MINNESOTA DEPARTMENT OF TRANSPORTATION

RESEARCH

2008-23

Effects of Seasonal Changes on Ride Quality at MnROAD

LRRB
LOCAL
ROAD RESEARCH
BOARD

Take the steps... Research...Knowledge...Innovative Solutions!

Transportation Research

Technical Report Documentation Page

1. Report No.	2.	3. Recipients Accession No.
MN/RC 2008-23		

4. Title and Subtitle	5. Report Date
Effects of Seasonal Changes on Ride Quality at MnROAD	July 2008
	6.
7. Author(s) Lev Khazanovich, Peter Bly, Atika Shamin and Randal Barnes	8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Civil Engineering University of Minnesota 500 Pillsbury Drive SE Minneapolis, Minnesota 55455	10. Project/Task/Work Unit No. 11. Contract (C) or Grant (G) No. (c) 89261 (wo) 21
12. Sponsoring Organization Name and Address Minnesota Department of Transportation 395 John Ireland Boulevard Mail Stop 330 St. Paul, Minnesota 55155	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes
http://www.lrrb.org/PDF/200823.pdf

16. Abstract (Limit: 200 words)

This project studied frost heave as it relates to different pavement design parameters and ride quality deterioration. Elevations of frost pins embedded in MnROAD test sections were measured over four years. Pin elevation changes were analyzed to show the amount of frost heave and degree of frost heave uniformity within a cell. Various plots were made to show the elevation change and interquartile range of the pins over time. Statistical approaches such as visual analyses, Student-t hypothesis testing, and ANOVA analysis were used in this study to evaluate the effect of pavement design features on frost heave and roughness.

Subgrade and base type, pavement thickness, and drainage capabilities are the major design factors that affect frost heave. The effects of frost heave on ride quality deterioration for flexible and rigid pavements could not be confirmed or statistically rejected in this study. No seasonal adjustment factor for IRI measurement is recommended for use in a pavement management system because no firm conclusions could be made from the data concerning a seasonal effect on IRI measurements.

17. Document Analysis/Descriptors	18. Availability Statement
Frost Heave, Pavement, IRI, Pavement Design, Ride Quality	No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161

19. Security Class (this report)	20. Security Class (this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	137	

Effects of Seasonal Changes on Ride Quality at MnROAD

Final Report

Prepared by:

Peter Bly
Atika Shamin
Randal Barnes
Lev Khazanovich

University of Minnesota
Department of Civil Engineering

July 2008

Published by:

Minnesota Department of Transportation
Research Services Section
395 John Ireland Boulevard, Mail Stop 330
St. Paul, Minnesota 55155

Acknowledgements

This research was sponsored by the Minnesota Department of Transportation (Mn/DOT) and Local Road Research Board. Furthermore, the work and final report is particularly indebted to Ben Worel, Erland Lukanen, Bernard Izevbekhai, Tom Burnham, Cory Johnson of Mn/DOTand Jill Thomas of Minnesoat Asphalt Pavement Association for their reviews of early drafts and/or provision of materials for research.

Table of Contents

List of Tables

List of Figures

Executive Summary

This project studied frost heave as it relates to different pavement design parameters and ride quality deterioration. To evaluate the frost heave effects, MnROAD personnel collected the elevation of frost pins embedded in the pavements over the course of 4 years. In this study, the frost heave data were analyzed. Changes in pin elevations were calculated and the values were analyzed to show the amount and degree of frost heave uniformity within a cell. Seven proposed data tables were created for addition into the MnROAD database.

Using the frost pin elevation data, various plots were made to show the change in elevation and the interquartile range of the pins over time for the study. The plots were examined for outlying data and the outlying data was removed if justified. The examined data was categorized based on the degree of variability seen in the median, interquantile range and IRI plots.

The primary goals of the project were to evaluate contribution of frost heave on seasonal and long term changes in ride quality of roads in Minnesota using pin elevation measurements and pavement performance data from the MnROAD test and to perform a comprehensive evaluation of the effects of the various design features on the frost heave action. The effects of the design features were isolated by comparing carefully selected cells and defining specific parameters to base comparisons off of to aid in data interpretation. This was essential to making meaningful comparisons among the test cells considered. Statistical approaches, such as visual analyses, Student-t hypothesis testing and ANOVA analysis, were used in this study to evaluate the effect of pavement design features on frost heave and roughness.

Subgrade and base type, pavement thickness and drainage capabilities are the major design factors that have the greatest affect on frost heave. The effect of frost heave on ride quality deterioration of flexible pavements could not be confirmed in this study and hypotheses that frost heave affects deterioration of ride quality for rigid pavements could not be rejected by statistical testing.

No firm conclusions could be made from the data concerning a seasonal effect on IRI measurements other than summer IRI values were the greatest throughout the year. No seasonal adjustment factor for IRI measurement is recommended for use in a pavement management system. The data showed that MnROAD flexible pavements were constructed smoother than rigid pavements, but deteriorated much faster. It should be noted, however, that the latter conclusion is based on ride quality of MnROAD test cells. This may not be the case on some other pavements.

Recommendations for improvements to design and construction practices include improvement in HMA mix design to reduce or eliminate thermal cracking, decrease the initial constructed roughness of concrete pavements. Since thicker MnROAD cells exhibited lower frost heave and there is an apparent correlation between the magnitude of frost heave and ride quality deterioration in PCC pavements, further investigation of the benefits of thick bases under concrete pavements is needed.

Introduction

This MnROAD project studied frost heave effect on pavement roughness corresponding to different pavement design parameters. This report documents the results of three smaller tasks completed for this project, listed below. The study also investigated the need for an adjustment factor to account for seasonal changes in IRI measurements.

1. Obtain initial data and develop parameters
2. Plot computed parameters
3. Perform statistical analysis

This project studied frost heave as it relates to different pavement design parameters and ride quality deterioration. To evaluate the frost heave effects, MnROAD personnel collected the elevation of frost pins embedded in the pavements over the course of four years. Other measurements recorded include weather data from a local weather station, MNDOT IRI road roughness measurements and frost depth values. In this study, the frost heave data were analyzed. Changes in pin elevations were calculated and the values were analyzed show the amount and degree of frost heave uniformity within a cell. Seven proposed data tables were created for addition into the MnROAD database.

Twenty pavement sections were selected from the MnROAD pavement research facility outside of Albertville, MN. The test sections consist of thirteen on the mainline test area and seven on the low volume test area. Eight of the sections are PCC pavements and the other twelve sections are HMA pavements. Each of the sections chosen has different cross-section properties, with variations in material type and thicknesses. Pavement section diagrams are located in appendix H.

To analyze the effects of frost heave, steel pins were embedded in various test cells. Survey equipment was used to accurately measure the elevation of the pins with respect to a benchmark reference point. Changes in pin elevations were calculated and the values were analyzed show the amount and degree of frost heave uniformity within a cell.

The project began by organizing the all the data into a proper format. Seven proposed data tables, shown in table 1, were created for addition into the MNROAD database. The table contents, location of source data and database programming notes are described in appendix A. Some data tables required calculated values. Computations for the data tables are shown in appendix B.

Table 1: Titles and Locations of Designed Tables

Table Title	File Name
CELL_REF_DATE	CELL_REF_DATE.xls
PIN_LANE	PIN_LANE.xls
PIN_CHANGE_ELEV_SINGLE	PIN_CHANGE_ELEV_SINGLE.xls
PIN_CHANGE_ELEV_SECT_SINGLE	PIN_CHANGE_ELEV_SECT_SINGLE.xls
PIN_CHANGE_ELEV_RANGES_SINGLE_YEAR	PIN_CHANGE_ELEV_RANGES_SINGLE_YEAR.xls
PIN_CHANGE_ELEV_SECT_YEAR	PIN_CHANGE_ELEV_SECT_YEAR.xls
PIN_CHANGE_ELEV_RANGES_SINGLE_TOTAL	PIN_CHANGE_ELEV_RANGES_SINGLE_TOTAL.xls

Using the organized tables, various plots were constructed in Microsoft Excel from the computed parameters. From these plots, the quality of the computed parameters was judged. Outlying data was examined and removed from the study if reasonably justified. Outliers were visually detected as points that did not follow the general trend of the plotted curve. Figure 1 shows an example of an outlying data point in an IRI vs. time plot. To remove outliers, data was copied into an adjacent column in the respective spreadsheet tab to maintain the original dataset. In the new data column, values were deleted and new charts were made using the new data column. Figure 2 shows a corrected chart with the outlier removed. The inspected data was then broken into different groupings based on maximum change.

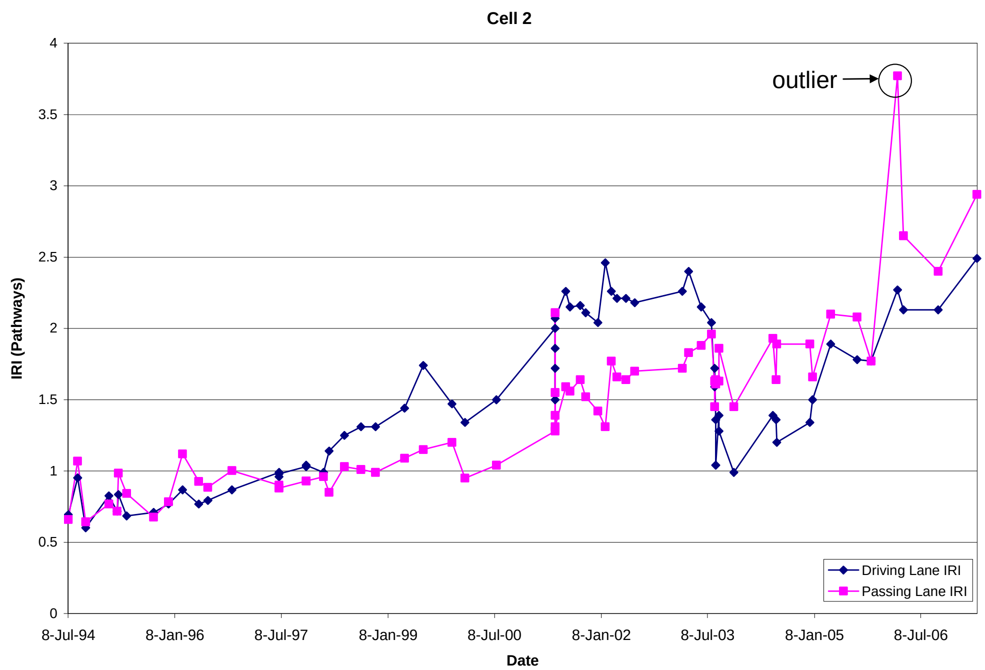


Figure 1: Example Dataset with an Outlier

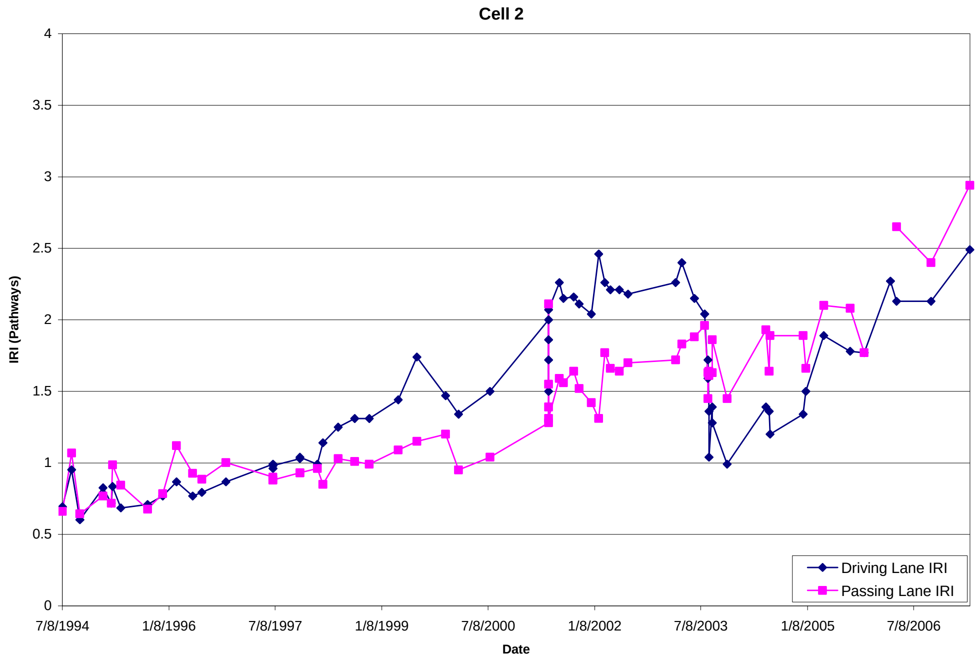


Figure 2: Corrected Example Dataset

To characterize the magnitude of pavement frost heave, a change in elevation (CE) parameter was calculated from each frost pin elevation measurement. The following procedure was used to calculate CE:

1. The earliest measurement date at which elevations for all frost pins were reported was determined. That date, December 15, 1993, was chosen as the reference date.
2. The frost pin elevation data recorded on December 15, 1993, was used as a reference values for pins.
3. For each frost pin elevation measurement, the corresponding change in elevation (CE) parameter was determined by subtracting the reference elevation for that pin from the current elevation value.

The CE for every pin was plotted as a function of time. These plots are shown in appendix C. Figure 3 shows a typical plot seen in appendix C from the data collected. A periodic trend in CE is observed from the plot. Every year the CE starts to increase from the end of September and reaches its maximum around early March, after which it starts to decrease until approximately the middle of April. For a majority of cells, the CE changes little from May to September before it starts to increase again.

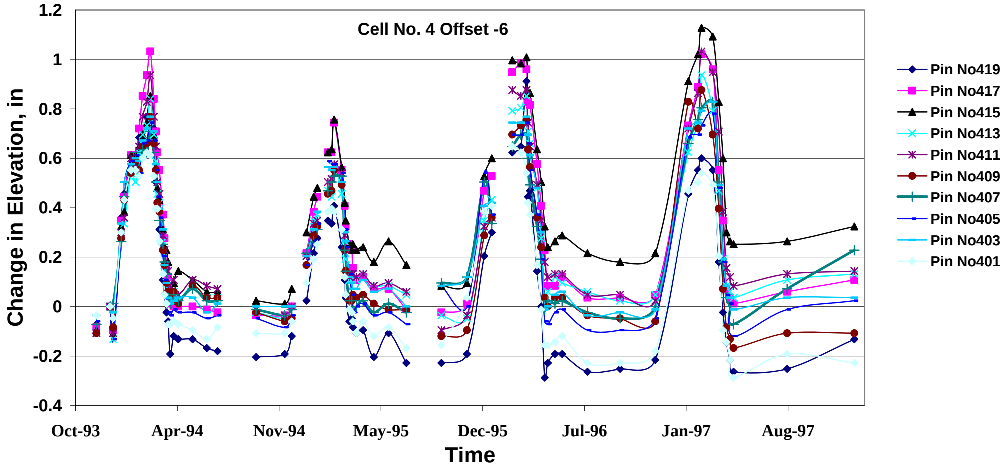


Figure 3: Change in Elevation vs. Time for Frost Pins in Driving Lane of Cell 4

To characterize the magnitude of seasonal variation in pin's elevation, the yearly range of change of elevation (YRCE) for each frost pin was considered. YRCE is defined as the difference between the maximum and minimum values of the CE for an individual pin for a particular year. Assuming that frost heave action is the primary cause of seasonal changes in a frost pin's elevation, YRCE is considered to be a parameter characterizing the seasonal magnitude of frost heave for a pin.

Initially, it was planned to compute the mean value and standard deviation of the changes in pin values for each section to characterize the distribution of the pin elevation changes within a section. The mean and standard deviation describe the central tendency [average] and spread of the data, respectively. However, these parameters are very sensitive to the values of the tail elements in the data set. Therefore, the computed parameters would be very sensitive to presence of outliers and erroneous measurements in the database. A preliminary analysis of the frost pin elevation data lead the research team to the conclusion that it would be very difficult to identify if tail measurements represented natural variability in frost heave. Removing these data points from the dataset could lead to a loss of important information about pavement frost heave behavior if the measurements were not erroneous. To overcome this issue, it was decided to use other characteristics of the frost heave distributions, namely the median and interquartile range.

In statistics, the mean is not considered a resistive measure of the center of a data set because outliers can cause extreme tail skewing. Since standard deviation is calculated using a data set mean, it is also very sensitive to the presence of outlier. To counteract outliers in the dataset, median and the Interquartile Range (IQR) is used to measure data central tendency and spread. The median is the midpoint of the distribution. This value is the typical change in pin elevation where 50 percent of the data is greater and less than the value. IQR is defined as the distance between the first (25^{th} percentile) and third (75^{th} percentile) quartile. The IQR is more resistive to outliers because outliers have less of an affect on the quartile value, thus making IQR a more robust measure of spread [Moore, 2006].

For this study, IQR was use as a measure of spread instead of the standard deviation. The spread in YRCE for the pins belonging to a particular cell contain information regarding differential frost heaving within the test section. Differential heaving across the cells would be shown by the differences in pin elevations within a specific cell. The differences of values across the cell would judge the uniformity of the heaving. The data is considered uniform when the spread of the data is low [low differential heaving] and seen through the pins by having about equal elevations over time. Non-uniformity would be seen as the opposite of this. Appendix D contains plots of IQR over time, as well as plots for the median values of pin elevation over time.

Road roughness data was collected using a PaveTech van equipped with ultrasonic sensors from 1994 to July 1997. The ultrasonic sensors were set to record the longitudinal profile at 6-inch intervals. In July 1997, the PaveTech van was replaced with a van purchased from Pathway Services Inc. The Pathway's laser sensors recorded a moving average (approximately 16 readings per inch) and the software processes the data into a longitudinal profile at 3-inch intervals. Ride data was collected quarterly through the summer of 2001. In July 2001, ride data was then collected monthly. In the summer of 2001, a new Pathway's van was purchased for Mn/DOT's Pavement Management Section to use for data collection throughout the state and MnROAD. The IRI roughness data of the selected test sections was plotted over time. These plots are shown in appendix E.

The final stage of the project involved using the pavement frost heave measurement data and test section properties to infer conclusions about pavement response. To test for the effect of frost heave on different design features, the YRCE and IQR values were statistically tested to investigate the response in the collected data. Various statistical approaches were used in this study to evaluate the effect of pavement design features on frost heave. Visual analyses of the datasets, matched pairs student t-testing of the dataset means [bivariate analysis] and ANOVA testing of regression equations was completed in this study.

Significant value was found from visually examining the data to observe patterns and trends. Box plots and normal quantile plots were two tools used for visual analysis of the data.

A box plot is a tool for visual examination of distributions. It graphically displays the minimum, the 25th percentile, median (50th percentile), 75th percentile, and the maximum of the distribution. The box itself contains 50% of the data with the upper edge of the box indicating the 75th percentile of the data set and the lower hinge indicating the 25th percentile. The height of the box corresponds to the IQR. The middle line in the box indicates the median value of the data. The ends of the vertical lines or "whiskers" indicate the minimum and maximum data values, unless outliers or suspected outliers are present. The whiskers can be extended to a maximum of 1.5 times the inter-quartile range and the points outside the ends of the whiskers are outliers or suspected outliers. Box plots are most suitable for side by side comparison of more than one distribution. For example, Figure 4 shows an example box plot of range of YRCE of cell 17 and 22. The figure indicates that the range of both cell 17 and 22 are similar, however, the median is lower for cell 22. It can be seen that cell 17 has a few outliers, as shown by points above the top whisker. The median line is equidistance from the hinges indicating the data is symmetric. On the other hand, cell 22 does not have any outliers, and the median line indicates that the distribution is slightly right skewed.

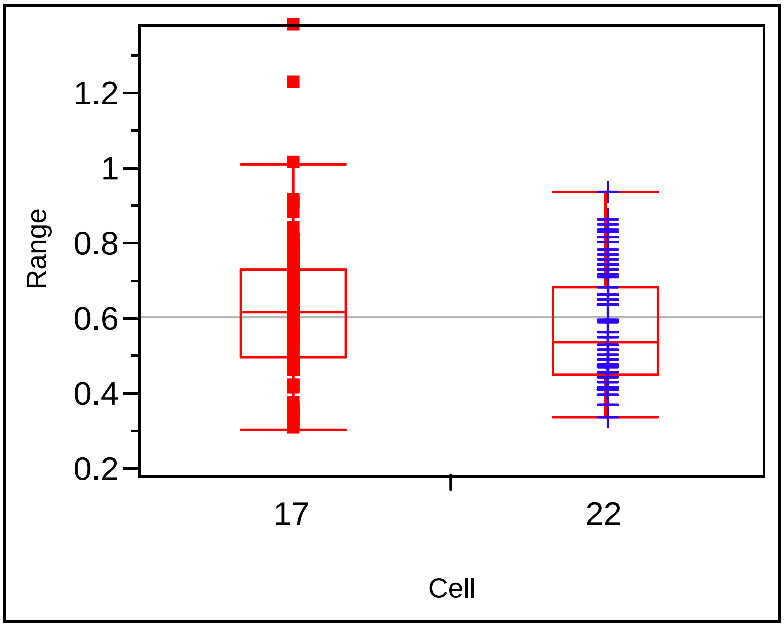


Figure 4: Example Box Plot of YRCE for Cells 17 and 22

A normal quantile plot is a tool used to check for normality in the data. A plot is made of the percentiles/z-statistic of the standard normal values versus the corresponding values of the raw data. In the case of this study, the YRCE or IQR were the variables on the x-axis. Normally distributed data will fall along a straight [linear] line on the plot because standardizing a normally distributed data point into z-value linearly transforms it into a standardized normal distribution. Using a linear transformation will only convert the data into a linear trend, not a curved trend like quadratic or other [Moore, 2006]. Figure 5 shows an example normal quantile plot of range of YRCE for cells 5 and 10. It can be seen that the plots are fairly linear and thus both data sets are normally distributed.

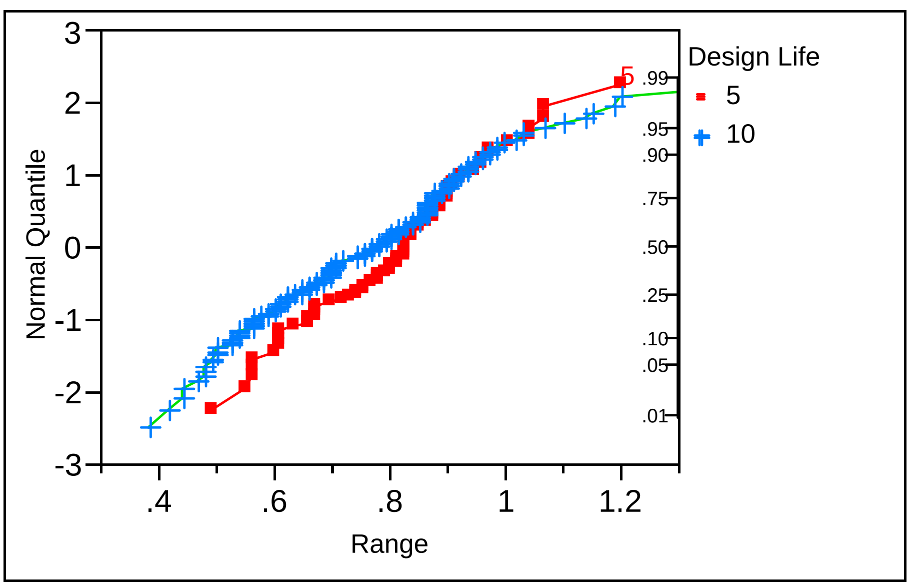


Figure 5: Example Normal Quantile Plot of Range of Cells 5 and 10

Comparing distributions of frost heave of two cells or groups of cells differing by a single design feature should give some preliminary idea about the contribution of the design feature on frost heave. A t-test was used to compare the distributions by performing hypothesis testing on the varying design characteristics of the test cells selected. The means of the two different groups for each design characteristic were tested in a matched pairs study to see if there was a difference between them.

The t-test statistic equations are calculated by equation 1 [Moore, 2006]. The equation uses the mean and standard deviation based on separate group estimates, thus allowing for differences in the group variances. This form is used when the variances and sample sizes for the groups are not equal. In this study, a two sample t-test was preformed in Microsoft Excel assuming an unequal variance between the groups.

$$t = \frac{\bar{x}_{difference} - \mu_0}{s_{difference}} \rightarrow \frac{(\bar{x}_1 - \bar{x}_2) - 0}{s_{\bar{x}_1 - \bar{x}_2}} \quad \text{where} \quad s_{\bar{x}_1 - \bar{x}_2} = \sqrt{\frac{s_1^{\ 2}}{n_1} + \frac{s_2^{\ 2}}{n_2}}$$

$$df = \frac{\left(\frac{s_1^{\ 2}}{n_1} + \frac{s_2^{\ 2}}{n_2}\right)^2}{\frac{\left(\frac{s_1^{\ 2}}{n_1}\right)^2}{n_1 - 1} + \frac{\left(\frac{s_2^{\ 2}}{n_2}\right)^2}{n_2 - 1}} \tag{1}$$

Where x_i is the sample mean of group i, s_i is the sample standard deviation of group i, n_i is the sample size of group i, and df is the number of degrees of freedom.

The t-test requires data with an approximately normal distribution with independent variables. The data used was checked for normality using the normal quantile plots. Independence is maintained in two ways. By breaking the analysis up into separate design features and carefully controlling test sections, the analysis forces results for a single design feature to reduce the interaction between features as much as possible. Also, equation 1 and the Excel analysis tool have no correlation term in the standard deviation calculation. No correlation means independence.

Hypothesis testing is a formalized procedure for comparing observed data where a hypothesis truth is assessed. In the case of this report, the hypotheses will relate to pavement performance. There will either be no effect or an effect due to the change in design characteristics. The null hypothesis is the tested statement. The test is designed to assess the strength of evidence against the null. In other words, does the data suggest no change between the two groups? Using this definition, the null was set as seeing no change in the population [$\mu_0 = 0$]. The alternative hypothesis is a statement about the population that is suspected to be true. This report hopes to show that the means of the groups are different [$\mu \neq \mu_0$]. The t-test evaluates the ratio of the difference between the two group means to the corresponding estimate of standard deviation of this difference. Using this ratio [t-value], the value is standardized to assess how far away the estimate of the mean difference is from the null. The use of this alternate hypothesis will yield a two sided p-value.

