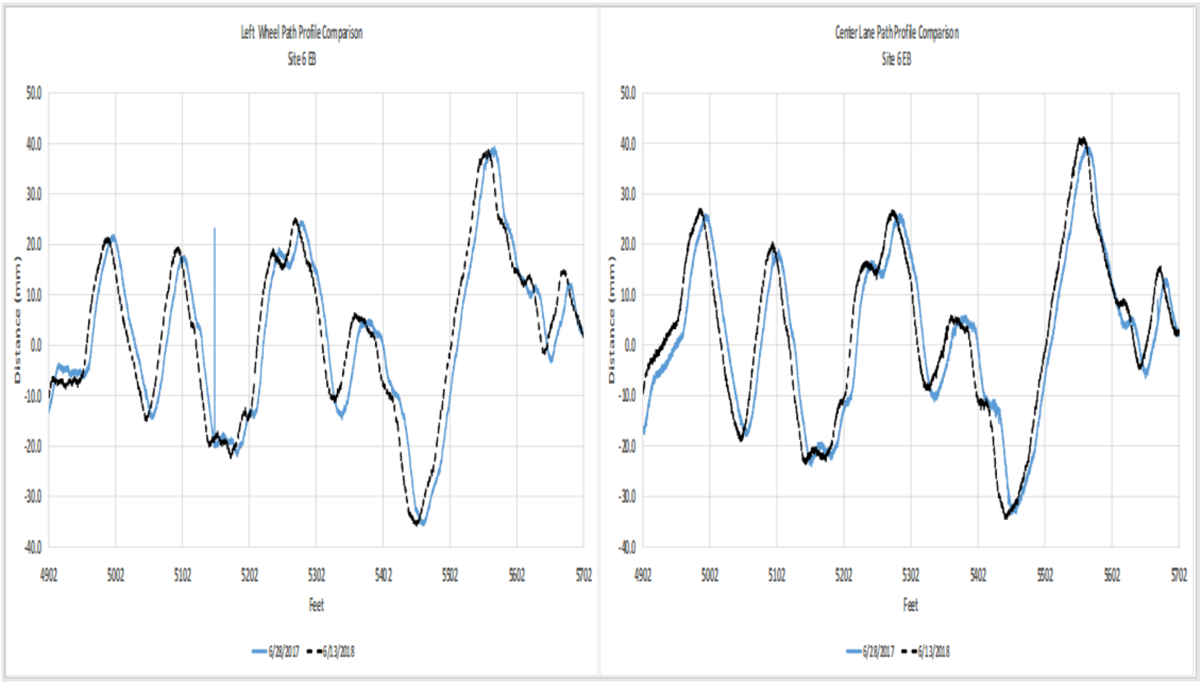

Figure 52

Site 6 EB longitudinal profile for left wheel path and center of lane

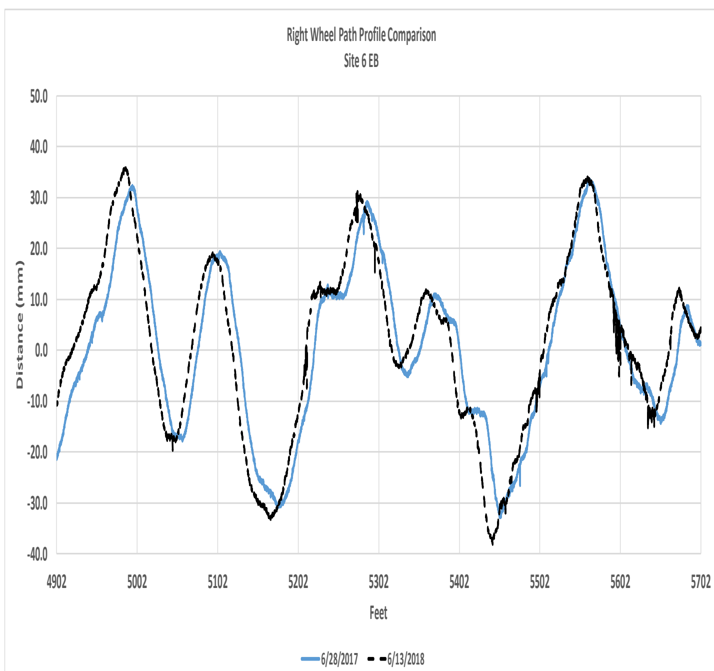

Figure 53