The actual probability computed under the null [or the null hypothesis is true] that the t-value test statistic takes on a value as or more extreme than observed from the sample is the p-value of the test. The smaller the p-value, the stronger the evidence against the null using the sample set. A large t-value implies a small p-value. This indicates the groups mean difference is due to something other than chance. On the other hand, a small t-value implies the opposite, a large p-value. Large p-values conclude that the difference seen in the means could be due to chance variation.

The conclusions of the test are based off the p-value and a user decided critical value. The set critical value for the p-value is the significance level of the test, typically referred to as α. Choosing a certain value for the significance level implies that a certain [specified] amount of data is needed to provide evidence against the null so strong that it would happen no more than α much of the time. The actual selection of a significance level depends on the amount of error a user is willing to accept. Decreasing the significance level requires stronger evidence against the null if the null is true. A typical value of 0.05 will be used for this analysis [Moore, 2006].

When making the test conclusion, the p-value is compared to the significance level. If the p-value was greater than or equal to 0.05, the null hypothesis was not rejected for the alternative. This suggests that there is no effect between the two groups and the design characteristic is not an important factor in the study or shows how uniform the results for each factor are. However, if the p-value is less than 0.05, null hypothesis would be rejected for the alternative hypothesis. In this case, the data provides enough statistical evidence to be statistically significant [show a difference] at this significance level.

A necessary assumption for the t-test is that the sample means are approximately normally distributed and the data is independent. The visual analysis checked for normality in the data and the testing setup as mentioned earlier should yield independent data. If these statements are followed, testing the variables should work reasonably well.

As mentioned before, bivariate statistical analysis only considered one design feature at a time. However, a good pavement design is based off multiple design factors that must be balanced for optimal performance for the amount of funding and life cycle desired. The problem with this systematic approach of testing is that the effects of combined multiple factors are not considered. The bivariate analysis does not take into account the interactions of the different variables and their effects on performance. The t-tests described earlier can not be used to isolate differences caused between the variables on pavement performance. Determining interrelationships between variables can only be statistically accomplished through a multivariate analysis. Regression analysis was used in an exploratory manner to identify the most significant variables.

Regression analysis for this report involves multiple linear regression, where multiple explanatory variables are used to predict a response. The term linear implies that linear coefficients are used, but this does not assume that the predictor variables are linear or any other distribution. The model for a typical multiple linear regression is shown by equation 2, where some predicted data is equal to a trend plus some data scatter that is normally distributed and has a constant variance. Each linear β coefficient [β_i] for each explanatory variable [x_i] is defined as the average change in y per unit change in x_i while holding all the other predictor terms constant and β_0 is the average value of y when all the explanatory variables are equal to 0.

$$y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_p x_p + \varepsilon \qquad for\ i = 1...p \tag{2}$$

Where p is the number of explanatory variables used in the model.

The linear coefficients were computer estimated by the method of least squares. The residual error of each data point used is found by subtracting the observed response from the predicted response from a model selected. The linear coefficients are changed until the sum of the squares of the residuals is minimized.

Hypothesis testing can be used to test the significance of explanatory variable to a regression model. The t-test statistic equations are calculated by equation 3 [Moore, 2006]. The equation uses the linear coefficients determined for each explanatory variable from least squares analysis.

$$\begin{aligned} t &= \frac{\beta_i - \beta_0}{SE_{\beta_i}} \rightarrow \frac{\beta_i - 0}{\sigma_{\beta_i}} \\ df &= n - (p+1) \end{aligned} \tag{3}$$

As described in the bivariate testing, the actual probability computed under the null [or the null hypothesis is true] that the t-value test statistic takes on a value as or more extreme than observed from the sample is the p-value of the test. The smaller the p-value, the stronger the evidence against the null using the sample set. A large t-value implies a small p-value. This indicates the behavior of the explanatory variable on the model is due to something other than chance. On the other hand, a small t-value implies the opposite, a large p-value. Large p-values conclude that the behavior of an explanatory variable seen in the model could be due to chance variation.

The hypotheses for testing will relate to pavement performance, but for each explanatory variable in this phase of testing. There will either be no effect or an effect due to the change in design characteristics. The null hypothesis is the tested statement. The test is designed to assess the strength of evidence against the null. Using this definition, the null was set as seeing no change in the average behavior of the predictor variable [$\beta_i = 0$]. The alternative hypothesis is a statement about the population that is suspected to be true. This report hopes to show that there is evidence that a design feature has an effect on the predictor [$\beta \neq \beta_i$] when the features are considered in relation to one another. The t-test evaluates the ratio of the difference between the two group means to the corresponding estimate of standard deviation of this difference. Using this ratio [t-value], the value is standardized to assess how far away the estimate of the mean difference is from the null.

The conclusions of the test are based off the p-value and a user decided critical value. The set critical value for the p-value is the significance level of the test, typically referred to as α. Choosing a certain value for the significance level implies that data is needed to provide evidence against the null so strong that it would happen no more than α much of the time.

Decreasing the significance level requires stronger evidence against the null if the null is true. A typical value of 0.05 will be used for this analysis.

When making the test conclusion, the p-value is compared to the significance level. If the p-value was greater than or equal to 0.05, the null hypothesis was not rejected for the alternative. This means that that the design characteristic in question has no effect on the behavior of the model and is not an important factor in the study or shows how uniform the results of the factor are. However, if the p-value is less than 0.05, null hypothesis would be rejected for the alternative hypothesis. In this case, the data provides enough statistical evidence to be statistically significant at this significance level and its presence in the model causes major changes in predictor.

An important side note on multivariable testing is that it can only be used to show effect of a single explanatory variable's effect on the predictor term. Multiple conditions [union or intersect operations in statistics] can not be determined.

All the linear coefficients in the model can be tested using a hypothesis test and the Analysis of Variance [ANOVA] F-test. In this analysis, an ANOVA table is made to compute an F-statistic. The F value tests the full linear regression model shown in equation 2, where the hypothesis test tests the null hypothesis that all explanatory variables have no effect [$B_i = 0$ for i = 1…p] against the alternate hypothesis of at least one linear coefficient is not 0. A typical ANOVA table is shown in table 2. The values inside each of the cells are detailed in equations 4 to 13 [Moore, 2006].

Table 2: Typical ANOVA Table

Source	d_f	Sum of Squares	Mean Square Value	F-value	P-value
Model	DFM	SSM	MSM	F	P
Residual Error	DFE	SSE	MSE		
Total	DFT	SST	MST		

$$
\begin{aligned}
&DFM = p \qquad DFE = n-(p+1) \qquad DFT = n-1 \\
&SSM = \sum(\hat{y}_i - \bar{y}_i)^2 \qquad SSE = \sum(y_i - \hat{y}_i)^2 \qquad SST = \sum(y_i - \bar{y}_i)^2 \\
&MSM = \frac{SSM}{DFM} \qquad MSE = \frac{SSE}{DFE} \qquad MST = \frac{SST}{DFT} \\
&F = \frac{MSM}{MSE} \qquad \sigma^2 = s^2 = MSE \qquad R^2 = \frac{SSM}{SST}
\end{aligned}
\qquad (4 - 15)
$$

Decisions on statistical significance are based off the ANOVA F value and corresponding p - value. When the alternative hypothesis is true, the MSM value is typically larger than the MSE value. This means large F values are evidence against the null in favor of the [two sided] alternative hypothesis and result in small p-values. As described before with hypothesis testing, if the p- value is less than the specified α, the null hypothesis is rejected for the alternate and this is statistically significant. If the p-value is greater than α, the null hypothesis can not be rejected and this is not statistically significant [Moore, 2006].

Other values that can be calculated from the ANOVA table equations are the proportion of variation in the predictor explained by the explanatory variables (R^2) and the estimate of variation for the model (σ^2). R^2 and σ^2 are shown by equations 14 and 15, respectively [Moore, 2006].

Results and Analysis

Statistical Analysis

In this section, different design features' effects on frost heave behavior were investigated in this study for both asphalt and concrete pavements. The features investigated are listed below in table 3 and incorporate many major pavement design considerations. For each design feature, the analysis began with a visual and bivariate analysis where MNROAD cells were grouped in such a way that the groups would differ by a single design feature. This was done to look at the effect of a single design feature. A t-test was conducted on the selected cells. Further investigation on the interaction of design features within a design was investigated by multivariate regression analysis using an ANOVA test on the selected data.

Table 3: Considered Design Features

Design Feature	Pavement Type Considered
Design Life	PCC and HMA
Subgrade Type	PCC and HMA
Drainage	PCC and HMA
Pavement Thickness	PCC and HMA
Binder Type	HMA Only
Base material	HMA Only
Joint spacing	PCC Only

Variables were separated into continuous and categorical variables for analysis. Continuous variables have numerical values where arithmetic can be used on the values. Asphalt or concrete thickness is an example of a continuous variable used in this study, where an average value can be determined. Categorical variables typically consist of items that must be counted in analysis and the counts have arithmetic done onto them. HMA or PCC pavement is an example of a categorical variable used in this study. This is done because it would not make sense to give an average pavement type [categorical] as opposed to an average layer thickness [continuous]. ANOVA has the ability to be used on both continuous and categorical variables where a hypothesis testing is typically only use on continuous variable. If a clever scheme is developed using a more binomial approach, categorical variables can be used in hypothesis testing by "turning on and off" specific regression terms developed for the differences in categories.

Visual and Bivariate Analysis

The details of the tests are described and discussed below. The figures produced for the visual analysis are shown in appendix F. The results bivariate analysis for YRCE and IQR are summarized in tables 4 and 5, respectively. Cross section diagrams for the analysis period of the cell dimensions and materials are shown in appendix H.

Table 4: Bivariate analysis results for YRCE

Pavement Type	Cells Considered		Design Feature	Mean Value		Statistic Testing		
	Group 1	Group2		Group1	Group2	t – value	d_f	P - value
HMA	4	14, 15	Design Life	0.813	0.770	1.986	213	0.048
	24, 25	26,27,31	Subgrade	0.214	0.804	-19.944	254	0.000
	18	23	Drainage-2	0.593	0.574	0.584	155	0.560
	15	17	Thickness-1	0.754	0.626	4.047	155	0.000
	4,14,15,23	17,18,22	Thickness-2	0.732	0.598	8.049	533	0.000
	14	15	Asp. Binder	0.786	0.754	1.038	152	0.301
	17	22	Base Type	0.626	0.574	1.921	148	0.057
PCC	6,7	10,11,12,13	Design Life	0.863	0.873	-0.574	570	0.566
	36	39	Subgrade	0.200	1.034	-23.622	98	0.000
	6	7	Drainage-1	0.976	0.766	10.845	202	0.000
	10	12	Drainage-3	0.686	0.861	-5.389	121	0.000
	11	12	Joint Spacing	0.849	0.861	-0.360	129	0.719

Table 5: Bivariate analysis results for IQR

Pavement Type	Cells Considered		Design Feature	Mean Value		Statistic Testing		
	Group 1	Group 2		Group 1	Group 2	t – value	d_f	P - value
HMA	4	14, 15	Design Life	0.102	0.091	2.164	300	0.031
	24, 25	26,27,31	Subgrade	0.080	0.213	-18.846	584	0.000
	18	23	Drainage-2	0.088	0.170	-11.864	214	0.000
	15	17	Thickness-1	0.087	0.078	1.574	252	0.117
	4,14,15,23	17,18,22	Thickness-2	0.113	0.119	-1.168	795	0.243
	14	15	Asp. Binder	0.095	0.087	1.384	262	0.168
	17	22	Base Type	0.078	0.191	-14.820	200	0.000
PCC	6,7	10,11,12,13	Design Life	0.114	0.115	-0.234	540	0.815
	36	39	Subgrade	0.055	0.123	-12.996	185	0.000
	6	7	Drainage-1	0.149	0.078	11.309	234	0.000
	10	12	Drainage-3	0.098	0.138	-6.677	262	0.000
	11	12	Joint Spacing	0.062	0.138	-14.739	189	0.000

1) Design Life

The MnROAD mainline test sections were designed for either 5 or 10 year design life. To find the effect of the design life on frost heave, both HMA and PCC cells in mainline section were analyzed. Cell 4, a mainline full depth HMA section with a 5 year design life, was compared with cells 14 and 15, mainline full depth HMA sections with 10 year design life. Also, mainline PCC cells 6 and 7 with 5 year design lives were compared to 10 year design lives sections 10, 11, 12 and 13.

Effect of Design Life on YRCE

The 5 year design life cell has a slightly higher median YRCE compared to YRCE for 10 year design life cells. However, the spread of 10 year design life is higher than that of 5 year design life. Both data sets show a right skew. The normal quantile plot shows that the distributions for both cases are normally distributed.

The corresponding p-value for HMA testing of 0.048 is a little less than the stated significance level. This shows that the means are not equal [reject the null hypothesis for the alternative]. Therefore, cells with a 10 year design life are less susceptible to frost action as compared to cells with a 5 year design life. For PCC sections, the p-value of 0.566 indicates that the means are equal [fail to reject the null hypothesis]. This suggests that design life does not have an effect on frost heave of PCC cells.

Effect of Design Life on IQR

Both 5 and 10 year design life cells show similar spread, although the median of the 5 year is greater than the 10 year. There is a right skew to the 10 year design life data. The 5 year design life data is symmetric. The normal quantile plot shows both groups of cells are normally distributed and fall on top of each other. A similar trend is also seen for PCC cells, except that the mean IQR are equal.

The low p-value of 0.031 suggests that the HMA mainline IQR means are unequal and suggests frost heave is more uniform in 10 year mainline HMA cells. For mainline PCC cells, the high p-value of 0.81 suggests that the difference between these means is statistically insignificant and design life has no effect on uniformity of frost heave in mainline PCC sections.

Discussion on Design Life

Pavement design life did not show any significance effect on either the YRCE or the IQR in PCC cells. However, greater design life of cells seem to have some effect on frost heave performance in HMA mainline cells. Designs with greater design life are constructed to withstand greater loadings. Depending on the design assumptions made, a more conservative approach is typically used to make sure the desired design life is reached. The increased strength from the conservative approach would explain the increase in performance.

2) Subgrade Type

Subgrade is a very important design feature which plays an important role on frost heave action. It is well know that frost-susceptible soils have a granulometric composition typical of silt or clays [Michalowski and Zhu, 2006]. Small size of capillaries of clay subgrade provide increases the ability of water to rise from the water table. A small particle size promotes formation of ice lenses when water is freezing. Sand subgrades, which have a low surface area to volume ratio, are considered to be non-frost susceptible as they do not support capillary moisture movement as clay does. The larger particle size negatively affects an ability of ice lenses to grow [Voller et al., 2003]. Both sand and clay subgrades were used for the Low Volume Road (LVR) test cells. To isolate the effect of subgrade on frost heave, LVR cells with the same subgrade were grouped together for both HMA and PCC. The frost heave measurements for all the cells within a grouping were compared.

Effect of Subgrade on YRCE

The sand subgrade has a much lower median range and spread in data than the clay subgrade. Judging from the normal quartile plot, it is important to note that the distribution for the sand subgrade is normal whereas the clay subgrade has a distinctive right tail. The right tail seen in the clay subgrade data mainly comes from outliers. Of 238 data points within the clay subgrade group examined, 22 outliers were ignored in this portion of the study. The distribution of clay subgrade is close to normal without the 22 outliers. The PCC visual analysis showed the same trend for the sand and clay subgrades.

The p-value of 0 suggests that the difference seen due to subgrade materials is statistically significant. HMA cells built on sand subgrade experience lower seasonal change in elevation than built on clay. For PCC LVR cells, the results show a similar trend of lower means and variances for sand subgrade. The results indicate that sand subgrades are less susceptible to frost heave for both types of pavements.

Effect of Subgrade on IQR

It can be seen that both the median and the spread in data of IQR for the clay subgrade are higher than those of the sand subgrade. The normal quantile plot indicates that the IQR of both the sand and clay subgrades are normally distributed.

The p-value for the IQR data is 0, indicating strong evidence of unequal means. This implies that different subgrade materials are not equally uniform. Similar results have been observed for the PCC LVR sections. This indicates that sand subgrades are more uniform than clay subgrades for both HMA and PCC sections.

Discussion on Subgrade Type

These results are consistent with findings from earlier studies and long held engineering knowledge that clay subgrades are more susceptible to the effects of frost heave than sand subgrades.

3) Drainage

The presence of a permeable base may reduce the amount of free water that enters subgrade and/or minimize the dynamic pore pressures in the unbound materials under the bound layers. Using a drainage layer allows water to drain out of cross section instead of infiltrating through the subgrade, reducing any subgrade bearing capacity issues. Therefore, a permeable base could reduce the effects of frost heave. A permeable base could also provide an insulating effect keeping soil temperatures higher and pavement surface temperatures lower.

To examine this, three separate studies were completed to test different drainage methods. The first study investigated frost heave behavior in cells with different aggregate drainage layers for PCC pavements. Cells 6 and 7 were used for this study. Both cells have similar design features except that one cell has a dense graded aggregate base [no attempt to increase drainage] while the other has two smaller base layers, where part is a permeable gap graded aggregate layer on top of a dense graded aggregate base. The additional two studies involved the use of a drainage structure compared to a permeable base. Both HMA and PCC sections were chosen, represented by cell 18 against 23 and 10 against 12 respectively. Both cell groups tested against each other have similar design features except that one group has two smaller base layers, consisting of a permeable gap graded aggregate layer on top of a dense graded aggregate base and the other is a conventional pavement design with an edge drain.

Effect of Drainage on YRCE for PCC Aggregate Drainage Layer

The YRCE distributions for cells 6 and 7 shows the spread in the data of cell 6 is slightly larger than cell 7. The median for cell 6 is much higher than cell 7. Both data sets for the considered cells have a left skew, where the skew seen is greater in cell 6 than cell 7. The normal quantile plots shows that the two distributions are pretty normal distributed.

The p-value of 0 demonstrates that there is evidence to show the means are not equal and the difference is statistical significance. This indicates that cell 7 is less frost susceptible than cell 6, which is consistent with the visual analysis. There is enough evidence to show that the presence of drainage layer reduces the frost heave in cell 7.

Effect of Drainage on IQR for PCC Aggregate Drainage Layers

The median and spread in data from cell 7 is much lower than that of cell 6. There is a left skew to the cell 6 data where as the cell 7 data is fairly symmetric. The normal quantile plot show strong linear trends, denoting normality in the datasets.

The p-value of about 0 suggests that the means are unequal and the presence of drainage capabilities produces non-uniform heaving. Cell 7 is more uniform compare to cell 6.

Effect of Drainage on YRCE for HMA Drainage Structures

The medians for cells 18 and 23 are fairly similar. The spread of cell 23 is much less than that of cell 18. Cell 18 shows a large right skew in the data set while cell 23 shows a large left skew. Both data sets contain many upper outliers. Both datasets are fairly normal as shown from the normal quantile plot. The upper outliers have the greatest contribution on any non-normality seen.

The large p-value of 0.560 suggests that the means are equal and the presence of aggregate drainage layers in HMA pavements have no effect. It was expected that the use of a drainage layer would have an effect. The amount of variables controlled between the two cells is not very great and their confounding effects may change the outcome of the results. Cell 18 has a conventional design that includes the use of higher quality base materials [class 6 base on a class 3 subbase] that have a low percentage of fines and is rather thick [31 inches] compared to cell 23 [permeable base on a class 4 subbase and 16 inches]. The amount of difference in the selected cells may be too great to yield great results.

Effect of Drainage on IQR for HMA Drainage Structures
The median and spread for cell 18 is smaller than cell 23. Cell 18 has fairly symmetric data whereas cell 23 data has a right skew. Cell 23 contains many more obvious outliers compared to the one seen in cell 18. The normal quantile plot shows both data sets are normally distributed.

The p-value of 0 implies that the means are not equal and the presence of drainage capabilities produces non-uniform heaving. Cell 18 is more uniform than cell 23.

Effect of Drainage on YRCE for PCC Drainage Structures
The median and spread for cell 10 are smaller than that of cell 12. Data from cell 10 is fairly symmetric compared to the left skew seen in data from cell 12. Two very clear outliers are shown in cell 12 data. The normal quantile plots show the data sets are very normally distributed.

The p-value of 0 suggests that the means are not equal and the data is statistically significant. The use of a permeable aggregate layer may perform better than a drainage structure like an edge drain.

Effect of Drainage on IQR for PCC Drainage Structures
The median and spread in the data from cell 10 is much less than data from cell 12. Cell 12 data is fairly symmetric compared to the right skew seen in cell 10 data. Both cells contain many upper outliers. Cell 12 data is fairly normally distributed from the normal quantile plot. The presence of the outliers in cell 10 data causes the data to be slightly non-normal.

The small p-value indicates that the means are not equal. Cell 10 data is more uniform than cell 12.

Discussion on Drainage
Since water is a necessary component for frost heaving, it is expected that the pavement with better drainage would experience the less heaving. The statistical analysis suggests this idea is correct by showing that cells with a drainage layer had heaved less over the year and were more uniform than non-drainable cells. Also shown is that the use aggregate drainage layer perform better than a drainage structure and most likely more efficient because the aggregate drainage can serve an additional load bearing purpose in a pavement structure.

4) Total Pavement Thickness

Total pavement thickness is defined as the sum of thickness of surface layer, base layer, and sub-base layer. This design feature was chosen to see if there is any correlation between the amount of pavement constructed and frost heave. In addition to increasing the structural capacity of a pavement by utilizing better performing soils compared to in-situ, some states require the total depth of the pavement to extend to the frost depth to reduce the effects of frost heaving. Extending the depth into the frost susceptible subgrade soil reduces the amount of susceptible in-situ subgrade under the pavement incurring frost action and in turn reduces frost related damage.

To study this effect, a two phase approach was used. First, only cells 15 and 17 were compared. These cells have total thicknesses of 11.1 inches and 35.9 inches, respectively and investigated the difference between a relatively thin and thick HMA pavement section. The second part of this study includes more mainline HMA cells divided among the two groups based on total thickness. Cell 4, 14, 15 and 23 fell into the first group, where the total thickness was less than 17 inches. The second group consisted of cells 17, 18 and 22 where the total thickness was greater than 26 inches.

Effect of Total Thickness on YRCE

The median of cell 17 is lower than that of cell 15. The spread of the data for both cells is fairly similar. Both cells have two clear outliers, but the outliers for cell 15 are much further away from the data that the outliers in cell 17. Cell 15 data has a left skew where as cell 17 data is much more symmetric. The normal quantile plot shows that the data from the test cells selected is normally distributed if the two outliers are subtracted. A visual comparison was also performed on the second set of data. Similar results were seen for the second part of this study.

The small p-values for both approaches indicate strong statistical evidence that the difference is statistically significant and thicker pavements are less susceptible to frost heaving than thin pavements.

Effect of Total Thickness on IQR

The medians and spread of these distributions are fairly similar. Cell 15 has a right skew and many noticeable upper outliers as compared to the symmetric distribution seen in cell 17. The normal quartile plot shows that the data from cell 17 is normally distributed. However, the large amount of upper outliers in cell 15 data makes the dataset non-normally distributed.

The p-values for both analyses are larger than the stated significance level, suggesting that the mean IQR values are equal. The data in all the cells selected is reasonably uniform.

Discussion on Total Pavement Thickness

The statistical analysis shows that higher total thickness reduces frost heave the magnitude. It was found that the YRCE for thin cells is much higher than YRCE for thin cells. This could be expected since a thicker pavement structure had less frost penetration into subgrade than a thinner pavement structure. All other factors being equal, it is expected that the deeper pavement structures will experience less frost heave action than shallower pavement structures because of the selection of pavement materials. Typically, the quality of pavement materials decreases with increasing pavement depth. Gravels and sands [less frost susceptible] are placed on top of silts and clays [more frost susceptible]. The design construction helps to reduce formation of ice lenses in the subgrade, which in turn reduces frost heave. Besides, a thicker pavement applies more weight on subgrade. Past research has shown that the magnitude of heave decreases as the external overburden pressure is increased (Voller et al. 2003, Penner and Ueda 1977, and Nixon and Morgenstern 1973).

At the same time, surprisingly no significant effect of the pavement thickness on uniformity of frost heave was found. The research team could not find any plausible explanation of this phenomenon. It should be noted that in the comparison the thin pavements were represented by the full depth cells. The results could be different for conventional flexible pavements with thin aggregate bases.

5) Effect of Asphalt Binder Type

Asphalt binder type is a critical characteristic affecting HMA pavement performance. Although it was anticipated that asphalt binder or its Performance Grade (PG) rating would have no effect on frost heave, the variable was considered to investigate the possibility of secondary effects of frost heave due to changes in temperature distribution throughout the pavement system. Cells 14 and 15 were chosen to compare the effect of asphalt binder type. These cells are virtually the same minus the binder type used. The binder PG rating of cells 14 and 15 are 58-28 and 64-22, respectively.

Effect of Asphalt Binder Type on YRCE
The box plots show the median and data spread of the cells selected are very similar, although cell 15 appears to have two outliers with values much higher than the upper whisker. Cell 15 data has a large left skew while the data for cell 14 has a slight right skew. The normal quantile plot of the two cells indicates that the data of the two cells is distributed normally and are very similar to one another from the overlap seen.

The p-value of 0.300 indicates that there is not enough evidence to reject that the two means are equal and suggest that asphalt binder type appears to have no effect on the YRCE.

Effect of Asphalt Binder Type on IQR
The visual analysis shows that although the median IQR values for the two cells are very close to each other, the spread is different. Among the 156 data points, cell 15 has 9 outliers compare to none for cell 14. Both data sets have a right skew. The normal quantile plots are fairly normally distributed. The results suggest that both cells experience similar non-uniform frost heave.

The p-value of 0.168 implies the mean IQR values are equal. The results suggest that the asphalt binder type has no effect on IQR and frost heave is uniform.

Discussion on Asphalt Binder Type
The visual and bivariate results of this study suggest that the asphalt binder type has no effect on either the YRCE or the IQR, and therefore binder type would not affect pavement's frost heave behavior. Changes in temperature distribution throughout the pavement caused by differing binder type do not affect pavement response to frost heave.