Site 6 EB longitudinal profile for right wheel path

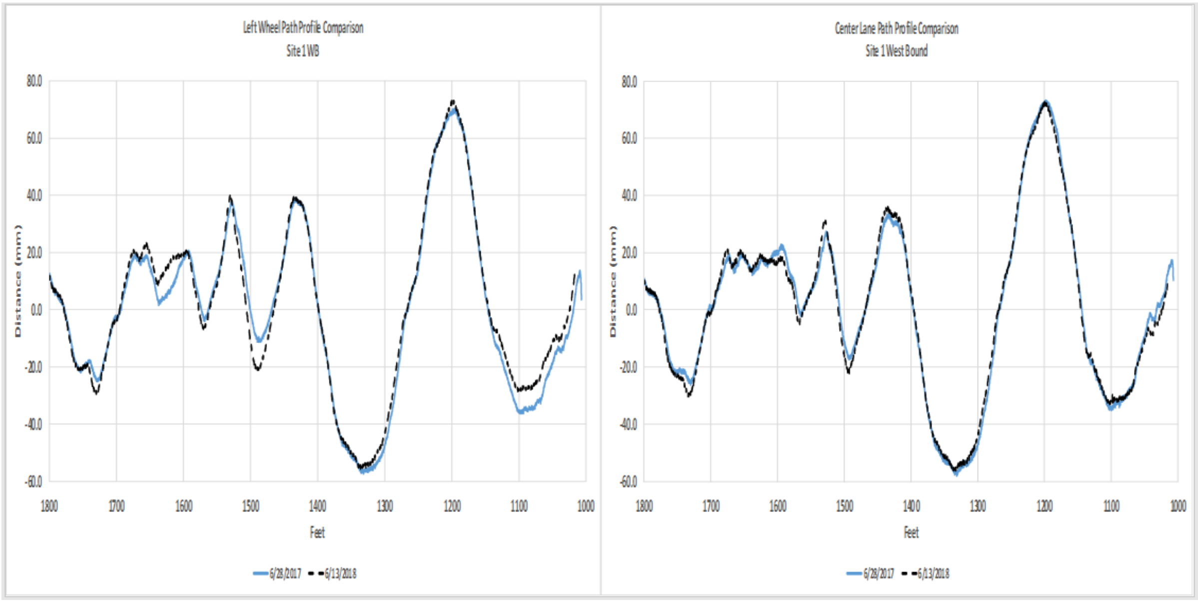

Figure 54
Site 1 WB longitudinal profile for left wheel path and center lane path