6) Base Material

Cells 17 and 22 were chosen to investigate the effect of base material on frost heave. Typical changes in base material are due to differences in aggregate gradations used. Denser mixes have a high unit weight [weight per volume] because more of the voids are filled. More voids are filled either by using smaller aggregates alone or adding smaller aggregates to larger aggregates.

Less voids allow for more aggregate interlock between aggregates, increasing the strength and stability of the mix. However, the smaller voids decrease the amount of water that can flow through the soil and the void volume water can expand into when freezing. Water available to infiltrate into the subgrade can decrease its strength.

The structure cells have the same asphalt thickness. Cell 17 has a 28 inches of class 3 base whereas cell 22 has 18 inches of class 6 base both placed on a clay subgrade.

Effect of Base Material on YRCE

The visual analysis of YRCE for cells 17 and 22 shows cell 22 has lower median than cell 17. The data spread for both cells is fairly similar. Cell 17 has a symmetric data distribution while cell 22 has more of a right skew. The distributions of both cells are close to normal, except three outliers in cell 17.

Based on the results for total pavement thickness, it is anticipated that a cell with a thicker structure would exhibit lower frost heave. Accordingly, cell 17 should have lower frost heave compare to cell 22 because the total thickness is greater. The p-value of 0.056 is very close to the cutoff [α] used for statistically significant. The data implies that the mean are not different and the any difference seen is not statistically significant. Therefore, it can be concluded that use of class-6 base might reduce the effect of frost heave.

Effect of Base Material on IQR

The box plots shows that the median and spread of cell 17 is much lower than that of cell 22. The data is cell 17 is fairly symmetric and the data in cell 22 has somewhat of a left skew. IQR data of both cells are normally distributed, as shown by the normal quantile plot.

The p-value of 0 indicates strong evidence of unequal means. Cell 17 is more uniform compared to cell 22 although cell 17 exhibited lower frost heave magnitude. This observation from the IQR analysis is quite interesting. Both cells 17 and 22 are "thick" cells according to the classification used in the total pavement thickness. Although that analysis concluded that thicker cell did not exhibit more uniform frost heave than thinner sections, increases in the base thickness within the group of "thick" cells lead to improvement in frost heave uniformity.

Discussion on Base Material

Base material seems to have an effect on the frost heave. Class 6 base material is found less frost susceptible compare to Class 3. This could be expected because Class 6 material has lower percentage of fines. More fines decreases the soil void volume and allows for less water drainage. More water in the soil can increase the chance for frost action. On the other hand, the analysis did not show any difference in frost heave uniformity when using a better base material.

It is important to point out that the cross sections were not equal in total thickness. Cell 22 has a more premium aggregate [class 6] as compared to cell 17, but less is used. Some variation in the results seen in this section could be explained by a confounding effect of base thickness since the pavement sections used were not as controlled as the research team would have liked.

7) Joint Spacing

Contraction joints are made in concrete pavements to control the temperature and moisture stresses that are created during concrete curing. Without joint placement, the concrete will crack in an uncontrolled spacing at locations of high stresses and uncontrolled cracking can lead to a variety of PCC pavement distresses. Most importantly, more cracks allows for more water to enter the pavement system due to more surface openings. Joint spacing also affects the size of joint opening under temperature loading and structural capacity of the slab itself.

To investigate the effect of joint spacing, PCC cells 11 and 12 were chosen. Both PCC cells have 1.25 inch diameter dowels and 5 inches of a dense graded base. The transverse joint spacing of cells 11 and 12 are 24 feet and 15 feet, respectively with 12 feet lane widths.

Effect of Joint Spacing on YRCE

The YRCE values are fairly similar but the data spread is much smaller in cell 11 as compared to 12. The data distribution in cell 11 has a right skew while the data distribution in cell 12 is roughly symmetric. Both cells contain very few outliers. The normal quantile plot shows the data sets are fairly normal.

The high p-value of 0.71 indicates that there is not enough evidence to reject the hypothesis that the two means are equal and there is no significant effect of joint spacing on the magnitude of frost heave.

Effect of Joint Spacing on IQR

The median and spread of cell 12 is much higher than that of cell 11. Cell 12 contains more upper outliers than cell 11. The data in cell 11 has a slight right skew. The data distribution in cell 12 is fairly symmetric. The IQR data of the two cells are normally distributed.

The low p-value suggests that the means are unequal. Therefore, the IQR analysis result suggests that cells with shorter joint spacings are subjected to more non-uniform heaving compared to cells with longer joint spacing.

Discussion on Joint Spacing

The observation that there is no apparent relationship between joint spacing and the magnitude of frost heave matches the expectations. It is not surprising that longer joint pacing exhibited more uniform frost heave compare to shorter joint spacing cell. A longer joint spacing allows for a more adaptive pavement surface to the loading conditions and increase the uniformity of the data. Slabs covering a larger plan area would show less distresses as a result of vertical shifts because the individual slab joints would be further apart. The vertical movement would be resisted because it must be distributed over a larger area. Shorter joint spacing would show more faulting because the soil uplift is more localized under the slab, make easier to vertically lift and cause higher roughness values.

Multivariate Regression Analysis

Multivariate linear regression analysis was completed individually for mainline HMA, mainline PCC, and HMA LVR. PCC LVR cells were not considered because there were only two cells with in the 20 selected for the study. A multiple linear fit was used for both the YRCE and IQR analysis using the design features discussed earlier as dependant variables. This multivariable regression analysis hopes to determine any interaction between the design factors on frost heaving, if any, since the previous bivariate analysis was not able to so. Estimates of the model coefficients and the ANOVA analysis for each model tested are shown in appendix G. Regression of each value began with the same basic model based on the key design features. Depending on the significance of each variable show in the coefficient estimates section of the ANOVA analysis, variables were removed if shown insignificant and the ANOVA analysis was repeated with the new model.

ANOVA has the ability to be used on both continuous and categorical variables where a hypothesis testing is typically only use on continuous variable. If a clever scheme is developed using a more binomial approach, categorical variables can be used in hypothesis testing by "turning on and off" specific regression terms developed for the differences in categories.

Forward and backward regression was carried out to find the variables with significant effect on frost heave. Both types of regression have the same outcome: maximize the multiple correlation coefficient (R-square) based off the sum of squares from the model to the total. Each procedure is fairly similar to one another; the only difference is forward regression adds additional regression terms to the model and backwards regression subtracts variables from the model while looking for variation in the R-square value. For standard regression models, the adjusted R-square indicates the amount of variability in the response that is explained by the model after adjusting for the number of parameters. The main purpose of this regression fit is to get an overall idea about the frost heave trend and relative contribution of different design features. These regression equations were not and are not intended for IRI prediction.

Since the results of the bivariate analysis indicated that the YRCE parameter yield to more reasonable and conclusive results, the regression analysis was conducted only for this parameter.

1) Mainline HMA Cells

YRCE

The critical design factors identified in the bivariate analysis were total thickness, design life, and drainage layers. Equation 16 gives the YRCE model used for the Mainline HMA cells. The drainage layer and design life are taken as categorical variables. Tables 6 and 7 show the binomial scheme discussed in the introduction to use the categorical variables more as numerical/continuous variables. This scheme uses two placeholder variables [D_1 and D_2] to describe the action of two categorical variables [drainage and base material].

$$YRCE_{HMA-ML} = \beta_0 + \beta_1 h_{total} + \beta_2 t_{design} + \beta_3 D_1 + \beta_4 D_2 \quad (16)$$

Table 6: Factors for Categorical Variable- Drainage

Category	**Explanatory Variable Value**	
Drainage Type	$\mathbf{D_1}$	$\mathbf{D_2}$
No drainage	0	0
Drainage with class 6 base	1	0
Drainage with PSAB base	0	1

Table 7: Factors for Categorical Variable- Design Life

Category	Explanatory Variable Value
Design Life	$\mathbf{t_{design}}$
5 year	0
10 year	1

The high p-value (p = 0.1458) for D_1 shows that this term is not significant, assuming that α remains as 0.05. Therefore, this base type parameter is considered insignificant. Also, the design life term p-value is 0.088, indicating that the design life is also insignificant in the YRCE model. Although this contradicts earlier findings from the bivariate analysis, this is no surprise. Pavements designed for a longer life are generally built more conservatively to achieve the additional design life. This is typically done by increasing total thickness, upgrading on construction materials or better coping for applied traffic and environmental loads. There is most likely a confounding effect from any one or more of these explanations.

The analysis was repeated with the results from above. The design life term was removed and the binomial scheme was modified to be more generalized. The updated model and scheme are shown in equation 17 and table 8, respectively.

$$YRCE_{HMA-ML} = \beta_0 + \beta_1 h_{total} + \beta_2 t_{design} + \beta_3 D_1 + \beta_4 D_2 \rightarrow \beta_0 + \beta_1 h_{total} + \beta_2 D_1 \quad (17)$$

Table 8: Factors for Categorical Variables- Drainage and Base Material

Category	Explanatory Variable Value
Drainage	$\mathbf{D_1}$
No Drainage or Drainage with Class 6 Base	0
Drainage with PSAB base	1

Equation 18 gives the complete regression model for mainline HMA cells. It suggests that the frost heave decreases with increasing total thickness and with a PSAB base drainage layer. From the model, a one inch increase in total thickness decreases frost heave by 0.007 inch and the presence of PSAB drainage layer decrease frost heave by 0.144 inch. These results are consistent with the conclusions drawn from hypothesis testing. The R^2 value may decrease by using less terms, but the change is less than 2 percent and insignificant.

$$YRCE_{HMA-ML} = \beta_0 + \beta_1 h_{total} + \beta_2 D_1 \rightarrow 0.8590 - 0.0083 h_{total} - 0.01511 D_1 \quad (18)$$

The amount of variables controlled between the two cells is not very great and their confounding effects may change the outcome of the results. Cell 18 has a conventional design that includes the use of higher quality base materials [class 6 base on a class 3 subbase] that have a low percentage of fines and is rather thick [31 inches] compared to cell 23 [permeable base on a class 4 subbase and 16 inches]. The amount of difference in the selected cells may be too great to yield great results.

2) HMA LVR Cells

YRCE

The bivatiate analysis showed that total thickness and subgrade type were the important design factors for frost heave in HMA LVR cells. Equation 19 gives the model used for this analysis. The subgrade type binomial scheme is used for the regression is shown in table 9.

$$YRCE_{HMA-LVR} = \beta_0 + \beta_1 h_{total} + \beta_2 S_{type} \qquad (19)$$

Table 9: Factors for Categorical Variable- Subgrade

Category	Explanatory Variable Value
Subgrade Type	$\mathbf{S_{type}}$
Sand	0
Clay	1

The high p-value (p = 0.988) for total thickness suggests that the variable is not a significant parameter. This is expected from the results of the subgrade type bivariate analysis. The sand data was fairly tight around the median as compared to the clay values that showed much more variation. The amount of variation seen would justify the subgrade term dominating the equation. The analysis was repeated with the pavement thickness term as shown in equation 20.

$$YRCE_{HMA-LVR} = \beta_0 + \beta_1 h_{total} + \beta_2 S_{type} \rightarrow \beta_0 + \beta_1 S_{type} \qquad (20)$$

Equation 21 is the complete model for the HMA LVR cells. The final model still shows a strong effect for subgrade type on heaving. When a sand subgrade is used, a 0.590 inch decrease in frost heaving is seen as compared to clay. This finding is consistent with the results obtained from the bivariate analysis.

$$YRCE_{HMA-LVR} = \beta_0 + \beta_1 S_{type} \rightarrow 0.213 + 0.590 S_{type} \qquad (21)$$

3) Mainline PCC Cells

YRCE

Linear regression was done for PCC mainline sections. Earlier findings from the hypothesis test suggest that total thickness, joint spacing and drainage are important factors for frost heave. Therefore YRCE model was fitted with these parameters as shown in equation 22. The scheme for the drainage variable shown in table 10.

$$YRCE_{PCC-ML} = \beta_0 + \beta_1 h_{total} + \beta_2 J_{space} + \beta_3 D_1 + \beta_4 D_2 \quad (22)$$

Table 10: Factors for Categorical Variable- Drainage

D_1	D_2	Drainage Type
0	0	No Drain
1	0	Drainage Structure
0	1	PSAB Base

The high p-value (0.504) for total thickness suggests the term is not significant for mainline PCC sections. Regression analysis was performed again without this variable following equation 23. The drainage variable follows table 11 as before.

$$YRCE_{PCC-ML} = \beta_0 + \beta_1 J_{space} + \beta_2 D_1 + \beta_3 D_2 \quad (23)$$

From the coefficient estimate table, the model shows some correlation with YRCE. The difference in the R^2 values from the first and second ANOVA analysis is very small. The updated linear fit is expressed by equation 24. All terms decrease the YRCE values. The use of a permeable base drainage layer has the greatest effect on the YRCE value. This follows the visual and bivariate analysis. However, the use of less or not permeable drainage layer also decreases the amount of frost heave. This contradicts the previous analysis as well as the visual and bivariate analysis. The joint spacing term is not a very large coefficient. Its effect on YRCE is small compared to the drainage terms, as expected.

$$\begin{aligned} &YRCE_{PCC-ML} = \beta_0 + \beta_1 J_{space} + \beta_2 D_1 + \beta_3 D_2 \\ &\rightarrow 1.196 - 0.011 J_{space} - 0.170 D_2 - 0.248 D_3 \end{aligned} \quad (24)$$

Correlation between Changes in IRI and Changes in Pin Elevation

Ride quality is one of the most important indicators of the pavement condition. Poor ride quality causes complaints from the traveling public and often trigger pavement rehabilitation. Traditionally, change in the ride quality was attributed mostly to the increase in amount of pavement surface distresses due to repeated heavy axle loading and material surface deterioration due to weather exposure. The effects of other environmental factors, like frost heave, have not been sufficiently studied.

In this study, the contribution of frost heave on seasonal and long term changes in ride quality of roads in Minnesota was evaluated using frost heave measurements and pavement performance data from MnROAD. Frost heave is characterized by YRCE and IQR as defined above. Ride quality is characterized using the International Ride Index (IRI).

To evaluate the effect of frost heave on long-term deterioration in ride quality, the HMA and PCC MnROAD cells were divided into groups with relatively high and low frost pin YRCE or IQR. The IRI measurements in the beginning of the pavement life and some time after opening to traffic were compared to identify any statistical difference in ride quality. The results of this analysis are presented below.

1) HMA Mainline cells

To investigate the effect of the magnitude of frost heave on ride quality deterioration, the HMA cells were divided based on the mean YRCE value. Two groups of HMA cells were identified:

- Group A: Cells 4, 14, and 15. Each of these cells has an average YRCE greater than 0.75 in.
- Group B: Cells 17, 18, 22, and 23. Each of these cells has an average YRCE less than 0.75 in.

For each of these two groups, two groups of IRI measurements in the driving (truck) lane were selected. The first group contained:

- IRI measurements taken from July 1994 to December 1995 using PAVETECH equipment and converted into PATHWAY measurement using the correlation equation. The total number of IRI measurements for each cell is 9. These measurements represent ride quality shortly after opening the cells to traffic.
- IRI measurements taken from April 1999 to July 2000 using PATHWAY. The total number of measurements for each cell is 5. These measurements represent ride quality after the cells were exposed to substantial traffic.

Figure 6 compares mean IRI for Groups A and B. The figure shows that in 1994-1995 the cells with higher frost heave, i.e. YRCE greater than 0.75 in, exhibited slightly higher mean initial IRI than the cells with lower frost heave (0.82 vs 0.75 m/km, respectively). However, after 5 years of a heavy traffic, these groups of cells exhibited virtually no difference in ride quality. The average IRI values for groups A and B were equal to 1.617 and 1.611 m/km, respectively. The results of the t-test yielded a p-value of 0.47 that confirms the difference is not statistically significant.

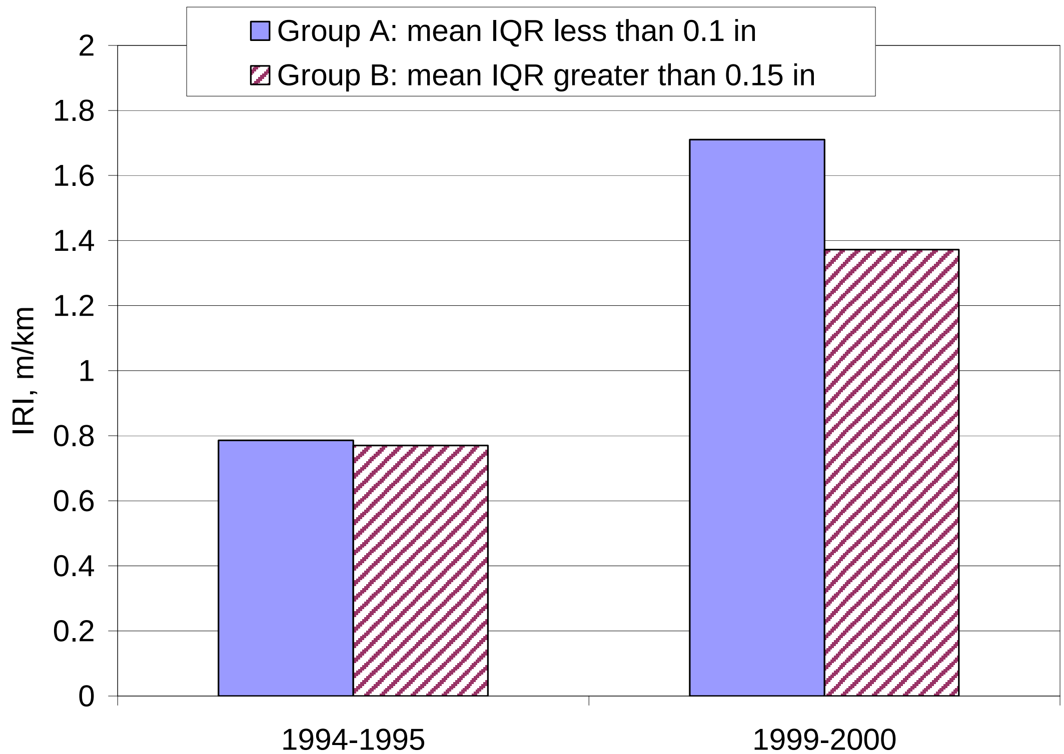


Figure 7: IRI Comparison for the HMA Cells with More and Less Uniform Frost Heave

The results of this analysis are quite surprising. If anything, the non-uniformity of frost heave was expected to increase roughness, not decrease it. It should be noted, however, that deterioration of ride quality of MnROAD HMA cells is predominately driven by development and deterioration of transverse [thermal] cracks in the asphalt layer. The effect of transverse cracking is possibly overshadowing the effect of frost heave.

2) PCC Mainline Cells

Unlike the MNROAD HMA cells, the MNROAD PCC cells did not exhibit any significant distresses after more than 10 years of service. Nevertheless, the ride quality deteriorated somewhat. Figure 8 shows IRI history for a driving lane of PCC cell 6. It can be observed that after 12 years, IRI increased for 1.0 m/km to 1.6 m/km. Frost heave could be one of the mechanisms responsible for ride quality deterioration.

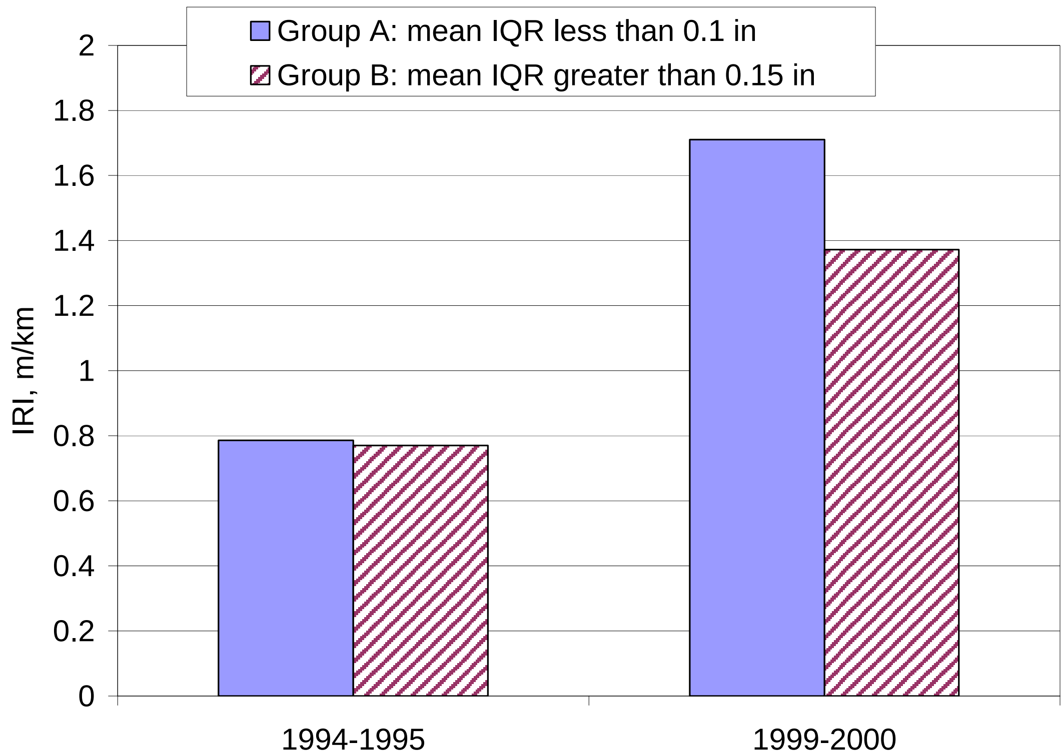


Figure 7: IRI Comparison for the HMA cells with More and Less Uniform Frost Heave

The results of this analysis are quite surprising. If anything, the non-uniformity of frost heave was expected to increase roughness, not decrease it. It should be noted, however, that deterioration of ride quality of MnROAD HMA cells is predominately driven by development and deterioration of transverse [thermal] cracks in the asphalt layer. The effect of transverse cracking is possibly overshadowing the effect of frost heave.

2) PCC Mainline Cells

Unlike the MNROAD HMA cells, the MNROAD PCC cells did not exhibit any significant distresses after more than 10 years of service. Nevertheless, the ride quality deteriorated somewhat. Figure 8 shows IRI history for a driving lane of PCC cell 6. It can be observed that after 12 years, IRI increased for 1.0 m/km to 1.6 m/km. Frost heave could be one of the mechanisms responsible for ride quality deterioration.

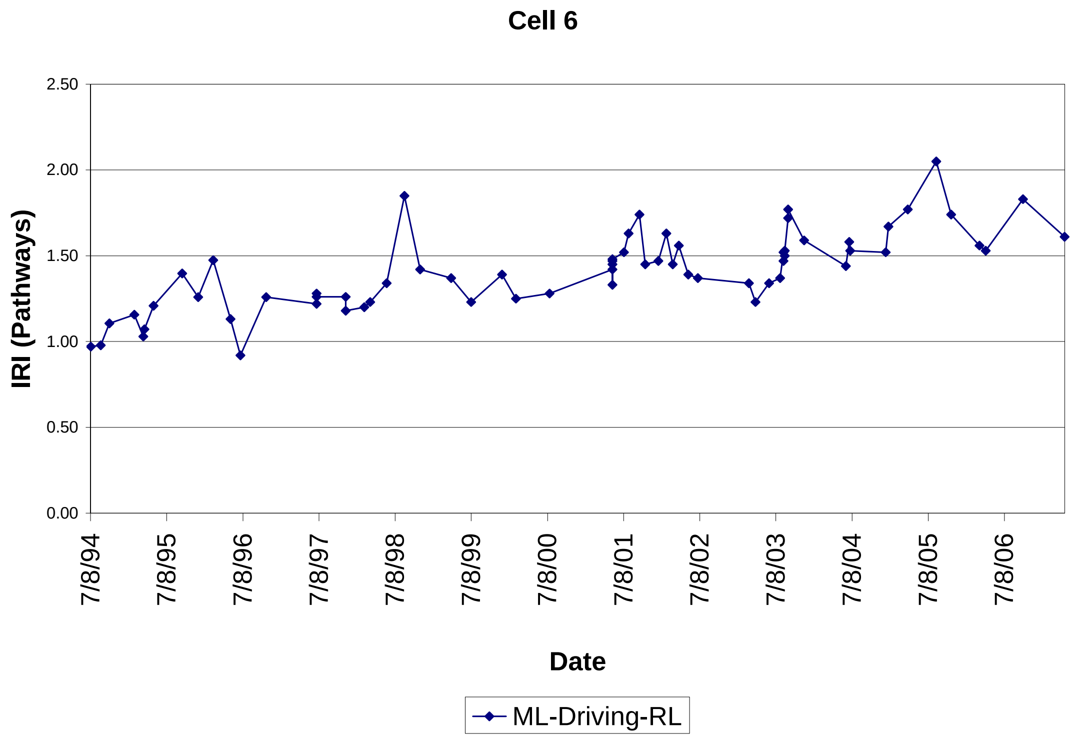


Figure 8: Change in Ride Quality for MnROAD Cell 6

To investigate the effect of the magnitude of frost heave on ride quality deterioration, the PCC cells were divided based on the mean YRCE value. Two groups of PCC cells were identified:

- Group A: Cells 7 and 10. Each of these cells has an average YRCE lower than 0.8 in.
- Group B: Cells 6, 11, 12, and 13. Each of these cells has an average YRCE greater than 0.8 in.

For each of these two groups, two groups of IRI measurements in the driving (truck) lane were selected. The first group contained:

- IRI measurements taken from July 1994 to December 1995. The total number of IRI measurements for each cell is 9.
- IRI measurements taken from April 2003 to December 2004. The total number of measurements for each cell is 14.

Figure 9 compares mean IRIs for Groups A and B. The figure shows that in 1994-1995 the cells with higher frost heave exhibited slightly higher mean IRI than the cells with lower frost heave (1.04 vs 0.97 m/km, respectively). The t-test, however, indicated that the difference is statistically insignificant. On the other hand, after 9 years of a heavy traffic, the difference in ride quality became more pronounced. The average IRI values for groups A and B were 1.21 and 1.44 m/km, respectively. The result of the t-test yielded a p-value of 0.47. The test suggests that the difference is statistically significant. Therefore, in absence of other distresses, higher levels of frost heave may accelerate deterioration of ride quality.