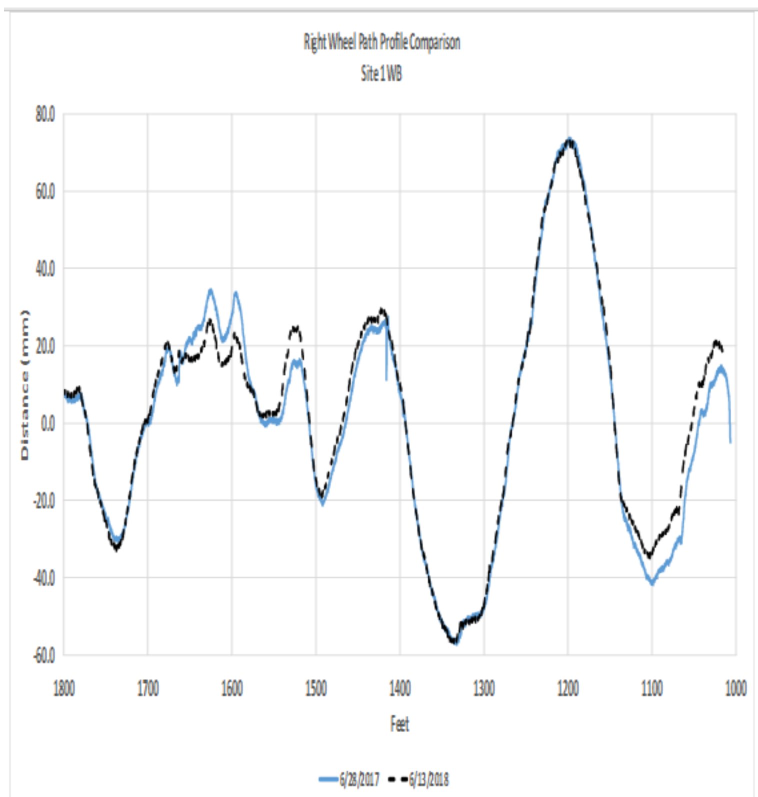

Figure 55
Site 1 WB longitudinal profile for right wheel path

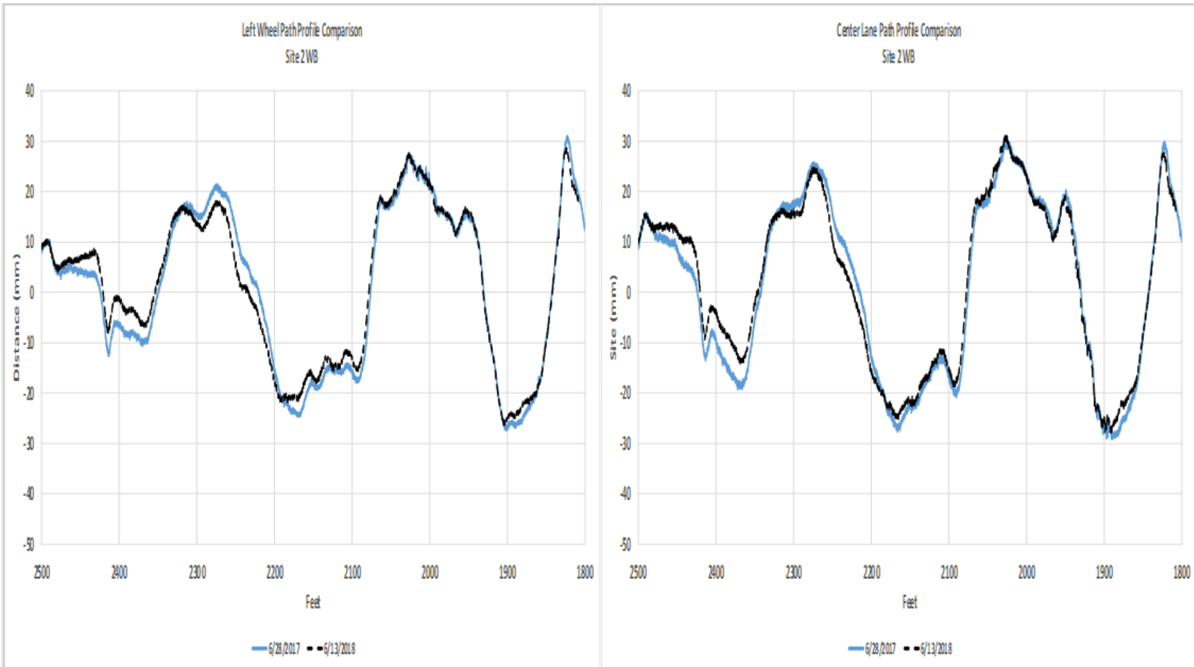

Figure 56

Site 2 WB longitudinal profile for left wheel path and center lane path