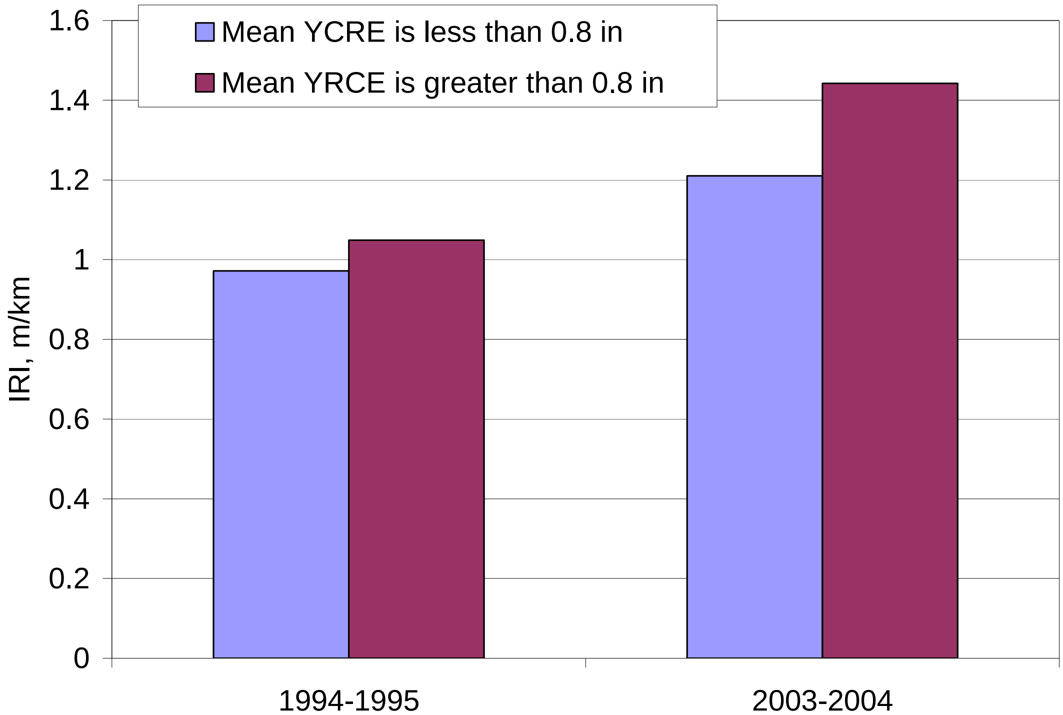


Figure 9: IRI Comparison for the PCC Cells with Higher and Lower Frost Heave

Figure 10 illustrated the effect of mean YRCE on the rate of IRI increase for the MnROAD PCC cells along with a trend line obtained from a linear regression. In spite of significant scatter in the data, the figure illustrates that an increase in YRCE leads to an increase in the rate of IRI increase. However, the linear relationship between these two parameters explains only 25 percent of the trend.

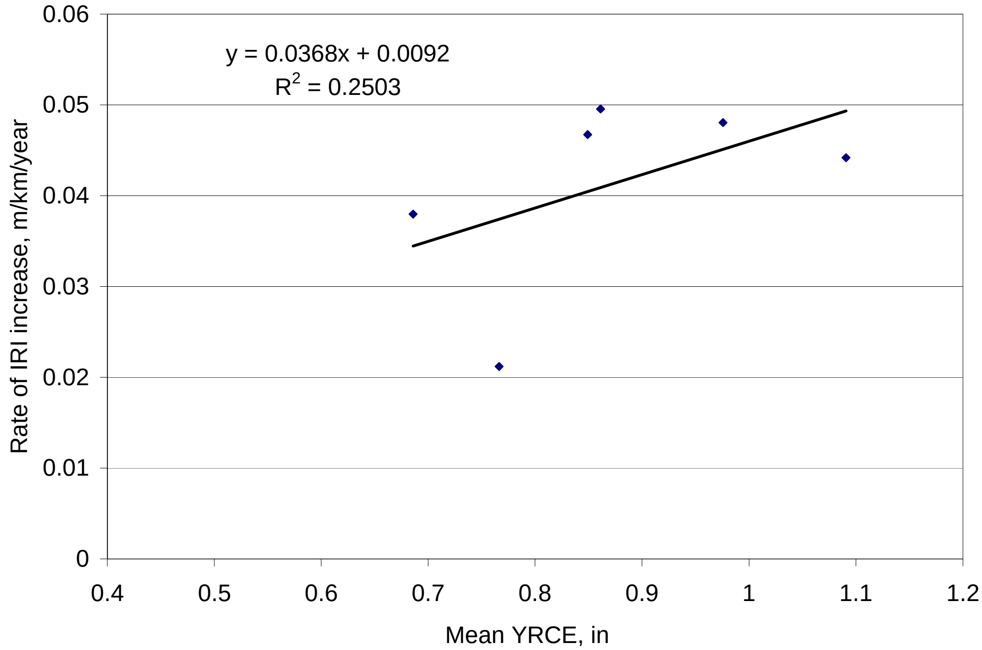


Figure 10: Effect of Mean Yearly Frost Heave Range on Rate of IRI Increase

To investigate the effect of frost heave uniformity on ride quality deterioration, the PCC cells were divided based on the mean IQR value. Two groups of PCC cells were identified:

- Group A: Cells 7, 10, and 11. Each of these cells has an average IQR lower than 0.1 in.
- Group B: Cells 6, 12, and 13. Each of these cells has an average IQR greater than 0.1 in.

Figure 11 compares mean IRIs for Groups A and B. The figure shows that in 1994-1995 the cells with lower frost heave non-uniformity (low IQR) exhibited slightly lower mean IRI than the cells with less uniform frost heave (1.049 vs 1.057 m/km, respectively). The t-test indicated that the difference is statistically insignificant. After 10 years of a heavy traffic, the difference in ride quality increased. The mean IRI for groups A and B increased to 1.339 and 1.390 m/km, respectively. The t-test ($p = 0.32$), however, indicated that the difference is not statistically significant. This suggests that frost heave non-uniformity expressed in IQR has less effect on deterioration of ride quality than the magnitude of frost heave expressed in YRCE.

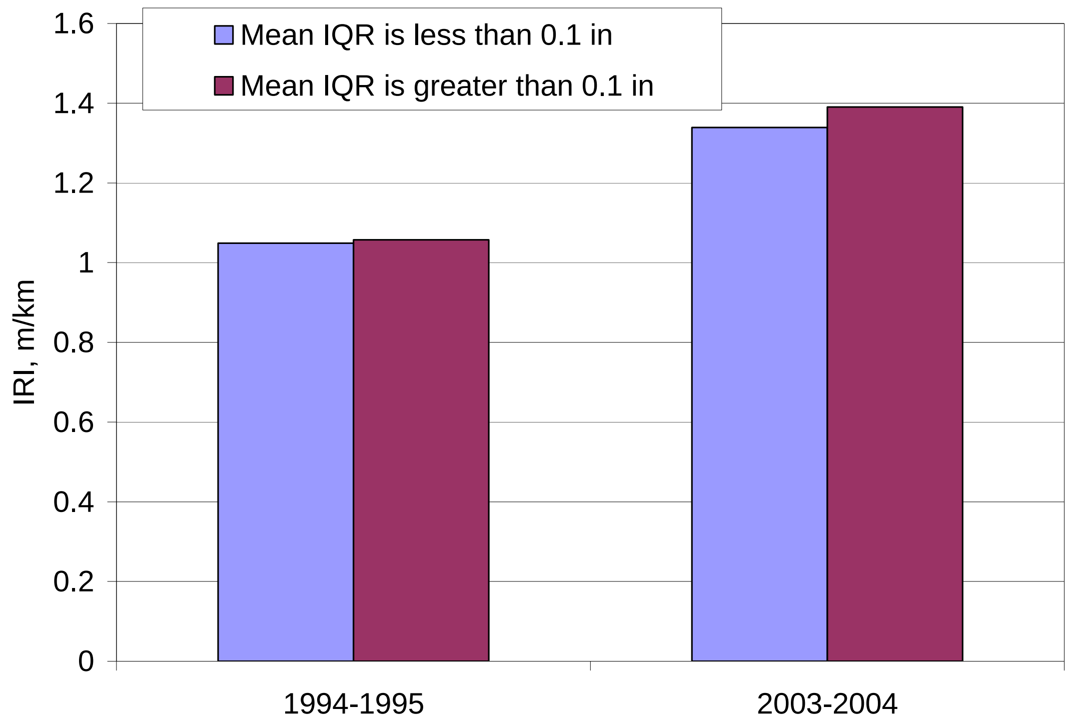


Figure 11: IRI Comparison for the PCC Cells with More and Less Uniform Frost Heave

Discussion

The statistical analysis presented above could not confirm a correlation between frost heave and ride quality deterioration of flexible pavements. At the same time, a hypothesis that frost heave affects deterioration of ride quality for rigid pavements could not be rejected. Since thicker pavements exhibit lower frost heave than thinner pavements, it cannot be conclusively said that thick select granular subbases do not provide substantial improvement in pavement performance.

The analysis of IRI data for MnROAD cells also revealed that MnROAD HMA cells were built much smoother than MnROAD PCC cells. The mean IRI in 1994-1995 were 0.8 vs 1.0 m/km for driving lanes of HMA and PCC mainline cells, respectively. At the same time, ride quality of HMA cells deteriorated at much faster rate than that of PCC cells. PCC cells after 10 years of service were much smoother than HMA cells after 5 years with an average IRIs for the driving lane of 1.35 vs 1.61 m/km, respectively.

Figures 12 and 13 show IRI measurements taken from 1994 to 2002 for MnROAD mainline and low volume cells, respectively. Figures 14 and 15 show the same data as figures 12 and 13, only in column form. Both sets of figures show that an initial ride quality was much higher for HMA cells, but the ride quality in 2002 was much better for PCC cells. To highlight this observation, figures 15 and 16 present IRI data taken in 1994 and 2002, respectively. The comparison of these two figures shows that IRI was lower for HMA sections in 1994 and higher in 2002 compared to PCC sections. The difference in the rates of deterioration can be explained by the presence of extensive thermal cracking in HMA pavements. Therefore, to improve ride quality of Minnesota pavements it is important to improve the initial smoothness at time of construction for PCC pavements and increase resistance to thermal cracking for HMA pavements.

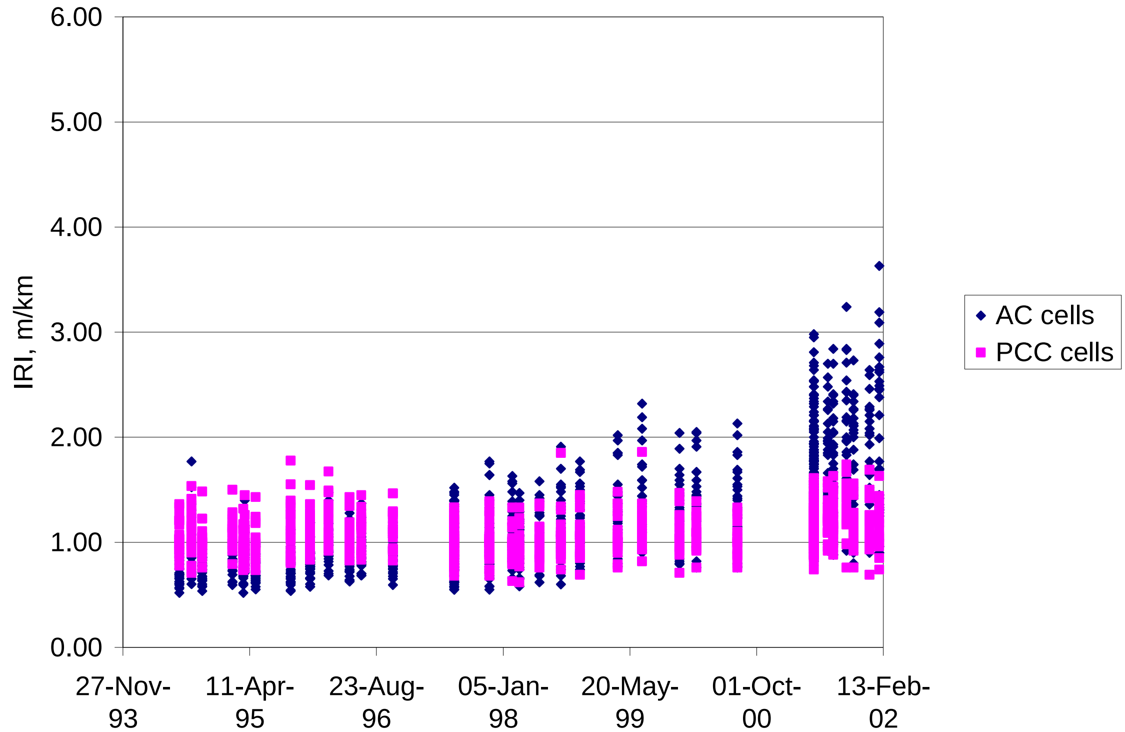


Figure 12: Comparison of IRI for MnROAD Mainline Test Sections

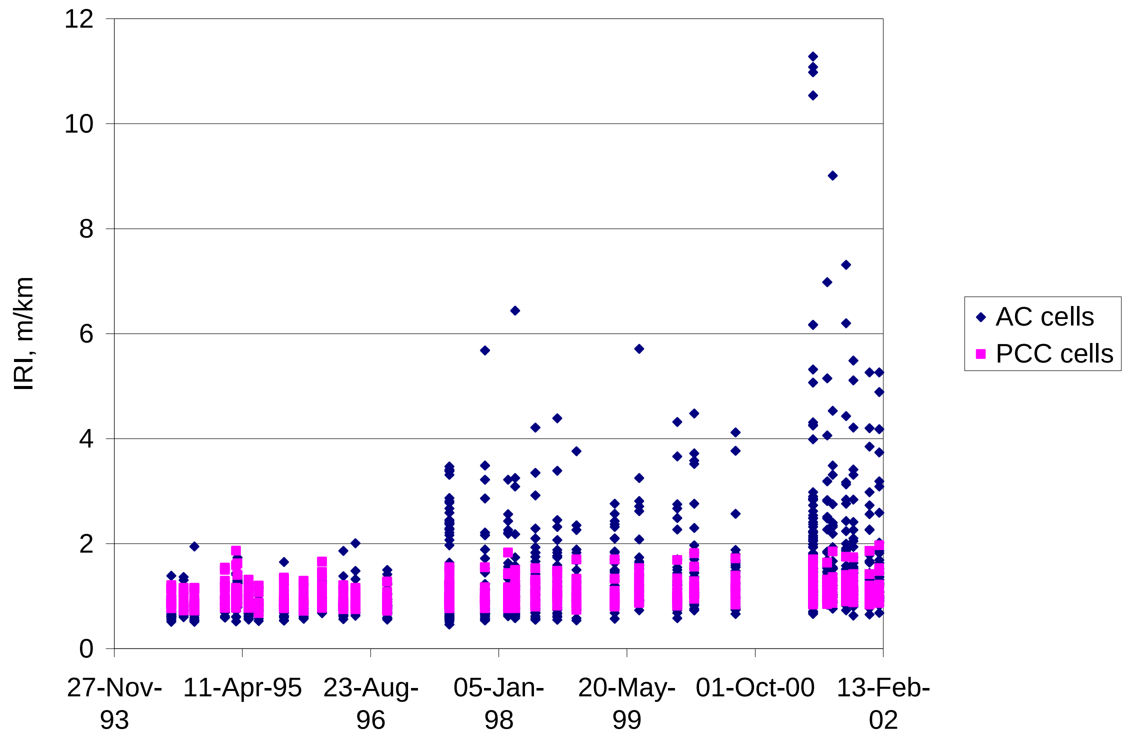


Figure 13: Comparison of IRI for MnROAD LVR Test Sections

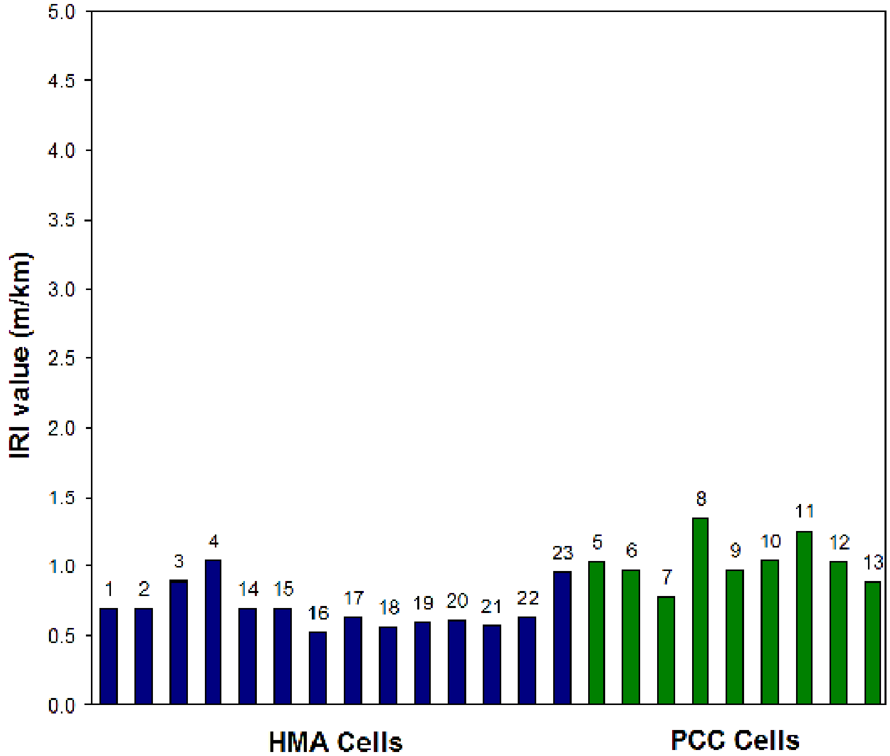


Figure 14: IRI Measurements for 1994 Mainline Test Sections

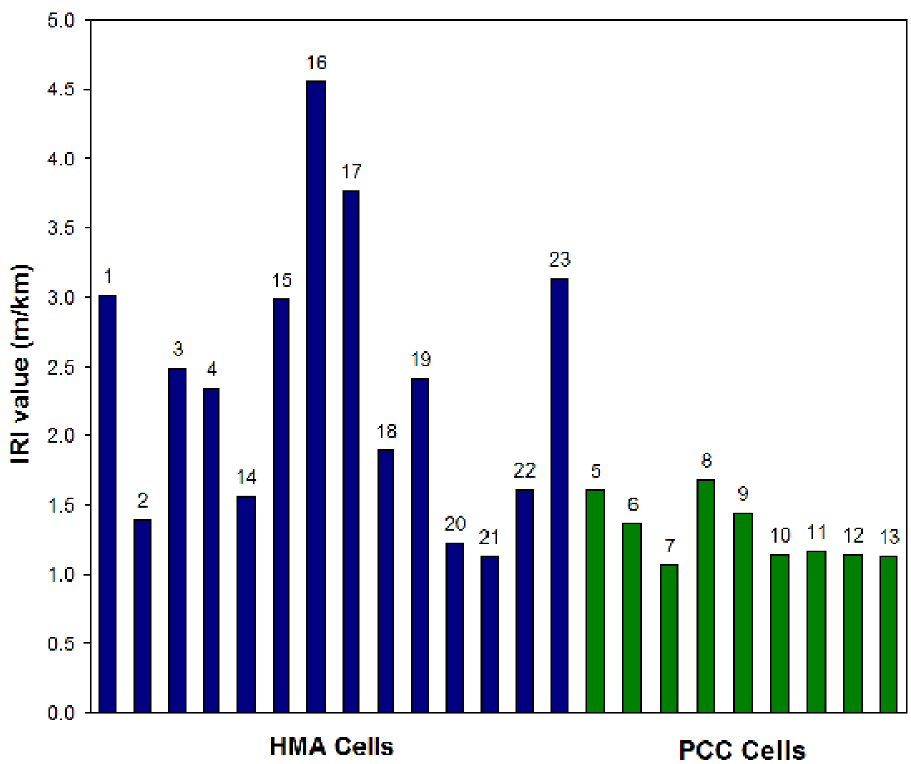


Figure 15: IRI Measurements for 2002 Mainline Test Sections

Seasonal Variations in IRI

The MnDOT pavement management unit has profile measures on some roads that have been particularly rough during the winter and corresponding summer measurements (Lukanen, personal communication). Anecdotal evidences suggest that, in general, Minnesota roads are rougher in winter time and their ride quality somewhat improve in summer time. Since IRI measurement may trigger or delay rehabilitating and maintenance activities, it is important to make sure that the timing of IRI measurements do not affect pavement management decisions. To address this concern, one of the objectives of this study was evaluation of contribution of frost heave toward seasonal changes in ride quality in Minnesota using measurements and pavement performance data from MnROAD and development of seasonal adjustment factors for ride quality for use in pavement management system.

To address this objective, IRI data for MNROAD cells were analyzed. Equation 26 gives a linear regression model was developed for each cell and lane.

$$IRI = a_o + a_1 * Age + a_2 * Age * Season \qquad (26)$$

Where *Season* is a discreet variable equal to 0 in summer time and 1 otherwise, and a_i are regression coefficients.

If there is a significant difference between summer IRI measurements and measurements in other seasons, then linear regressions for MnROAD cells should result in statistically significant coefficients a_2. That would provide a basis for development of the IRI seasonal adjustment factor.

To eliminate the effects of the factors unrelated to the seasonal effect, only the following subset of the MnROAD IRI database was used:

- To eliminate the effect of IRI equipment measurement variability, only Pathway IRI measurements were used.
- To eliminate the effect of maintenance activities, only IRI measurements until May of 2002 were used for flexible MnROAD cells.
- Low volume loop cells 26, 27, 28, 29, 21, and 32 were excluded from the analysis.

Table 11 presents the results of the regression analysis for each MnROAD cell and lane. The cells for which the coefficient a_2 is significant ($p > 0.05$) are presented in a bold font.

It is interestingly to note that only the models for several concrete cells resulted in a significant a_2 parameter. It is also important to note that for all the cases when the season adjustment term is significant, the coefficient a_2 is negative. This means IRI values for MnROAD cells measured in summer time and adjusted to time are greater than IRI values measured in other seasons. This is opposite to common belief. Considering that only a small number of cells exhibited a sensitivity to a season variation in the IRI measurement and that summer IRI measurements are found to be conservative, it was decided not to recommend any seasonal adjustment procedures.

It should be noted that MNROAD cells may not be representative of Minnesota pavements with respect to subgrade preparation. Due to a nature of subgrade “creation” at MNROAD, the cells may have a more uniform subgrade than a typical Minnesota pavement. The results of this study indicate that MNROAD IRI data cannot be used for development of an IRI seasonal adjustment factor. However, it would be incorrect to generalize them as proof that an IRI seasonal adjustment factor is not required.