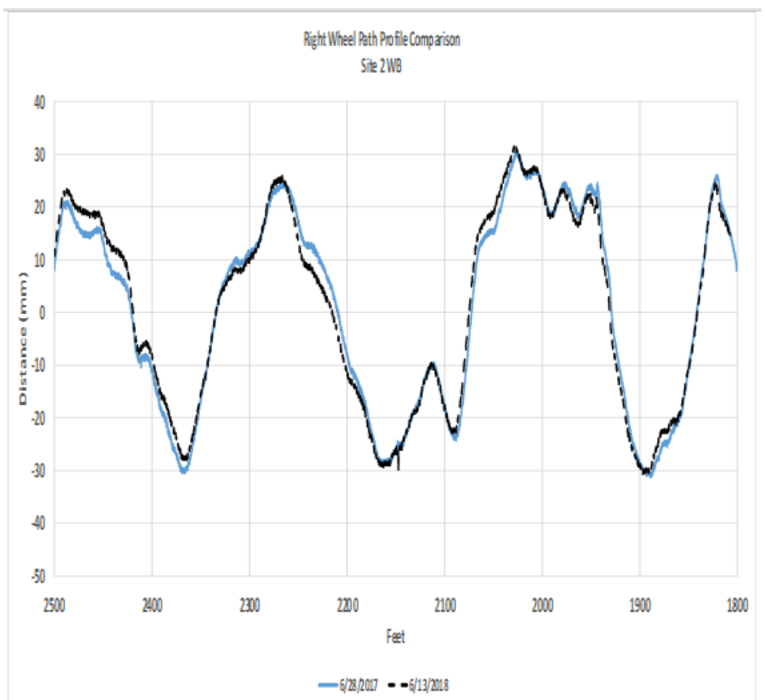

Figure 57

Site 2 WB longitudinal profile for right wheel path

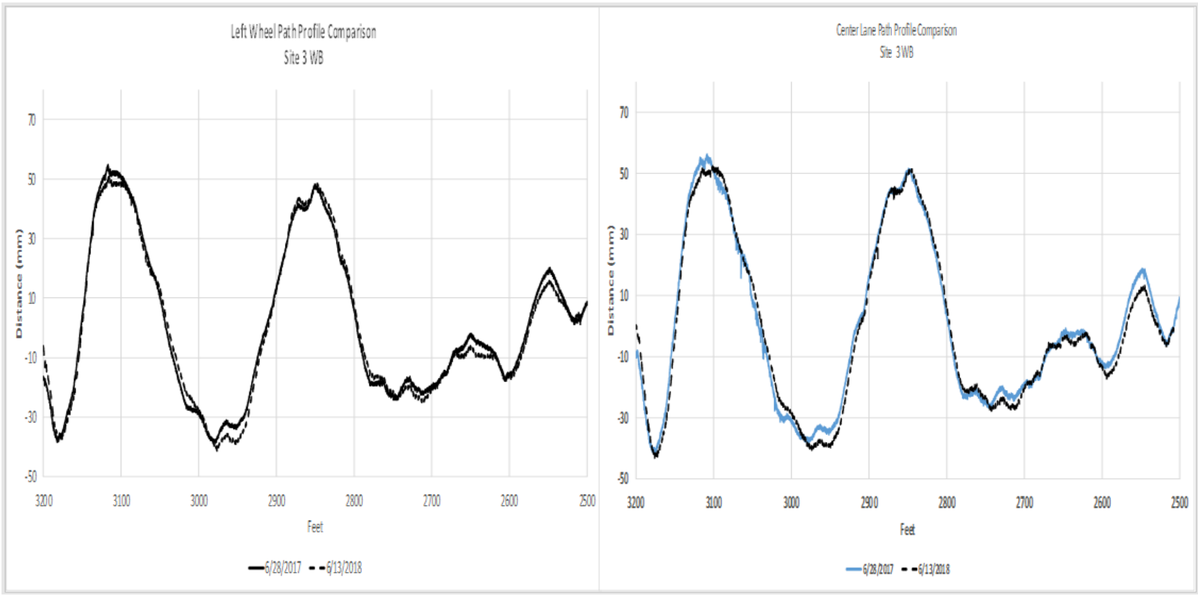

Figure 58

Site 3 WB longitudinal profile for left wheel path and center lane path

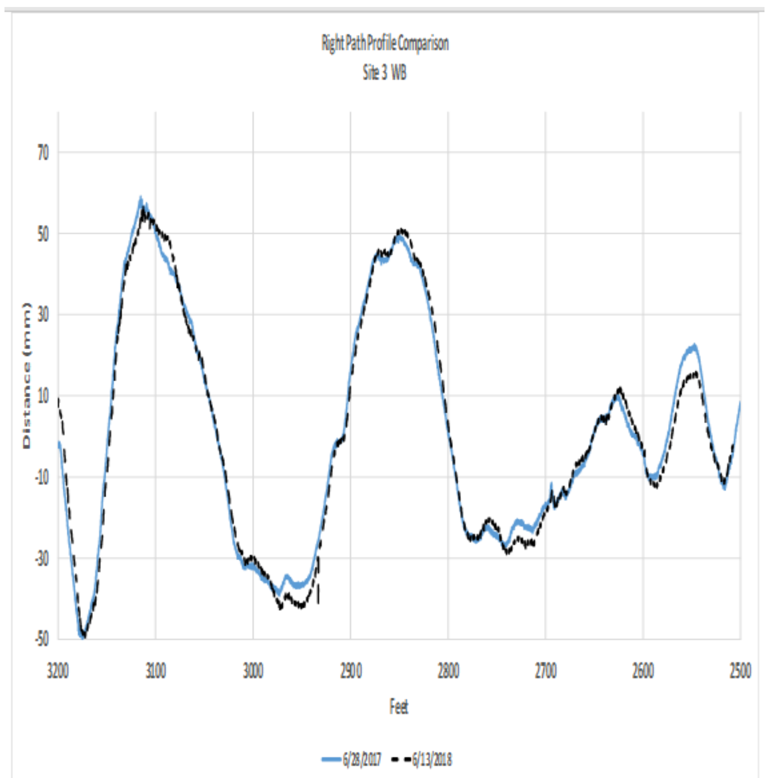

Figure 59

Site 3 WB longitudinal profile for right wheel path

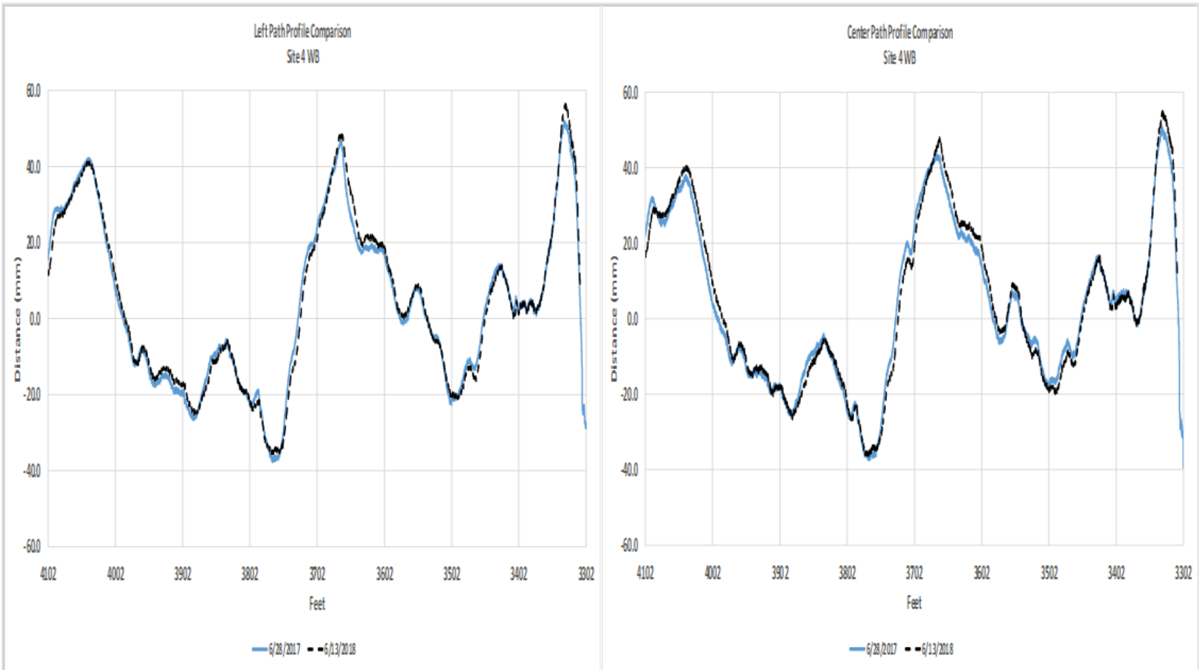

Figure 60
Site 4 WB longitudinal profile for left wheel path and center lane path