Table 11: ANOVA Analysis of Equation 26

Cell	Lane	a_0	a_1	a_2	p-value		
					a_0	a_1	a_2
1	Driving	0.33519	0.158858	-0.01098	0.00705	1.55E-07	0.334369
1	Passing	0.355464	0.145701	-0.0047	4.14E-05	1.79E-10	0.495352
2	Driving	0.108578	0.280589	-0.00614	0.34746	1.22E-11	0.590077
2	Passing	0.311265	0.168163	-0.00588	0.005956	1.32E-08	0.565094
3	Driving	0.821736	0.14983	-0.01732	2.93E-06	2.68E-06	0.188637
3	Passing	0.634532	0.142389	-0.00952	3.33E-05	2.04E-06	0.431879
4	Driving	0.139257	0.369891	0.015468	0.499272	2.72E-09	0.450912
4	Passing	0.274021	0.265272	0.003232	0.174312	2.94E-07	0.868958
5	Driving	0.761532	0.065302	-0.00659	1.37E-07	0.000281	0.517149
5	Passing	0.668697	0.096581	-0.0158	5.06E-07	2.32E-07	0.103294
6	Driving	1.143662	0.044942	-0.00041	2.62E-16	0.000337	0.954007
6	Passing	1.001166	0.049781	0.01176	2.62E-16	1.41E-05	0.064135
7	Driving	0.52125	0.054328	-0.00867	1.88E-11	1.9E-08	0.07403
7	Passing	0.5289	0.073812	-0.01037	7.18E-09	6.25E-09	0.09708
8	Driving	1.020614	0.075562	-0.00756	4.36E-20	9.4E-12	0.123954
8	**Passing**	**0.756221**	**0.072283**	**-0.00814**	**3.39E-19**	**3.99E-14**	**0.038185**
9	**Driving**	**0.82446**	**0.060827**	**-0.02147**	**2.71E-13**	**8.98E-07**	**0.001836**
9	**Passing**	**0.72037**	**0.055579**	**-0.01101**	**6.3E-17**	**9.74E-10**	**0.013364**
10	**Driving**	**0.68989**	**0.069836**	**-0.00952**	**2.76E-16**	**2.96E-12**	**0.031327**
10	Passing	0.708377	0.075434	-0.00171	4.36E-14	6.54E-11	0.742906
11	Driving	0.798271	0.077461	-0.00481	2.24E-11	9.89E-08	0.512148
11	Passing	0.67125	0.07246	0.000554	2.28E-14	2.59E-11	0.908446
12	**Driving**	**0.748894**	**0.078118**	**-0.01933**	**1.97E-13**	**4.06E-10**	**0.001796**
12	Passing	0.729528	0.051442	-0.00438	4.23E-15	1.42E-07	0.378771
13	Driving	0.808266	0.0453	0.000997	5.74E-11	0.000751	0.896741
13	Passing	0.802363	0.06264	-0.00073	4.47E-13	4.32E-07	0.908777
14	Driving	-0.44891	0.370645	-0.00485	0.008008	1.83E-11	0.752359
14	Passing	-0.2335	0.281887	0.003982	0.040801	4.08E-12	0.71145
15	Driving	-0.66236	0.424297	-0.00973	0.014556	7.98E-09	0.69686
15	Passing	-0.09164	0.284769	0.005892	0.420629	7.43E-12	0.600688
16	Driving	0.046765	0.340965	-0.00838	0.824515	1.67E-08	0.689827
16	Passing	-0.3112	0.304443	0.024222	0.040732	1.79E-10	0.102174
17	Driving	0.132725	0.298565	-0.00488	0.361747	2.5E-10	0.733747
17	Passing	-0.16554	0.268575	0.017948	0.377511	9.92E-08	0.336671
18	Driving	0.23813	0.338731	-0.02092	0.261926	1.6E-08	0.319784
18	Passing	0.034274	0.328676	-0.00181	0.745003	1.42E-13	0.86258
19	Driving	-0.02776	0.339762	0.013235	0.874373	8.26E-10	0.451386
19	Passing	-0.3943	0.376472	0.015867	0.044666	3.95E-10	0.396116
20	Driving	0.282299	0.103059	-0.00022	0.012284	1.98E-05	0.983294
20	Passing	0.462206	0.066166	0.012517	9.06E-06	0.00015	0.123767
21	Driving	0.331609	0.092822	0.003621	0.000953	7.56E-06	0.675268

Cell	Lane	a_0	a_1	a_2	p-value		
					a_0	a_1	a_2
21	Passing	0.345285	0.088462	-0.00029	3.16E-07	1.18E-09	0.949378
22	Driving	0.427398	0.156245	-0.00716	0.001374	3.15E-07	0.538753
22	Passing	0.231688	0.170691	-0.00216	0.004465	3.14E-11	0.766739
23	Driving	0.945496	0.118254	-0.0093	1.93E-10	9.2E-08	0.258278
23	Passing	0.785432	0.103195	-0.00733	6.43E-10	1.25E-07	0.314745
24	LVR-102K	0.857647	0.035388	0.007106	7.04E-10	0.021783	0.373472
24	LVR-80K	0.358341	0.05976	-0.0049	6.21E-05	0.000157	0.495857
25	LVR-102K	0.464185	0.081298	-0.00541	5.89E-08	9.96E-08	0.338612
25	LVR-80K	0.305674	0.077511	0.002068	0.005421	0.0003	0.834102
30	LVR-102K	0.337248	0.123228	-0.00259	0.001577	4.03E-07	0.780369
30	LVR-80K	0.411892	0.094614	-0.00154	7.78E-06	2.84E-07	0.821935
33	LVR-102K	3.434331	-0.30894	-0.02239	8.38E-10	2.96E-05	0.486392
33	LVR-80K	5.966961	-0.56077	-0.03783	1E-06	0.001817	0.663451
34	LVR-102K	2.225825	-0.14312	-0.01045	2.5E-08	0.00526	0.681406
34	LVR-80K	3.122553	-0.22116	-0.00161	2.74E-08	0.002654	0.964066
35	LVR-102K	2.50484	-0.16802	0.00504	7.17E-10	0.00064	0.827445
35	LVR-80K	3.45085	-0.25625	-0.03048	3.71E-09	0.000446	0.35148
36	**LVR-102K**	**0.776095**	**0.041447**	**-0.00993**	**2.92E-18**	**2.07E-07**	**0.019156**
36	LVR-80K	0.879588	0.036207	0.006638	1.77E-13	0.001423	0.299127
37	LVR-102K	0.724712	0.021859	0.001404	7.27E-24	6.75E-06	0.590917
37	LVR-80K	0.729966	0.037858	-0.00448	1.06E-21	3E-09	0.146739
38	LVR-102K	0.763554	0.052164	0.001794	8.9E-17	1.63E-08	0.6922
38	LVR-80K	0.894916	0.054169	-0.00085	1.29E-15	7.81E-07	0.879352
39	**LVR-102K**	**0.908229**	**0.034203**	**-0.008**	**2.39E-27**	**7.11E-10**	**0.003599**
39	**LVR-80K**	**0.964648**	**0.057826**	**-0.01176**	**1.76E-20**	**7.34E-10**	**0.010416**
40	LVR-102K	1.648977	0.004702	0.006725	3.19E-22	0.65923	0.31426
40	LVR-80K	1.074165	0.059453	-0.0005	9.57E-20	1.49E-08	0.923183

Conclusion

This report evaluated the contribution of frost heave on seasonal and long term changes in ride quality at MnROAD. The analysis of this report was used to develop seasonal adjustment factors for ride quality for use in a pavement management system and recommendations for improvements of design practices.

From the analysis of the frost pin and ride data, subgrade and base type, pavement thickness and drainage capabilities are the major design factors that have a great affect on seasonal pavement frost heave separately and in combined effects for the test sections chosen.

The effect of frost heave on ride quality deterioration of flexible pavements could not be confirmed in this study and hypotheses that frost heave affects deterioration of ride quality for rigid pavements could not be rejected by statistical testing. The data showed that MnROAD flexible pavements were constructed smoother than rigid pavements, but deteriorated faster. After 5 years, the flexible cells were much rougher than the rigid cells after 10 years.

Any conclusions of a seasonal effect on IRI measurements are inconclusive. If anything can be taken from the IRI data, it is that summer IRI values were greater than IRI values from the rest of the year. Therefore, no seasonal adjustment factor for IRI measurements is recommended for any potential use in a pavement management system.

The amount of subgrade construction is an important difference should be noted between the test sections at MnROAD and what is typically done on city and county roadways. The MnROAD cells were over excavated by about 6 feet and replaced with a more uniform silty clay or sand [Newcomb]. This was done to control subgrade response by limiting the variability seen from differential soil properties across the cells. Due to the expense of over excavating soil, municipal governments typically use a cut and fill procedure with in-situ soils. In-situ soils are usually not high quality and will have more frost action compared to MnRoad cells.

Three recommendations can be made for improvements in design and construction practices. First, an improve mix design for HMA pavements are needed to reduce or eliminate thermal cracking, the main cause of roughness in HMA sections. Second, improve the initial roughness of concrete pavements. Third, additional investigation of the benefits of thick bases under concrete pavements is needed.

References

Dore, Guy, Martin Flamand and Susan Tighe. "Prediction of Winter Roughness Based on Analysis of Subgrade Soil Variability." *Transportation Research Record*, National Research Council, Washington, DC, No. 1755, p 90-96, 2001.

Fradette, Nicolas, Guy Dore, Pascale Pierre, and Serge Hebert. "Evolution of Pavement Winter Roughness." *Transportation Research Record*, National Research Council, Washington, DC, No 1913, p 137-147, 2005.

Khazanovich, L. et al. *Common Characteristics of Good and Poorly Performing PCC Pavements*. McLean, Virgina: Department of Transportation Federal Highway Administration, Office of Engineering Research and Development [1998 Jan].

Lukanen, E. O., B. J. Worel, and T. Clyne. "MnROAD Environmental Factors that Affect Ride." *Proceedings of the 13th International Conference on Cold Regions Engineering*, Michael Davies, Jon E. Zufelt - Editors, July 23–26, 2006, Orono, Maine, USA.

Michalowski, Radoslaw L. and Ming Zhu. "Frost Heave Modeling Using Porosity Rate Function." *International Journal for Numerical and Analytical Methods in Geomechanics*. 30 (2006): 703–722.

Moore, David S. and G. P. McCabe. *Introduction to the Practice of Statistics*. 5th ed. New York: W.H. Freeman and Company, 2006.

Newcomb, David E. et al. *Initial Characterization of Subgrade Soils and Granular Base Materials at the Minnesota Road Research Project*. St. Paul, Minnesota: Department of Transportation, Office of Research Services [1995 Dec].

Voller, Vaughn, Ling-jun Hou, and Raymond Sterling. *Progressive Lifting of Shallow Sewers Due to Frost Heave Actions: Investigation of a Lumped Parameter Frost Heave Model*. St. Paul, Minnesota: Department of Transportation, Office of Research Services [2003 Aug].

Appendix A

Descriptions of Proposed Data Tables

PIN_LANE contains the type of lane for which the change of elevation is computed. For mainline cells, offset +6 denotes driving lane and offset -6 denotes passing lane. And for low volume loop offset +6 represents 102k lane and offset -6 represents 80k lane.

PIN_CHANGE_ELEV_SINGLE includes change in elevation for each pin with time. For a particular pin the measured elevation on the REF_DATE is taken as reference, which is subtracted from all the measured elevation data belonging to that pin to give the change in elevations. The results for each pin are recorded in the data sheet **PIN_CHANGE_ELEV_SINGLE** If the reference elevation is e_{Ref} then according to the above definition, change in elevation,

$$d_i = e_i - e_{Ref},$$

where, d_i is the change in elevation and e_i is the measured elevation on i-th measurement day.

PIN_CHANGE_ELEV_SECT_SINGLE includes the computed median, 25 percentile, 75 percentile and the difference between 75 and 25 percentiles of change in elevation for each cell and lane on every measurement day. These median and percentile values are calculated for all the pins belonging to a particular cell and lane on a particular measurement day.

PIN_CHANGE_ELEV_RANGES_SINGLE_YEAR contains the RANGE (difference between maximum and minimum values) of change in elevation for each pin in a particular year and median of that range for each cell and lane in a particular year.

PIN_CHANGE_ELEV_SECT_YEAR includes maximum of 75 percentile, minimum of 25 percentile, the difference between maximum 75 percentile and minimum 25 percentile and median of the differences between the maximum and minimum change in elevation for each cell and lane on a particular year.

PIN_CHANGE_ELEV_RANGES_SINGLE_TOTAL contains the RANGE (difference between maximum and minimum values) of change in elevation for each pin in the entire period.

The data source for **CELL_REF_DATE** is:
Existing MnROAD table: **PIN_ELEVATION**

The data source for **PIN_LANE** is:
Existing MnROAD table: **PIN_ELEVATION**

The data source for **PIN_CHANGE_ELEV_SINGLE** is:
Existing MnROAD table: **PIN_ELEVATION**

The data source for **PIN_CHANGE_ELEV_SECT_SINGLE** is:
New MnROAD table proposed in this memo: **PIN_CHANGE_ELEV_SINGLE**

The data source for **PIN_CHANGE_ELEV_RANGES_SINGLE_YEAR** is:
New MnROAD table proposed in this memo: **PIN_CHANGE_ELEV_SINGLE**

The data sources for **PIN_CHANGE_ELEV_SECT_YEAR** are:
New MnROAD table proposed in this memo: **PIN_CHANGE_ELEV_SECT_SINGLE**

The data source for **PIN_CHANGE_ELEV_RANGES_SINGLE_TOTAL** is:
New MnROAD table proposed in this memo: **PIN_CHANGE_ELEV_SINGLE**

Computation Parameters:	Reference date
Project Title:	Effects of Seasonal Changes on Ride quality at MnROAD, Task 1
CELL_REF_DATE	Assigned reference dates

Table 1: Schema and field definition for table **CELL_REF_DATE**

Column Name	Units	Field Type	Codes	Data Dictionary Description
CELL				There are total 20 cells for this analysis.
REF_DATE		15-DEC-93		Assigned reference date. It is the first available date at which measurements are reported for all pins.

Computation Parameters:	Lane Type
Project Title:	Effects of Seasonal Changes on Ride quality at MnROAD, Task 1
PIN_LANE	Assigned lane name for each pin

Table 2: Schema and field definition for table **PIN_LANE**

Column Name	Units	Field Type	Codes	Data Dictionary Description
PIN NO		I5		Steel pins which are embedded in the test cells.
CELL				There are total 20 cells for this analysis.
OFFSET				Offset +6 is defined for driving lane and Offset -6 is defined for passing lane.
LANE		CHAR(13)		Driving or passing lane for the mainline cells, 80kip or 102 kip lane for the low volume loop cells

Computation Parameters:	Change in elevation
Project Title:	Effects of Seasonal Changes on Ride quality at MnROAD, Task 1
PIN_CHANGE_ELEV_SINGLE	Statistical parameters for each pin

Table 3: Schema and field definition for table **PIN_CHANGE_ELEV_SINGLE**

Column Name	Units	Field Type	Codes	Data Dictionary Description
PIN NO		I5		Steel pins which are embedded in the test cells.
DAY		DATE		The day when the measurement was taken.
CELL				There are total 20 cells for this analysis.
STATION				
LANE		CHAR(13)		Driving or passing lane for the mainline cells, 80kip or 102 kip lane for the low volume loop cells.
CHANGE_ELEVATION	in	F3.3		Each number in this field for a particular pin and date indicates the change in elevation from the reference elevation (obtained from the reference date).

Computation Parameters: Statistical analysis of change in elevation
Project Title: Effects of Seasonal Changes on Ride quality at MnROAD, Task 1
PIN_CHANGE_ELEV_SECT_SINGLE Statistical parameters for each cell and lane

Table 4: Schema and field definition for table **PIN_CHANGE_ELEV_ SECT_SINGLE**

Column Name	Units	Field Type	Codes	Data Dictionary Description
DAY		DATE		The day when the measurement was taken.
CELL				There are total 20 cells for this analysis.
LANE		CHAR(13)		Driving or passing lane for the mainline cells, 80kip or 102 kip lane for the low volume loop cells
25_PERCENTILE	in	F3.3		25 percentile of change in elevation for all the pins in each cell and lane of every measurement day.
MEDIAN	in	F3.3		Median of change in elevation for all the pins in each cell and lane of every measurement day.
75_PERCENTILE	in	F3.3		75 percentile of change in elevation for all the pins in each cell and lane of every measurement day.
DIFFERENCE OF 75 AND 25 PERCENTILE	in	F3.3		Difference between 75 and 25 percentile of change in elevation for each cell and lane of every measurement day.
NUMBER OF MEASURMENTS		I2		Number of measurement data available for each cell and lane on every measurement day.

Computation Parameters:	Range of the change in elevation
Project Title:	Effects of Seasonal Changes on Ride quality at MnROAD, Task 1
PIN_CHANGE_ELEV_RANGES_SINGLE_YEAR	Statistical parameters for each pin

Table 5: Schema and field definition for table **PIN_CHANGE_ELEV_RANGES_SINGLE_YEAR**

Column Name	Units	Field Type	Codes	Data Dictionary Description
PIN NO		I5		Steel pins which are embedded in the test cells.
YEAR				The year of the measurement.
CELL				There are total 20 cells for this analysis.
STATION				
LANE		CHAR(13)		Driving or passing lane for the mainline cells, 80kip or 102 kip lane for the low volume loop cells
RANGE	in	F3.3		The difference between the maximum and minimum change in elevation for a particular pin in a particular year.

Computation Parameters: Statistical analysis of the change in elevation
Project Title: Effects of Seasonal Changes on Ride quality at MnROAD, Task 1
PIN_CHANGE_ELEV_SECT_YEAR Statistical parameters for each cell

Table 6: Schema and field definition for **PIN_CHANGE_ELEV_SECT_YEAR**

Field Name	Units	Field Type	Codes	Data Dictionary Description
CELL				There are total 20 cells for this analysis.
LANE		CHAR(13)		Driving or passing lane for the mainline cells, 80kip or 102 kip lane for the low volume loop cells
YEAR				The year of the measurement.
25 PERCENTILE_MIN	in	F3.3		Minimum value of the 25 percentile of change in elevation for each cell and lane in a particular year.
75 PERCENTILE_MAX	in	F3.3		Maximum value of the 75 percentile of change in elevation for each cell and lane in a particular year.
DIFFERENCE OF MAX_75 AND MIN_25 PERCENTILE	in	F3.3		Difference between the maximum value of 75 percentile and minimum value of 25 percentile of change in elevation for each cell and lane in a particular year.
DIFFERENCE OF MAX_MEDIAN AND MIN_MEDIAN	in	F3.3		Difference between the maximum and minimum median of change in elevation for each cell and lane in a particular year
MEDIAN_RANGE	in	F3.3		The median of the differences between the maximum and minimum change in elevation for particular pins in a given year for each cell and lane.

Computation Parameters:	Change in elevation
Project Title:	Effects of Seasonal Changes on Ride quality at MnROAD, Task 1
PIN_CHANGE_ELEV_RANGES_SINGLE_TOTAL	Statistical parameters for each pin

Table 7. Schema and field definition for table **PIN_CHANGE_ELEV_RANGES_SINGLE_TOTAL**

Column Name	Units	Field Type	Codes	Data Dictionary Description
CELL				There are total 20 cells for this analysis.
PIN NO		I5		Steel pins which are embedded in the test cells.
STATION				
LANE		CHAR(13)		Driving or passing lane for the mainline cells, 80kip or 102 kip lane for the low volume loop cells
RANGE	in	F3.3		The difference between the maximum and minimum value of change in elevation of a particular pin considering data of the entire period.

Minimum Data Elements ("C" Level Checks)

Note: All required fields in the level C specifications should be coded as non-null

Table	Field	Condition
CELL_REF_DATE	CELL	**X**
	REF_DATE	**X**
PIN_LANE	PIN NO	**X**
	CELL	**X**
	OFFSET	**X**
	LANE	**X**
PIN_CHANGE_ELEV_ SINGLE	CELL	**X**
	STATION	**X**
	LANE	**X**
	PIN NO	**X**
	DAY	**X**
	REF_DATE	**X**
	CHANGE_ELEVATION	**X**
PIN_CHANGE_ELEV_ SECT_SINGLE	DAY	**X**
	CELL	**X**
	LANE	**X**
	MEDIAN	**X**
	25_PERCENTILE	**X**
	75_PERCENTILE	**X**
	DIFFERENCE OF 75 AND 25 PERCENTILE	**X**
	NUMBER OF MEASURMENTS	**X**
PIN_CHANGE_ELEV_ RANGES_SINGLE_YE AR	PIN NO	**X**
	YEAR	**X**
	CELL	**X**
	STATION	**X**
	LANE	**X**
	RANGE	**X**
PIN_CHANGE_ELEV_ SECT_YEAR	CELL	**X**
	LANE	**X**
	YEAR	**X**
	25 PERCENTILE_MIN	**X**
	75 PERCENTILE_MAX	**X**
	DIFFERENCE OF MAX_75 AND MIN_25 PERCENTILE	**X**

Table	Field	Condition
	DIFFERENCE OF MAX_MEDIAN AND MIN_MEDIAN	**X**
	MEDIAN_RANGE	**X**
PIN_CHANGE_ELEV_RANGES_SINGLE_TOTAL	CELL	**X**
	STATION	**X**
	LANE	**X**
	PIN NO	**X**
	DAY	**X**

Expanded Data Elements ("D" Level Checks)

Table	Field	Units	Range
PIN_CHANGE_ELEV_SINGLE	CHANGE_ELEVATION	in	-4.32 – 3.036
PIN_CHANGE_ELEV_SECT_SINGLE	MEDIAN	in	-0.492 – 1.14
	25_PERCENTILE	in	-0.768 – 1.092
	75_PERCENTILE	in	-0.381 – 1.296
	DIFFERENCE OF 75 AND 25 PERCENTILE	in	0 – 0.669
PIN_CHANGE_ELEV_RANGES_SINGLE_YEAR	RANGE	in	0 – 5.016
PIN_CHANGE_ELEV_SECT_YEAR	25 PERCENTILE_MIN	in	-0.768 – 0
	75 PERCENTILE_MAX	in	-0.024 – 1.296
	DIFFERENCE OF MAX_75 AND MIN_25 PERCENTILE	in	0.054 – 1.584
	DIFFERENCE OF MAX_MEDIAN AND MIN_MEDIAN	in	0.012 – 1.368
	MEDIAN_RANGE	in	0.03 –1.416
PIN_CHANGE_ELEV_RANGES_SINGLE_TOATAL	RANGE	in	0.228 – 5.016

Intramodular Checks ("E" Level Checks)

Programmer's note: The QC checks on **PIN_CHANGE_ELEV_SINGLE** and **PIN_ELEVATION** should be run before running checks on other tables.

Table: CELL_REF_DATE and PIN_ELEVATION

- For each record in **PIN_ELEVATION** with matching CELL and DAY=REF_DATE , PIN-ELEVATION should be non-empty.

Error message: There is no non-empty matching record in **PIN_ELEVATION** {PIN, and DAY= REF_DATE }

Table: PIN_CHANGE_ELEV_SINGLE and PIN_ELEVATION

- For each CELL, STATION, LANE, and PIN in **PIN_ELEVATION**, there is a DAY same as the REF_DATE.

Error message: There is no non-empty matching record in **PIN_ELEVATION** {PIN, and DAY= REF_DATE}

- For each non-null CHANGE_ELEVATION field in **PIN_CHANGE_ELEV_SINGLE**, there is a record of ELEVATION_IN in **PIN_ELEVATION** with matching CELL, STATION, LANE, PIN, and DAY.

Error message: There is no matching record in **PIN_ELEVATION** {CELL, STATION, LANE, PIN, and DAY}

- For each CELL, STATION, LANE, and PIN in **PIN_CHANGE_ELEV_SINGLE**, the value of the CHANGE_ELEVATION field on the REF_DATE is 10^{-8}.

Error message: Possible error in reading ELEVATION_IN from **PIN_ELEVATION** and subtracting from the ELEVATION_IN data of the REF_DATE.

- For each null **PIN_CHANGE_ELEV_SINGLE.** CHANGE_ELEVATION field, there is no record in **PIN_ELEVATION** with matching CELL, STATION, LANE, PIN, and DAY.

Error message: There is a record of ELEVATION_IN in **PIN_ELEVATION** {CELL, STATION, LANE, PIN, DAY, and ELEVATION_IN}, which is missing in **PIN_CHANGE_ELEV_SINGLE.**

Table: PIN_CHANGE_ELEV_SECT_SINGLE

- For each CELL and LANE in **PIN_CHANGE_ELEV_SECT_SINGLE**, the value of the 25_PERCENTILE should be grater than or equal to the Minimum value of the

CHANGE_ELEVATIONs in **PIN_CHANGE_ELEV_SINGLE** belonging to the same CELL and LANE.

Error message: Possible error in calculating 25 PERCENTILE.

- For each CELL and LANE in **PIN_CHANGE_ELEV_SECT_SINGLE**, the value of the 75_PERCENTILE should be less than or equal to the Maximum value of the CHANGE_ELEVATIONs in **PIN_CHANGE_ELEV_SINGLE** belonging to the same CELL and LANE.

Error message: Possible error in calculating 75 PERCENTILE.

- For each CELL and LANE in **PIN_CHANGE_ELEV_SECT_SINGLE,** median > 25_PERCENTILE and median < 75_PERCENTILE

Error message: 25_PERCENTILE is greater than median. Median is grater than 75_PERCENTILE.

- For each CELL and LANE in **PIN_CHANGE_ELEV_SECT_SINGLE**, the value of the Medain, 25_PERCENTILE, and 75_PERCENTILE on the REF_DATE is 10^{-8}.

Error message: Possible error in reading CHANGE_ELEVATION from **PIN_CHANGE_ELEV_SINGLE**. Or possible error in calculation of Median, 25_PERCENTILE or 75_PERCENTILE.

Appendix B

Computational Algorithms

This appendix describes all the computational algorithms that are needed to compute the fields in all the proposed tables. Figure 1 shows the flow chart of the table generation process.

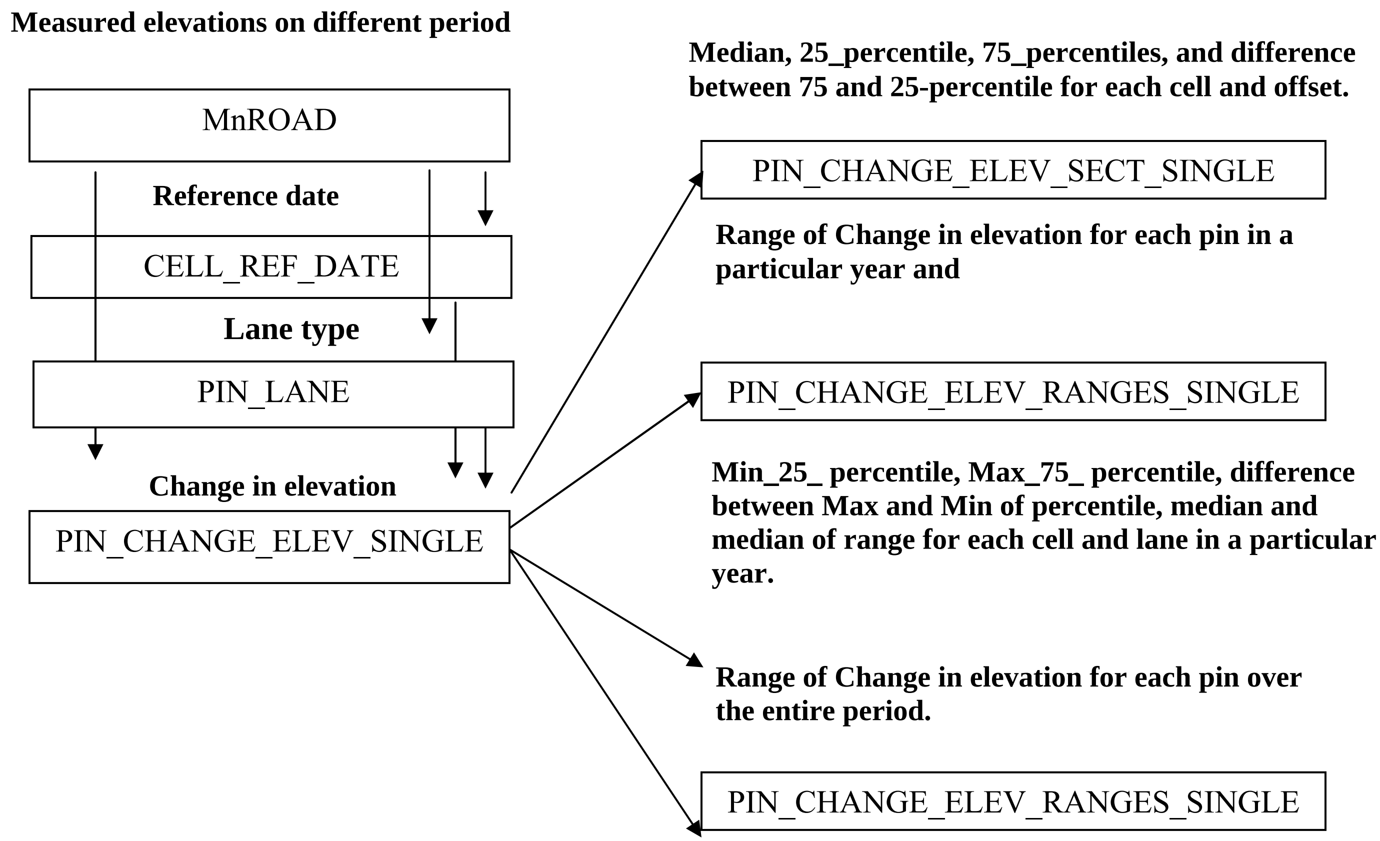


Figure 1: Flow chart showing the sequence of different Tables generated from the MnROAD data (PIN-ELEVATION).