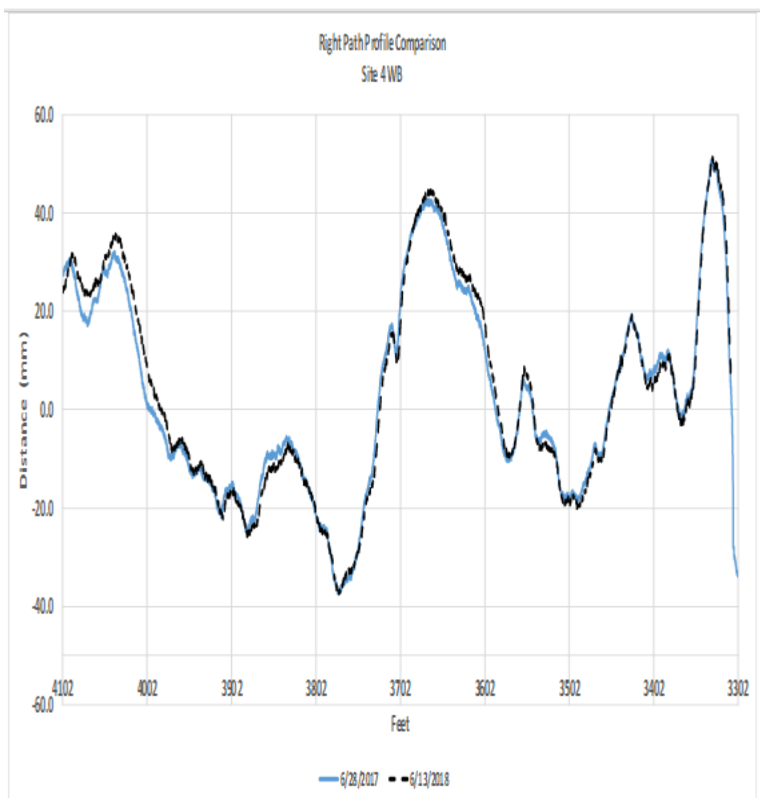

Figure 61
Site 4 WB longitudinal profile for right wheel path

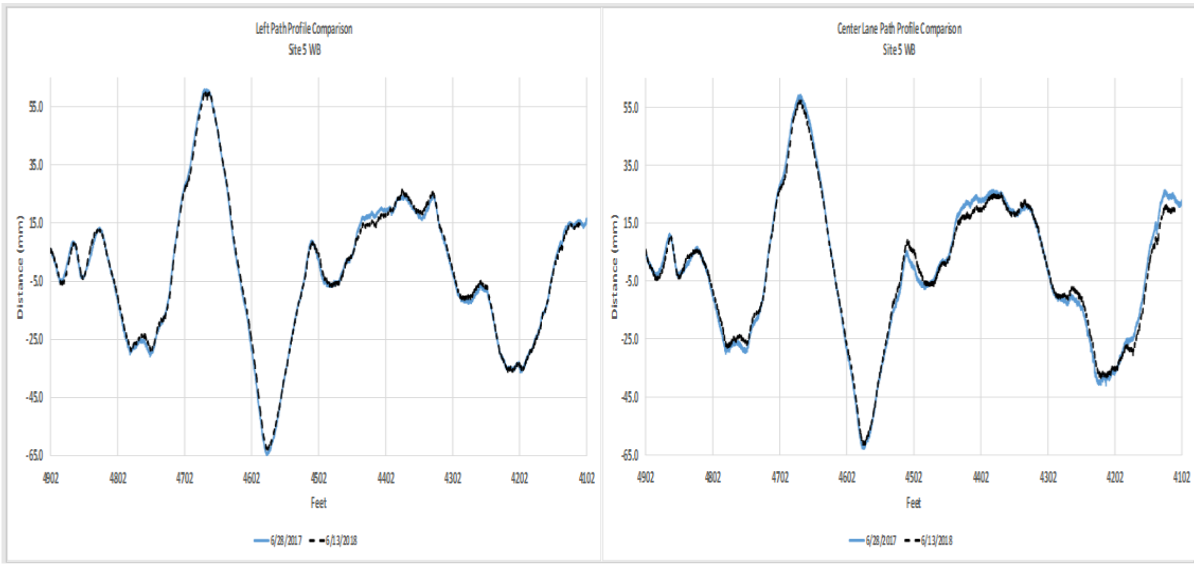

Figure 62
Site 5 WB longitudinal profile for left wheel path and center lane path

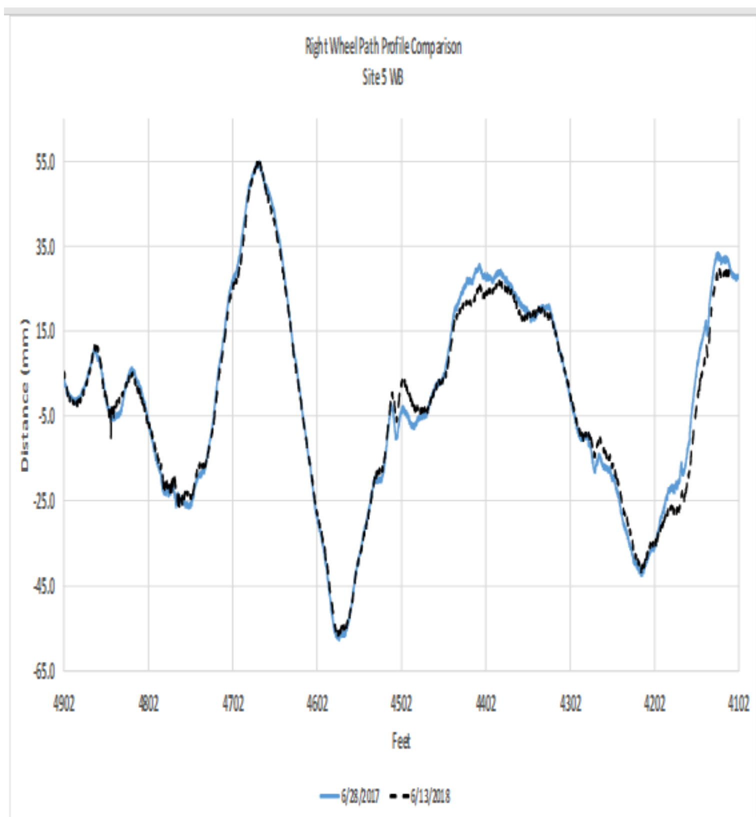

Figure 63
Site 5 WB longitudinal profile for right wheel path

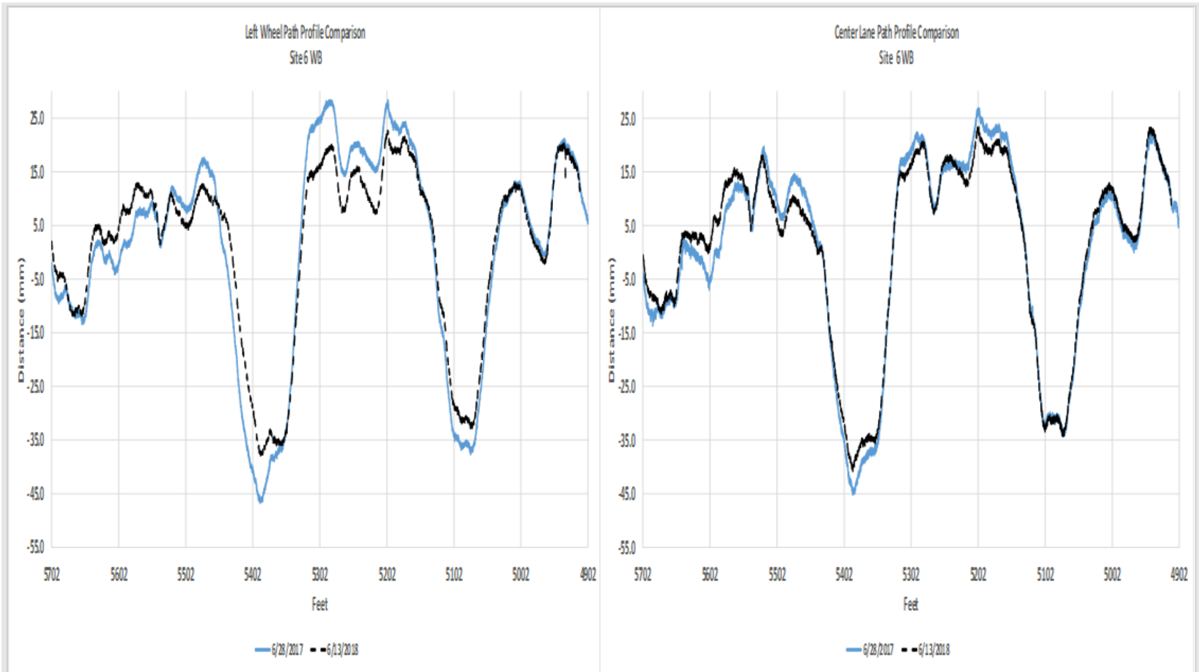

Figure 64
Site 6 WB longitudinal profile for