Procedure of Table Calculation

The step-by-step procedures adopted to calculate each field in the proposed tables are described below.

Table 1: **CELL_REF_DATE**

- The whole data in **PIN_ELEVATION** is searched for the earliest measurement date at which all the test pins has reported elevation data.
- That date is chosen as REF_DATE to ensure consistent comparison between all the cells, lanes, and pins.

Table 2: **PIN_LANE**

- The **PIN_ELEVATION** data has two offset s, offset +6 and offset -6. For mainline cells offset +6 denotes driving lane and offset -6 denotes passing lane. And for low volume loop cells, offset +6 represents 102k lane and offset -6 represents 80k lane.

Table 3: **PIN_CHANGE_ELEV_SINGLE**

- PIN_ELEVATION data is converted from ft to inch.
- Each field on this table represents change in elevation.
- Each field belonging to a particular pin on a particular date is calculated by subtracting the elevation on the REF_DATE from the elevation of that date.
- For a particular pin subtraction from the reference elevation ensures consistency within the change in elevation for that pin.

Table 4: **PIN_CHANGE_ELEV_SECT_SINGLE**

- This table contains five worksheets containing 25 Percentile, Median, 75 Percentile, difference between 75 percentile and 25 percentile, and number of measurements.
- For the three worksheets, CHANGE_ELV_25 percentile, Ch_Elv_Q50 (Median), and CHANGE_ELV_75_PERCENTILE, each field corresponding to a particular cell, lane, and date is the statistical estimate (25 Percentile/ Median/ 75 Percentile) taken over the data belonging to all the pins under that cell, lane and on that date.
- Each field of the worksheet CHANGE_ELEVATION_Q75-Q25 is the difference between the 75 percentile and 25 percentile data (available in the previous worksheets) for a particular cell, lane, and date.
- Each field of the worksheet NUMBER OF MEASUREMENTS corresponding to a particular cell, lane and date is the number of data available for the statistical analysis.

Table 5: **PIN_CHANGE_ELEV_RANGES_SINGLE_YEAR**

- This table contains two worksheets containing PIN_CHANGE_ELEV_RANGES_SINGLE_YEAR Each field of the worksheet PIN_CHANGE_ELEV_RANGES_SINGLE_YEAR represents the RANGE of change in elevation for a particular pin and year.
- For a particular pin and year, the maximum and minimum of the change in elevation is determined from all the reported data of that particular year. Then the RANGE is calculated by taking the difference between the maximum and minimum values of change in elevation.

Table 6: **PIN_CHANGE_ELEV_SECT_YEAR**

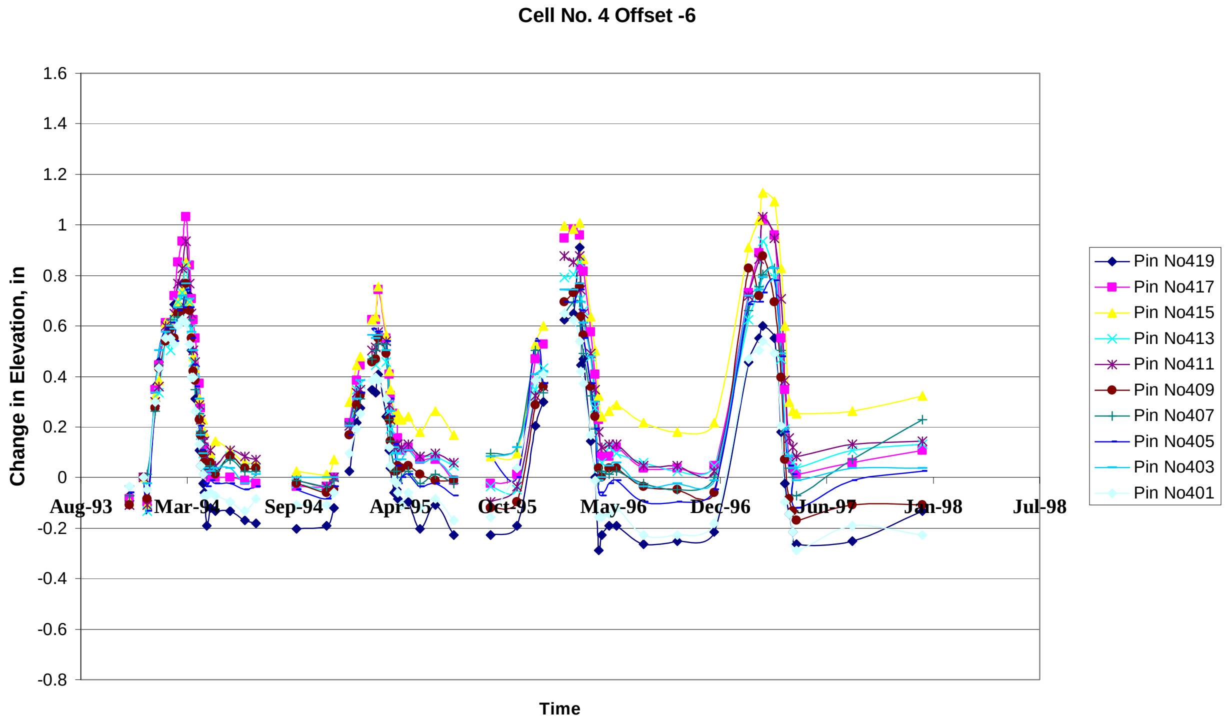
- This table contains four worksheets containing Minimum of 25 Percentile, Maximum of 75 Percentile, difference between Max_75_percentile and Min_25_percentile, difference between Max_Median and Min_Median and MEDIAN_RANGE.
- For the first two worksheets, MIN_25 PERCENTILE and MAX_75_PERCENTILE, each field corresponding to a particular cell, lane, and year is the estimate (Minimum/ Maximum) taken over all the data (available from the table 3 **PIN_CHANGE_ELEV_SECT_SINGLE**) on that year.
- Each field of the worksheet Max_75PERCENTILE-Min_25PERCENTI is the difference between the Max_75 percentile and Min_25 percentile data (available in the previous worksheets) for a particular cell, lane, and year.
- For the worksheet “Median_Max-Min”, first for a particular cell, lane, and year, the maximum and minimum values of Median data (available from the table 3 **PIN_CHANGE_ELEV_SECT_SINGLE**) is searched from all the available date of that year. Then the difference between the maximum and minimum values is taken and recorded in each field of this worksheet.
- For the worksheet MEDIAN_RANGE, each field corresponds to the median which is calculated from the sheet PIN_CHANGE_ELEV_RANGES_SINGLE_YEAR for each cell and lane for a particular year.

Table 7: **PIN_CHANGE_ELEV_RANGES_SINGLE_TOTAL**

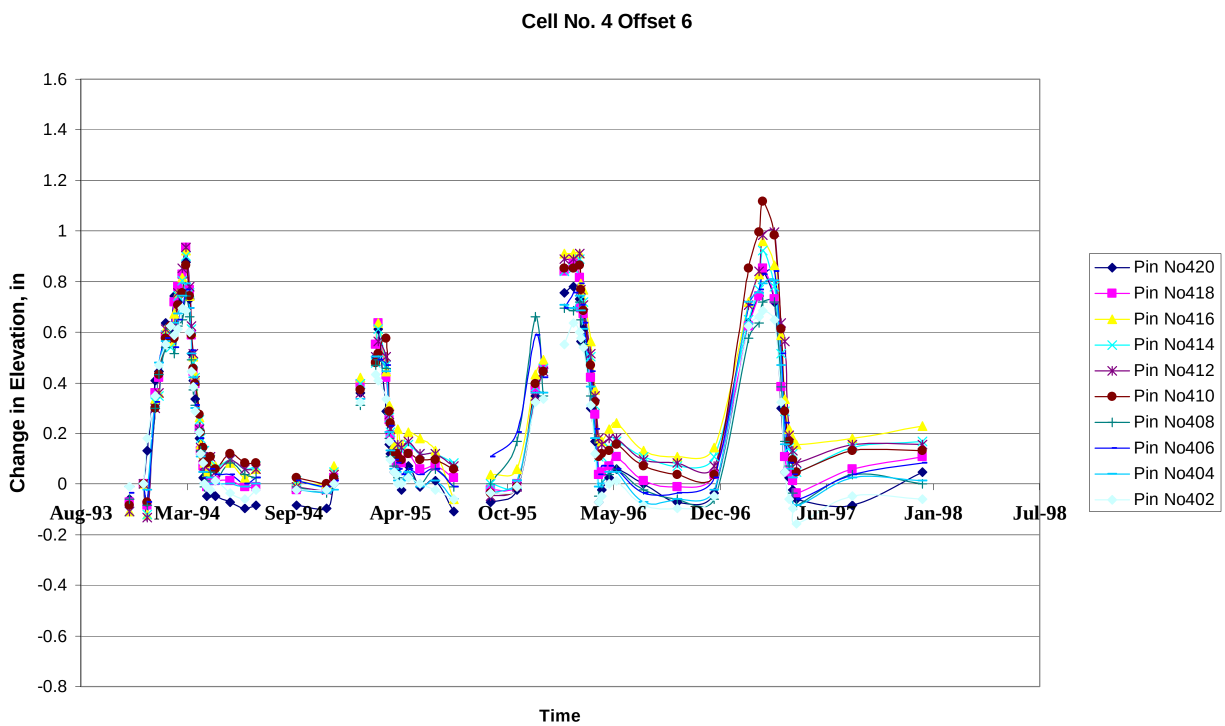
- Each field on this table represents the RANGE of change in elevation for a particular pin. For a particular pin, the maximum and minimum of the change in elevation is determined from all the reported data over the total period. Then the RANGE is calculated by taking the difference between the maximum and minimum values of change in elevation.

Appendix C

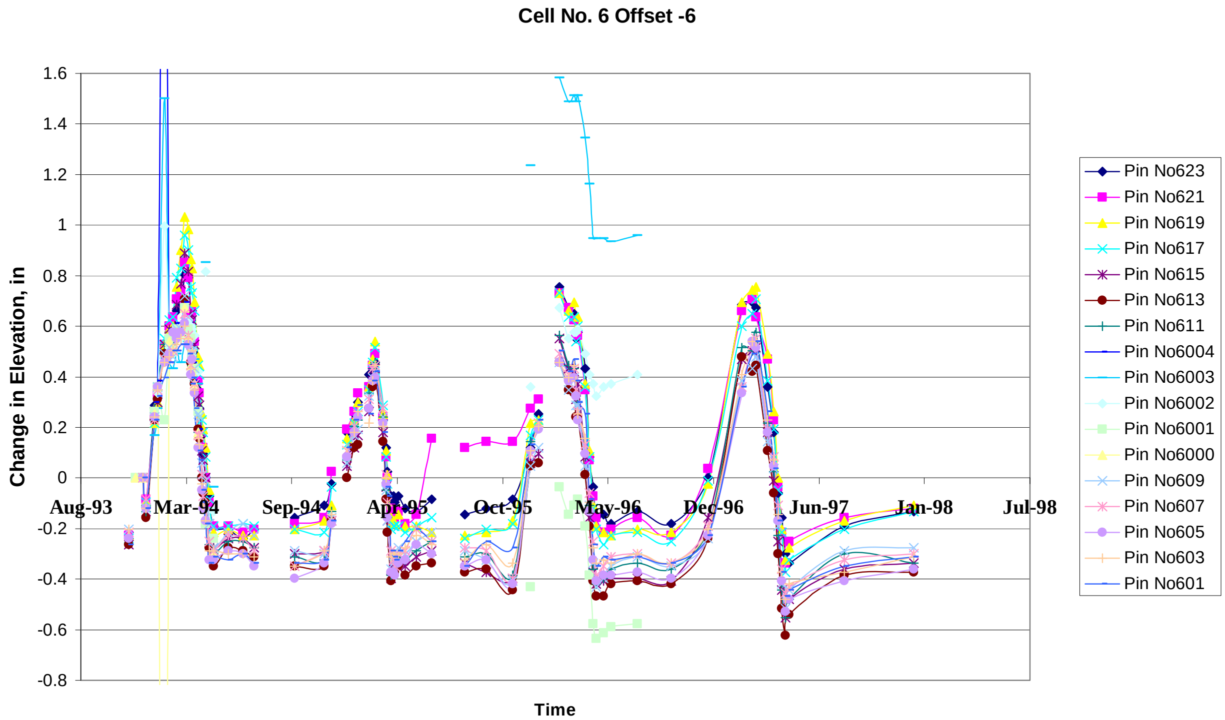
Changes in Elevation for Individual Pins



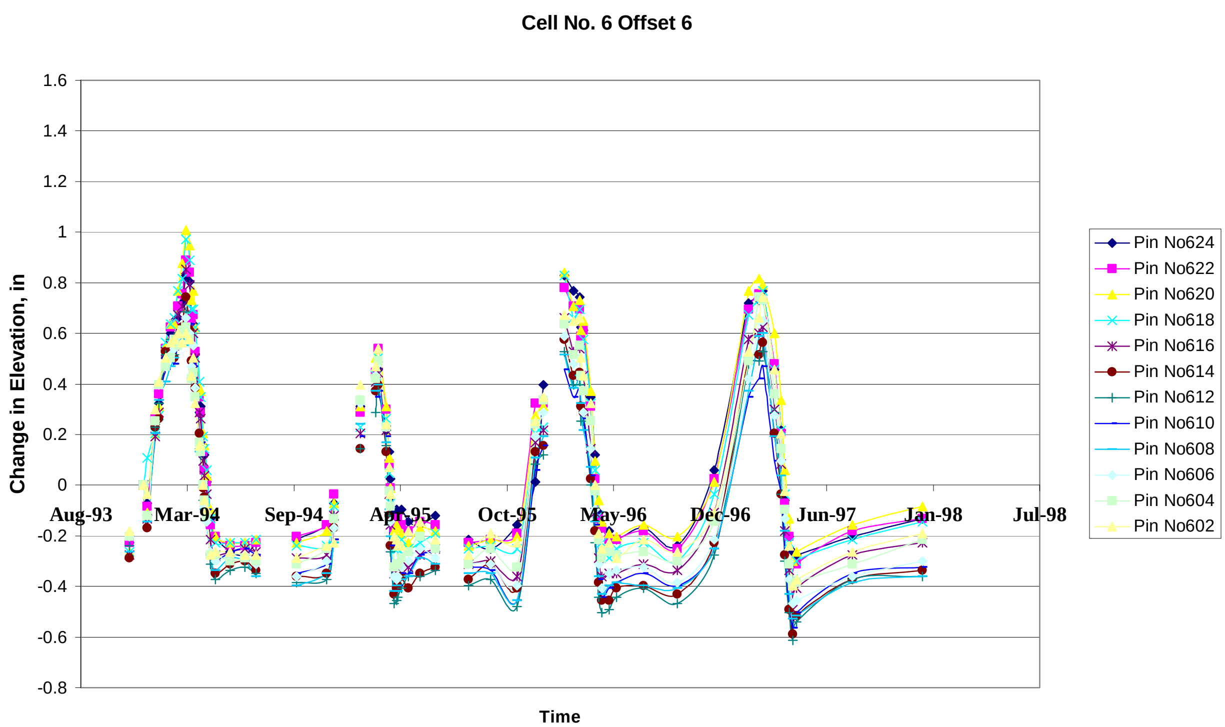
Change in Pin Elevations for Passing Lane of Cell 4



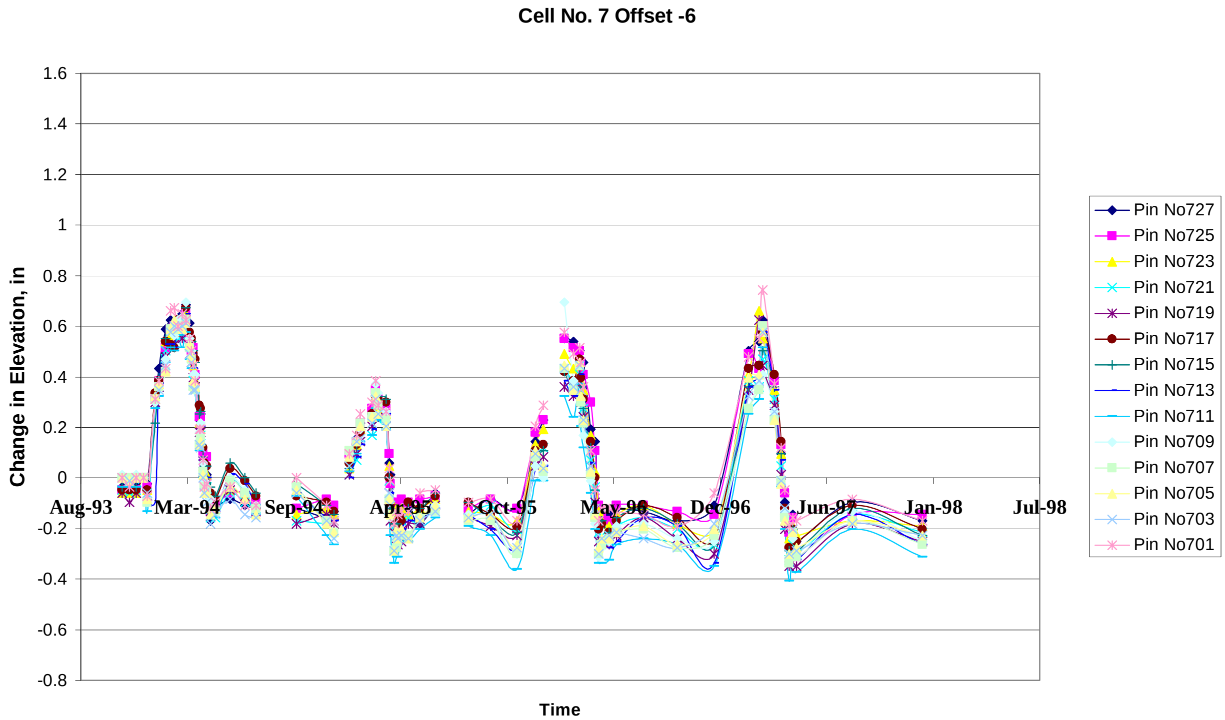
Change in Pin Elevations for Driving Lane of Cell 4



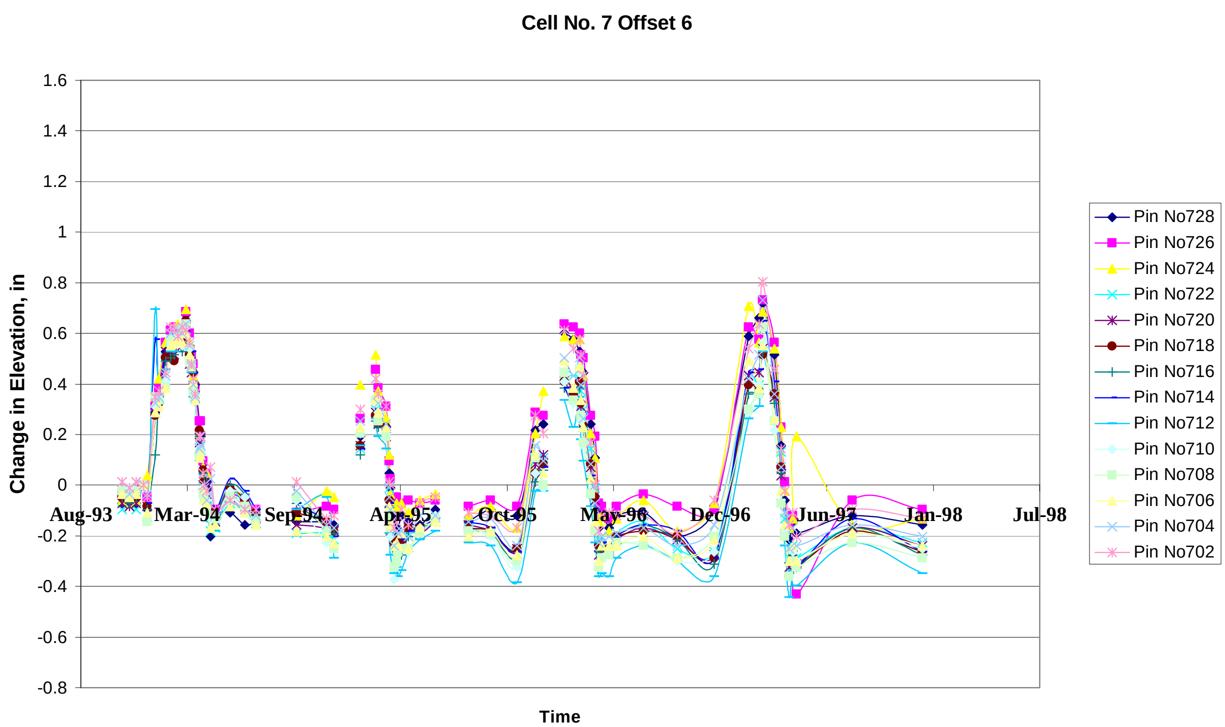
Change in Pin Elevations for Passing Lane of Cell 6



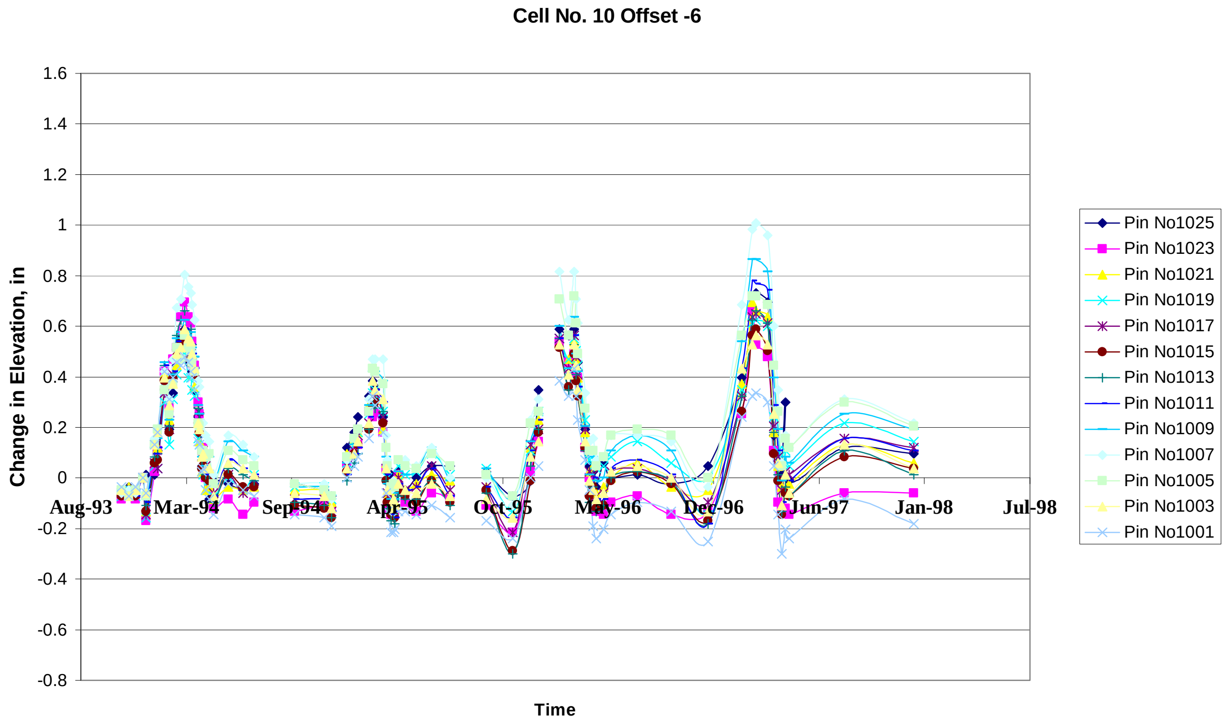
Change in Pin Elevations for Driving Lane of Cell 6



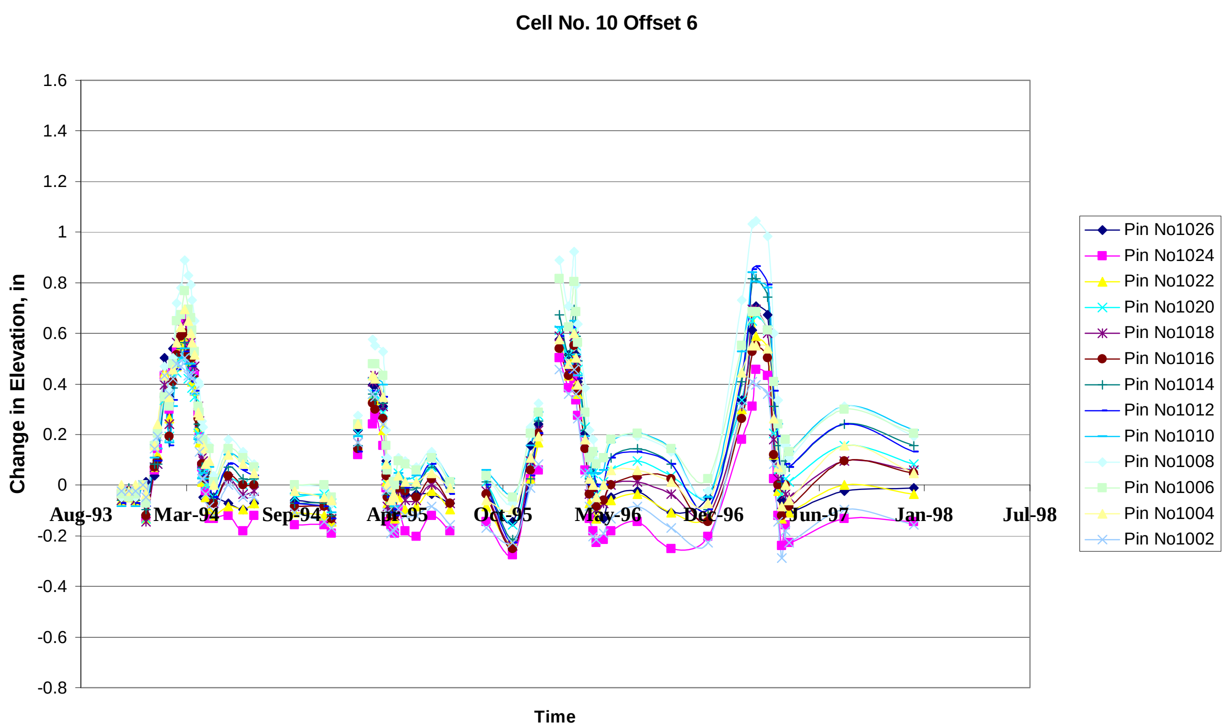
Change in Pin Elevations for Passing Lane of Cell 7