left wheel path and center lane path

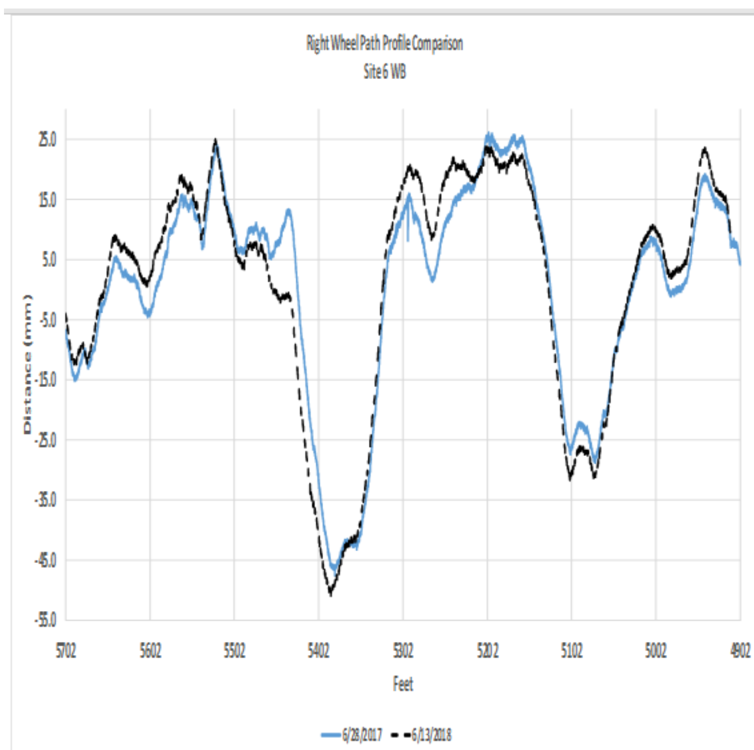

Figure 65
Site 6 WB longitudinal profile for right wheel path

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