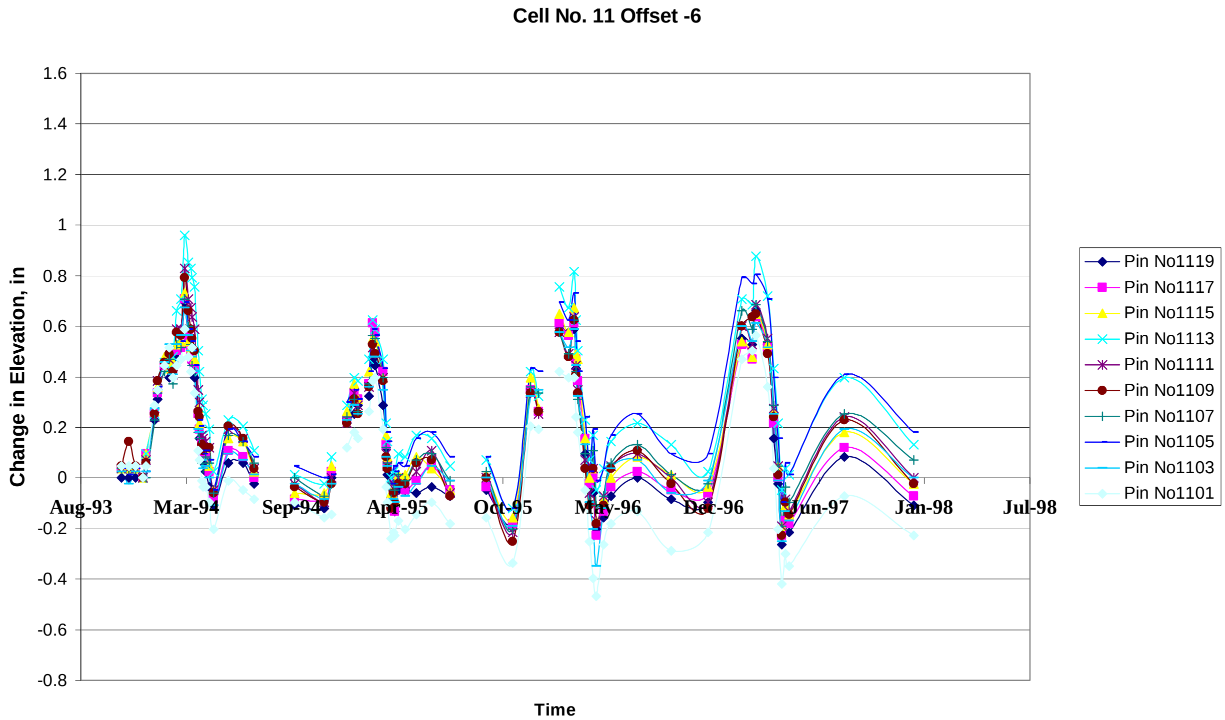
Change in Pin Elevations for Driving Lane of Cell 7



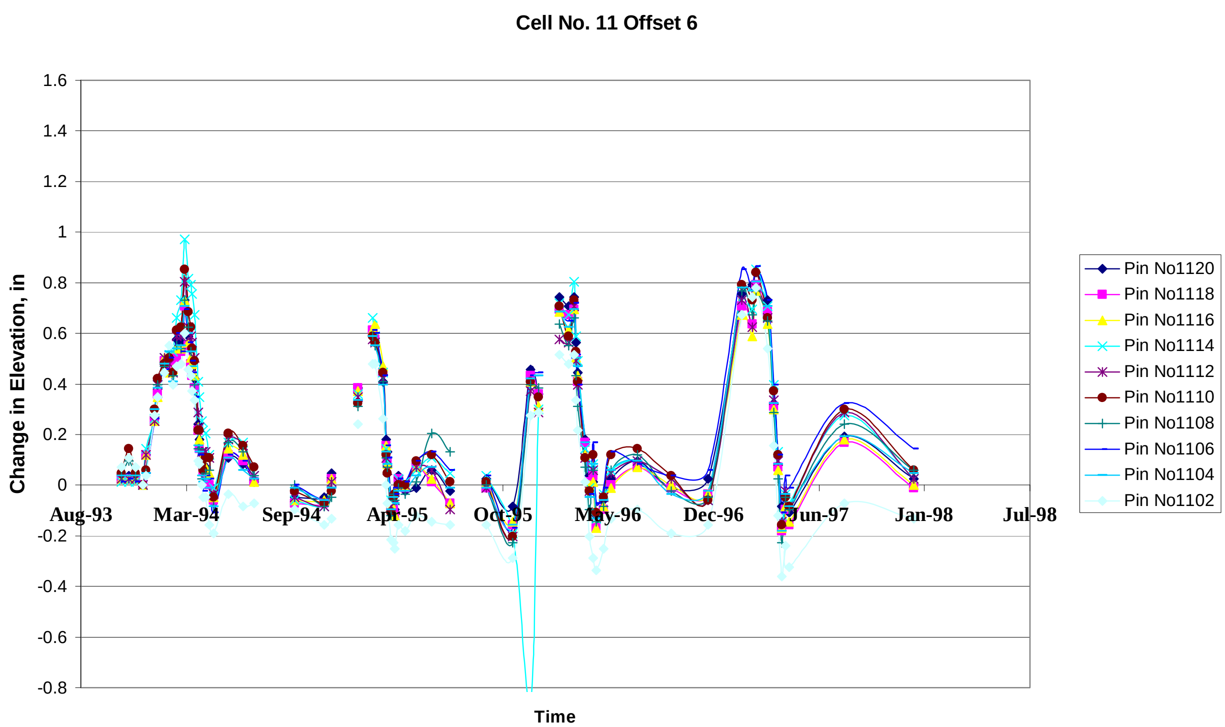
Change in Pin Elevations for Passing Lane of Cell 10



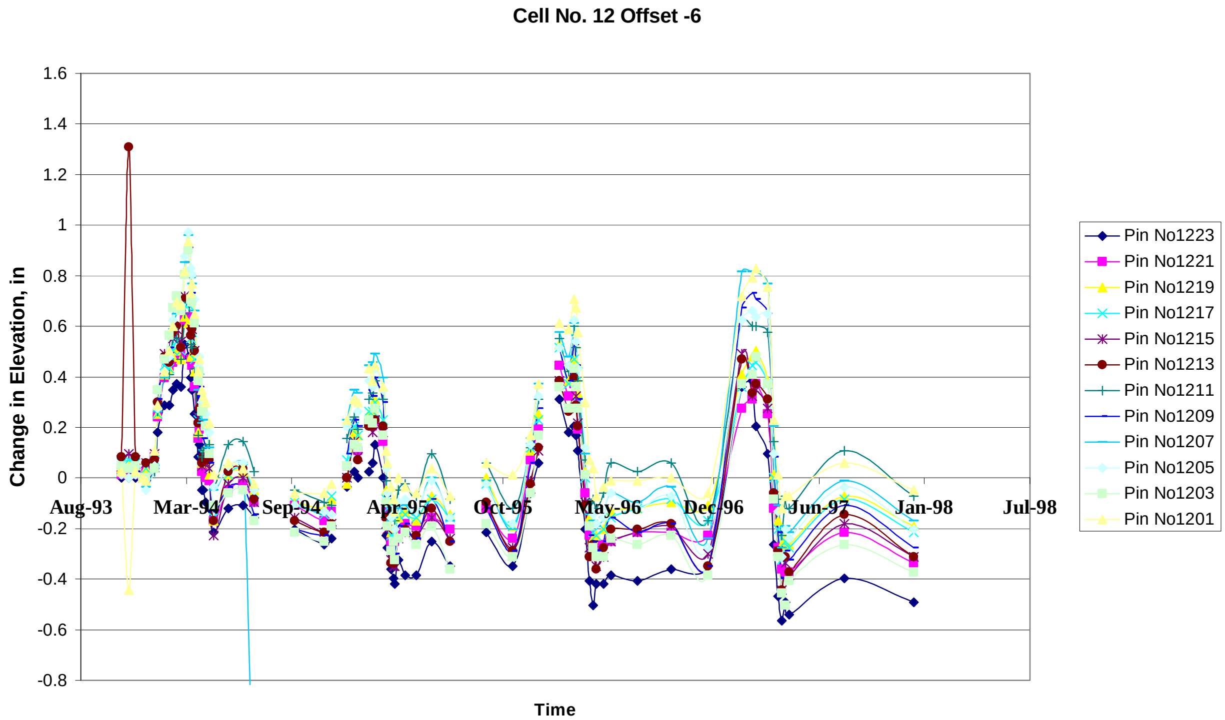
Change in Pin Elevations for Driving Lane of Cell 10



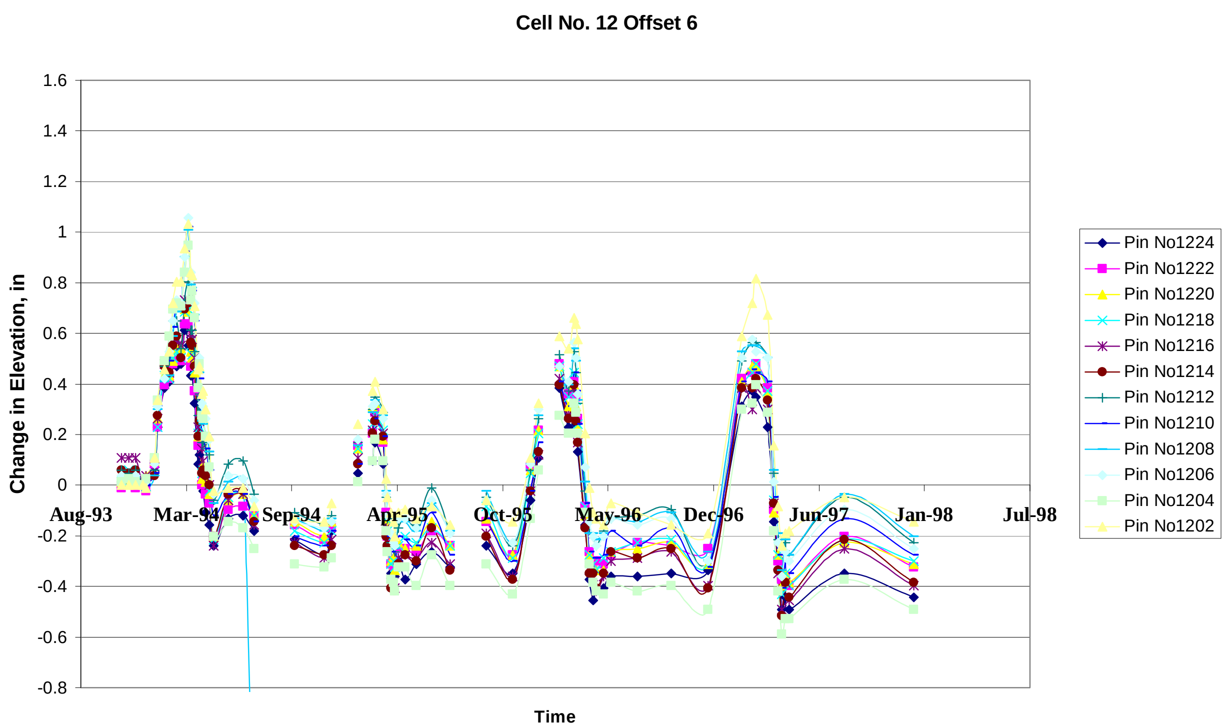
Change in Pin Elevations for Passing Lane of Cell 11



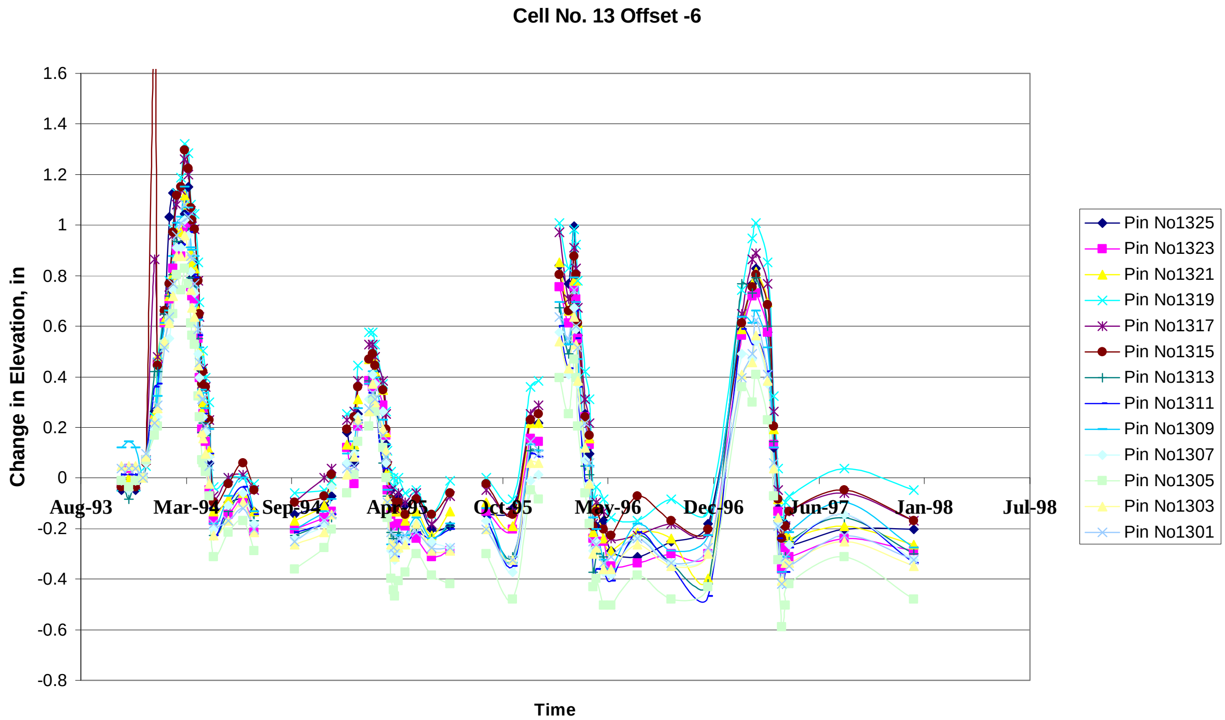
Change in Pin Elevations for Driving Lane of Cell 11



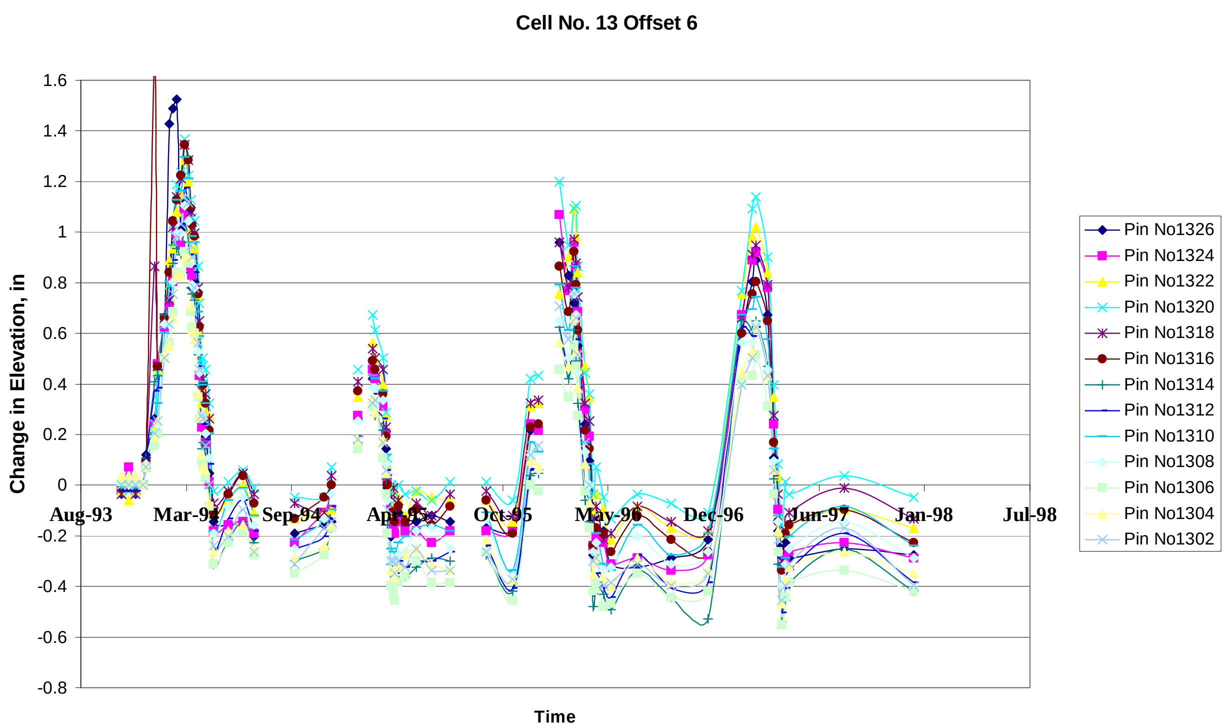
Change in Pin Elevations for Passing Lane of Cell 12



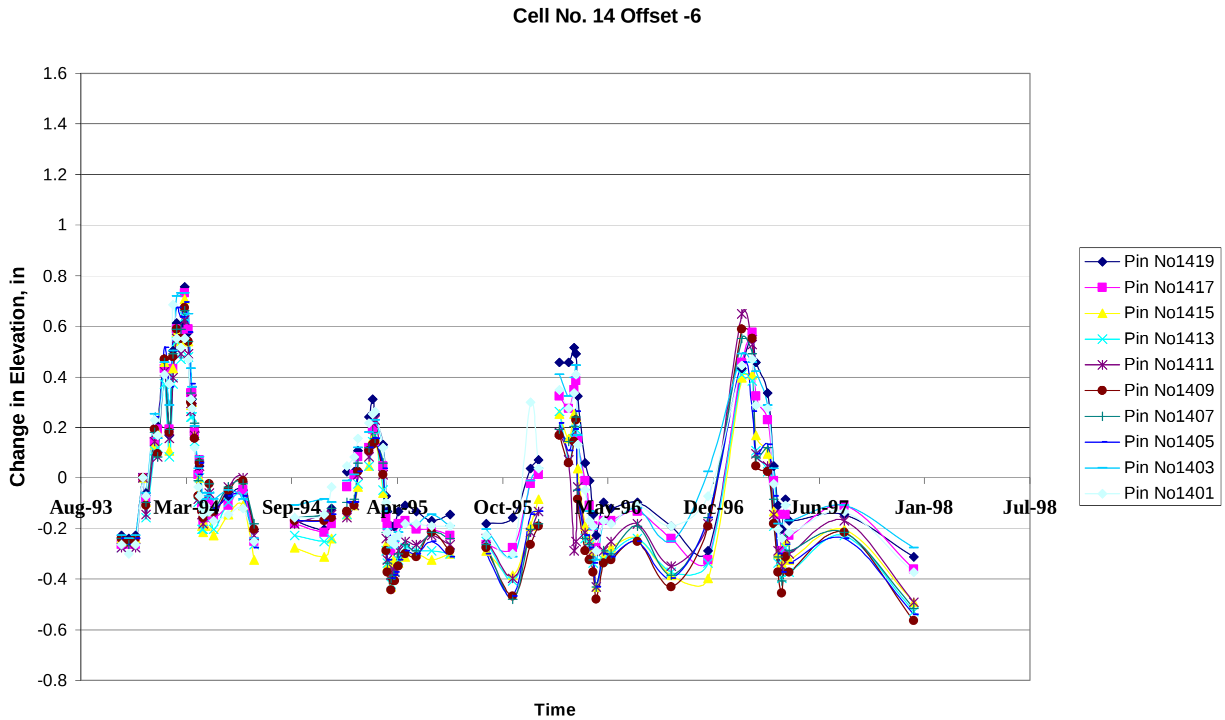
Change in Pin Elevations for Driving Lane of Cell 12



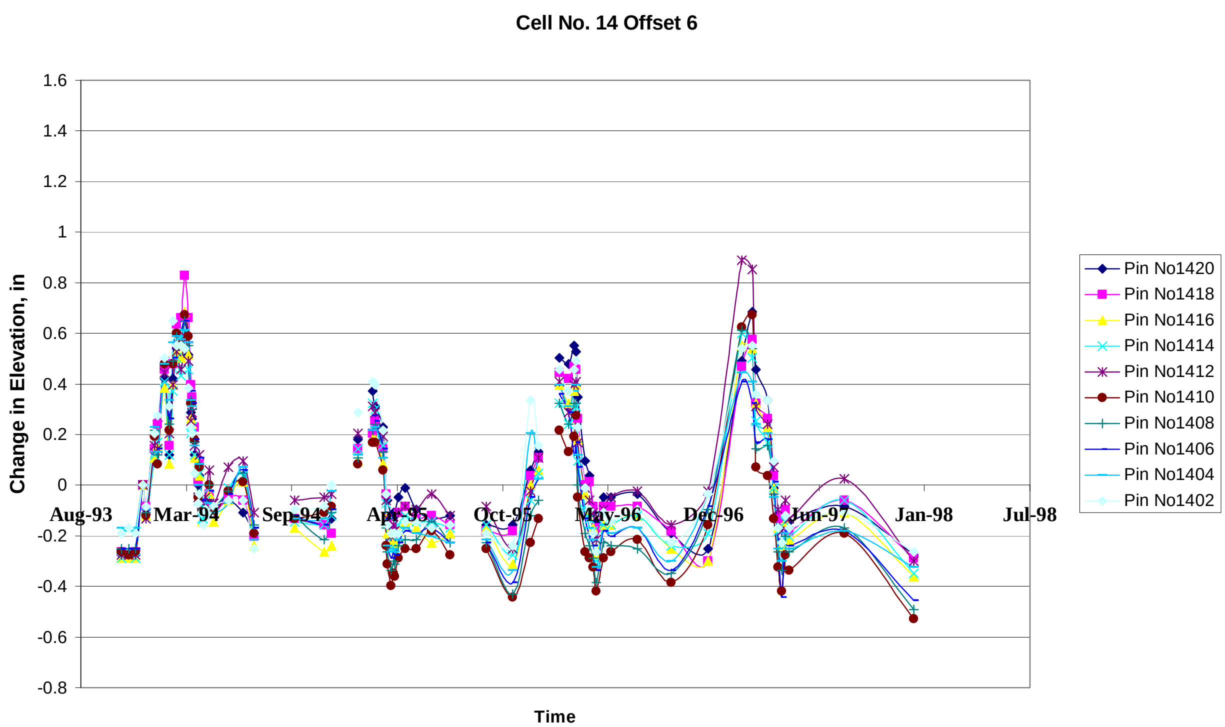
Change in Pin Elevations for Passing Lane of Cell 13



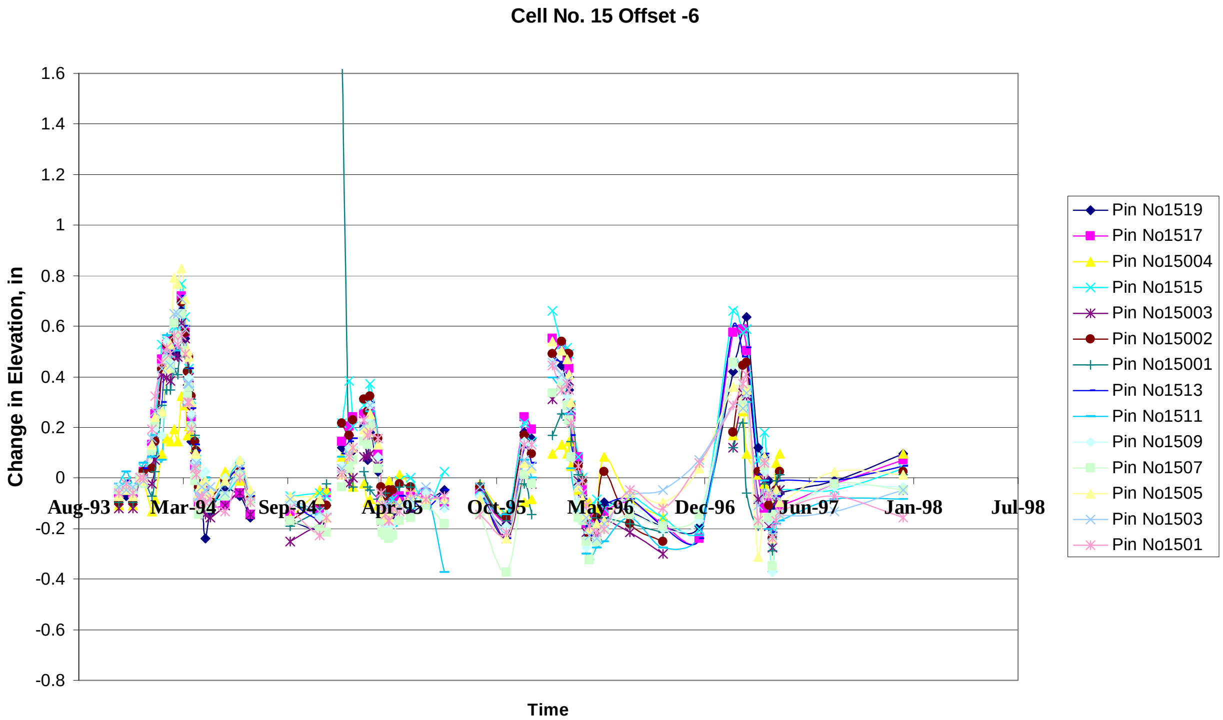
Change in Pin Elevations for Driving Lane of Cell 13



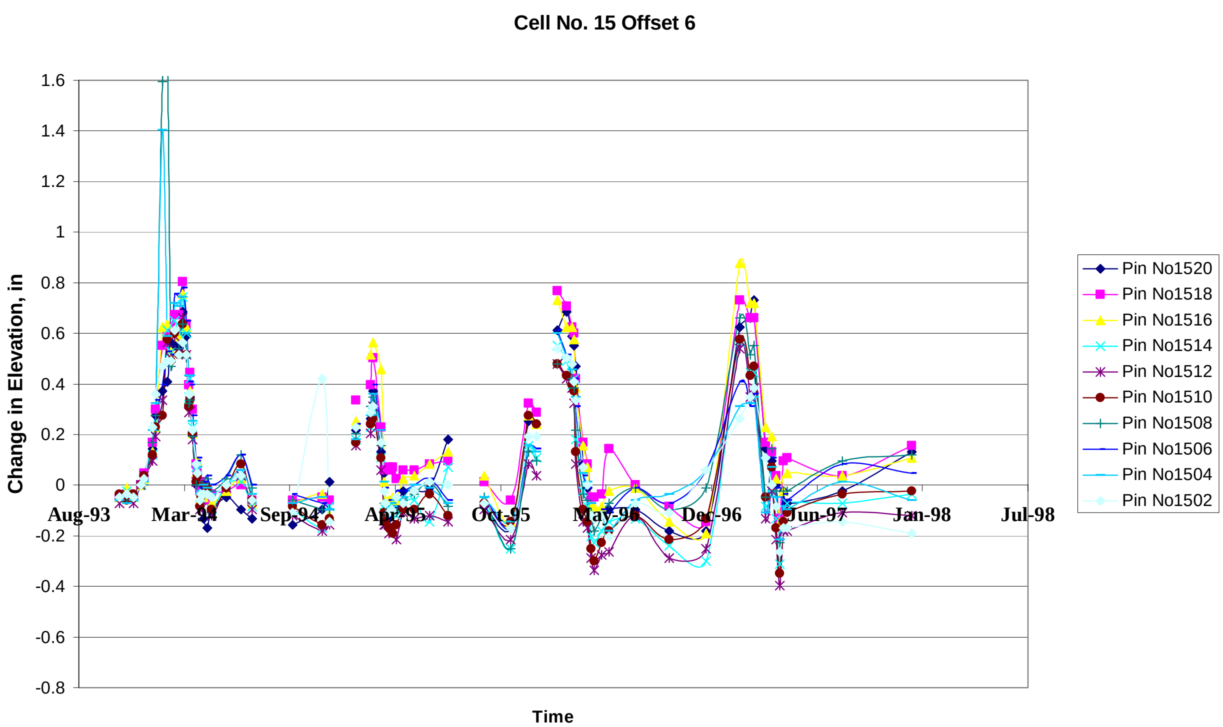
Change in Pin Elevations for Passing Lane of Cell 14



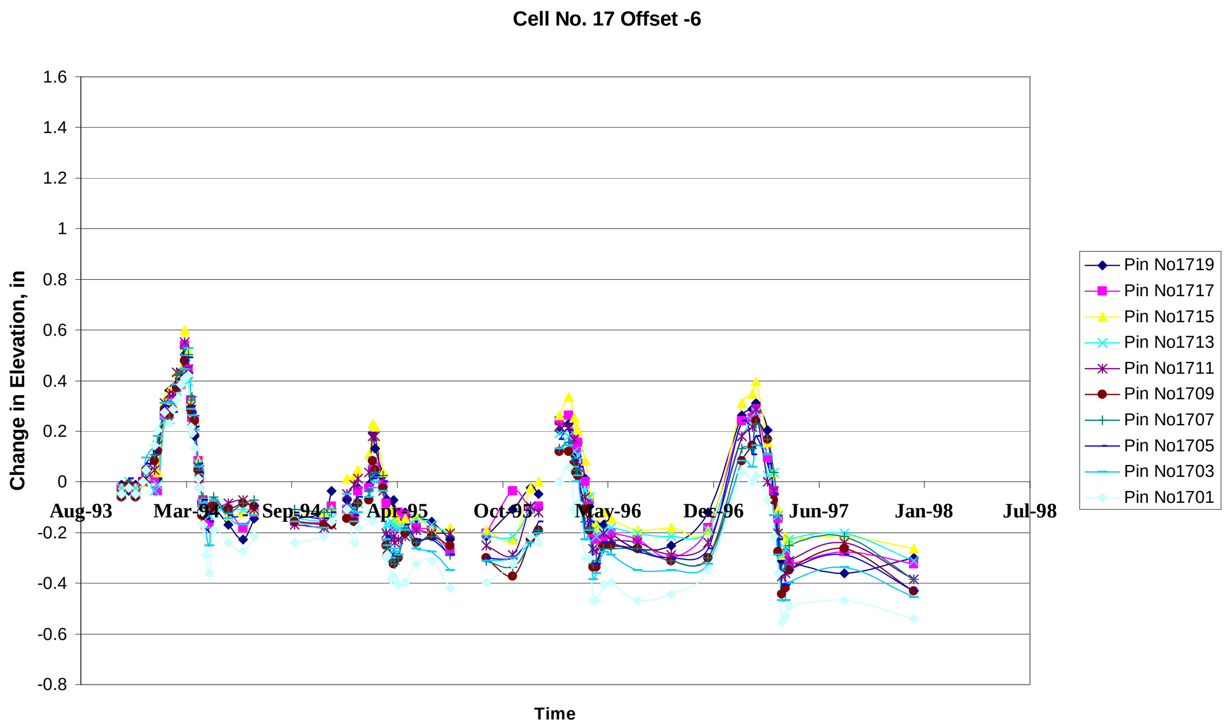
Change in Pin Elevations for Driving Lane of Cell 14



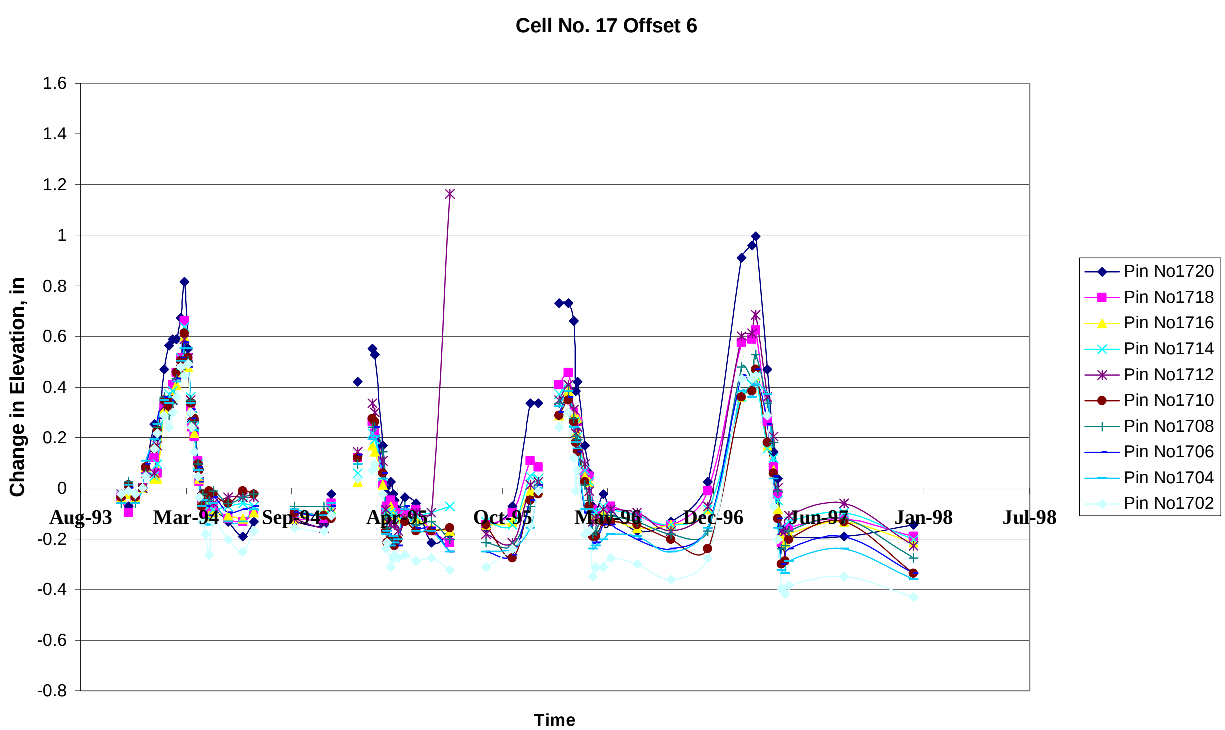
Change in Pin Elevations for Passing Lane of Cell 15



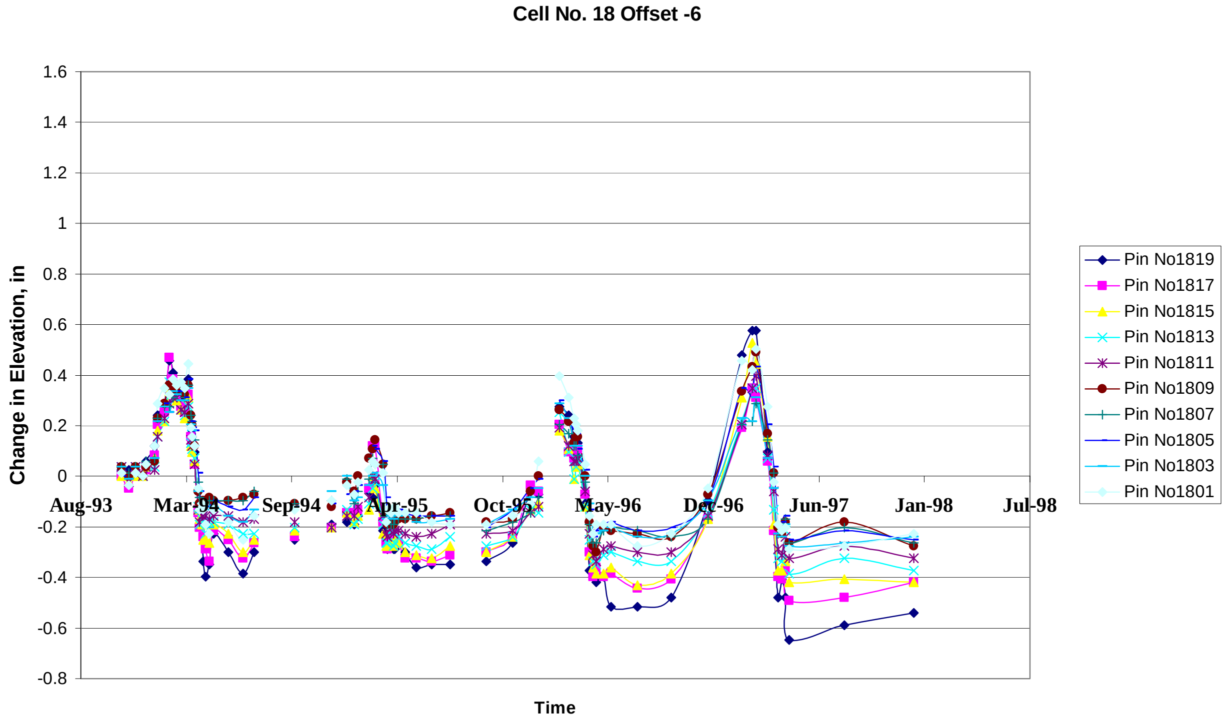
Change in Pin Elevations for Driving Lane of Cell 15



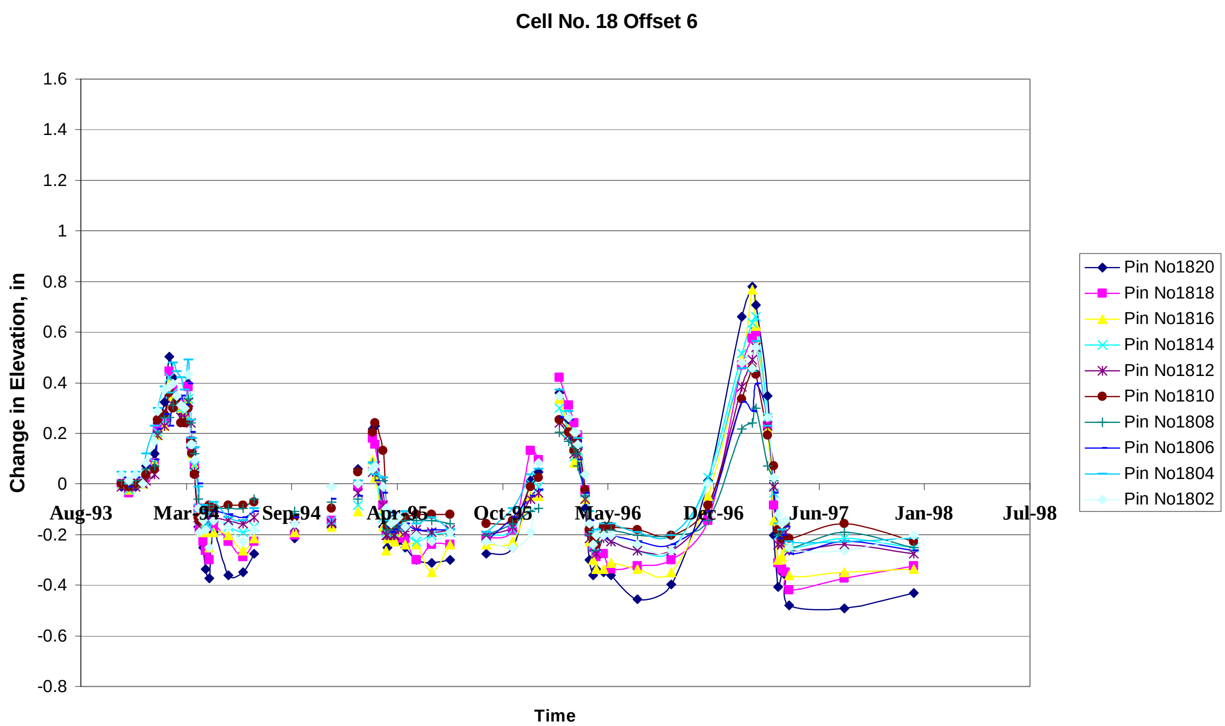
Change in Pin Elevations for Passing Lane of Cell 17



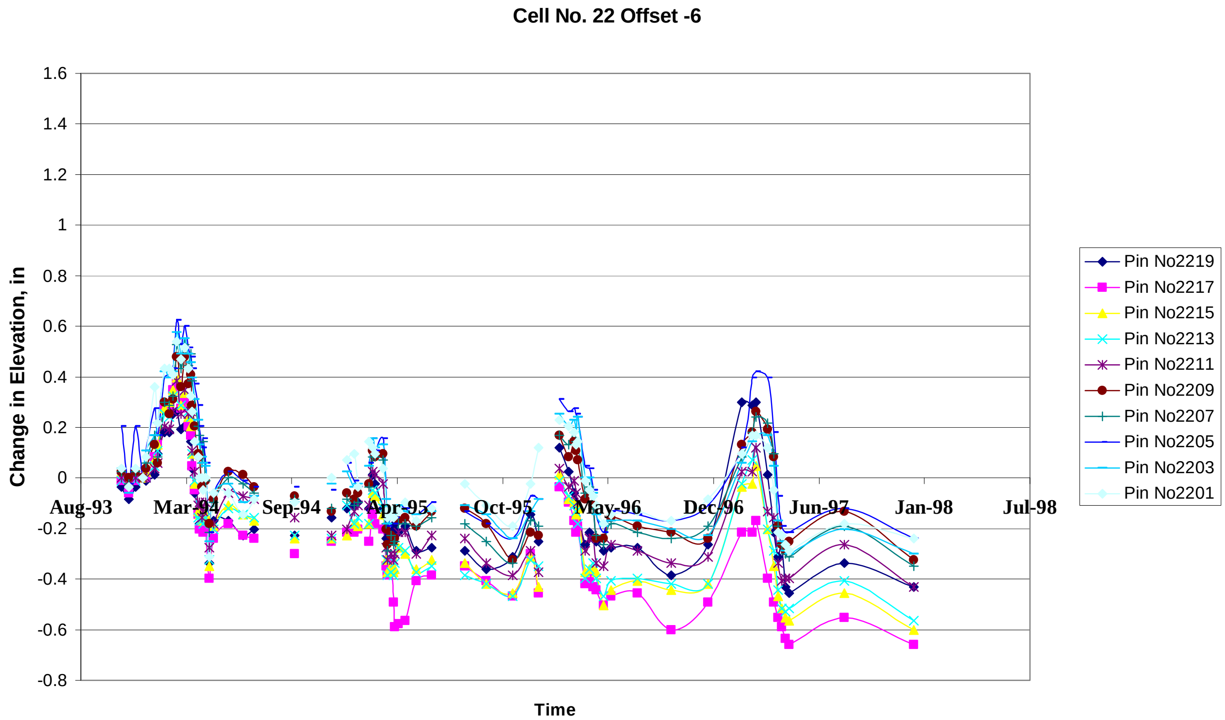
Change in Pin Elevations for Driving Lane of Cell 17



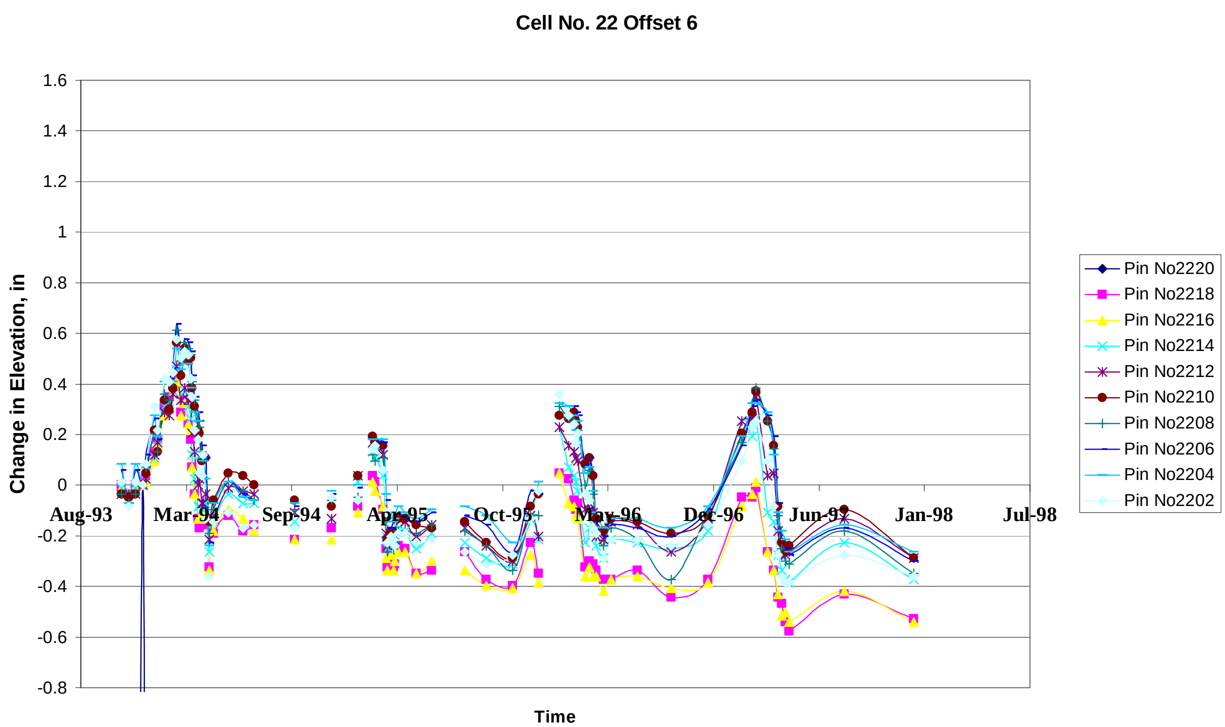
Change in Pin Elevations for Passing Lane of Cell 18



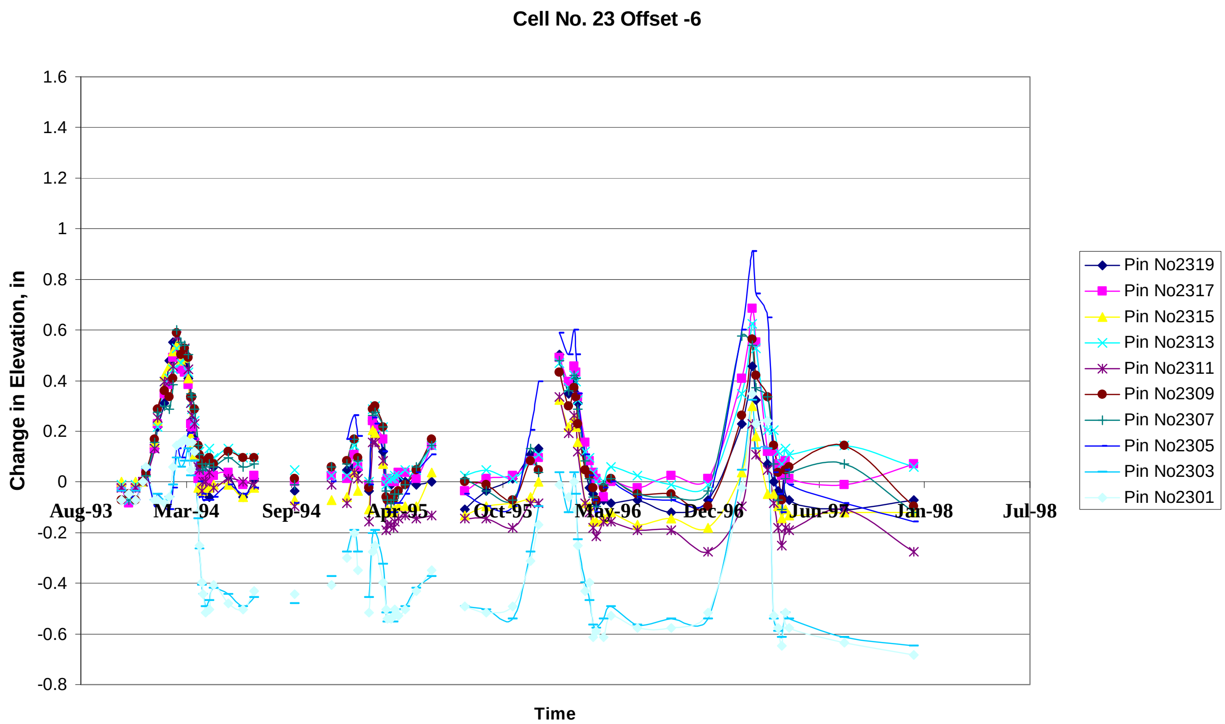
Change in Pin Elevations for Driving Lane of Cell 18



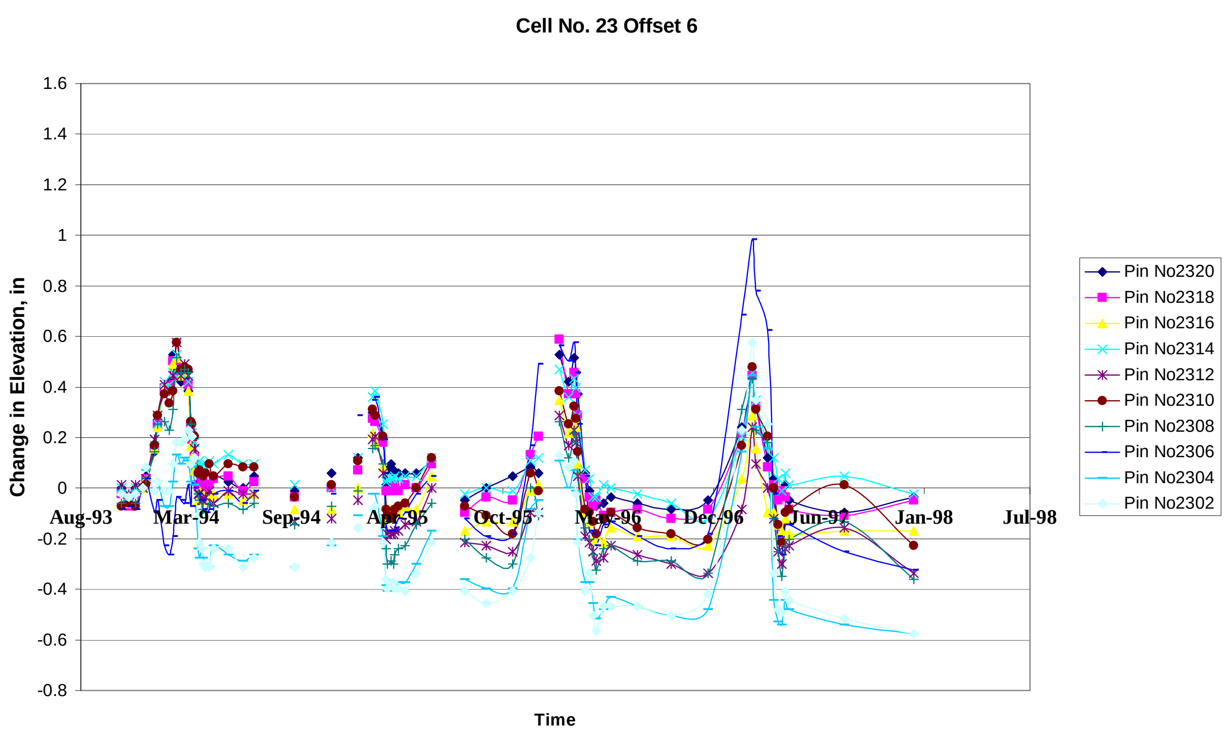
Change in Pin Elevations for Passing Lane of Cell 22



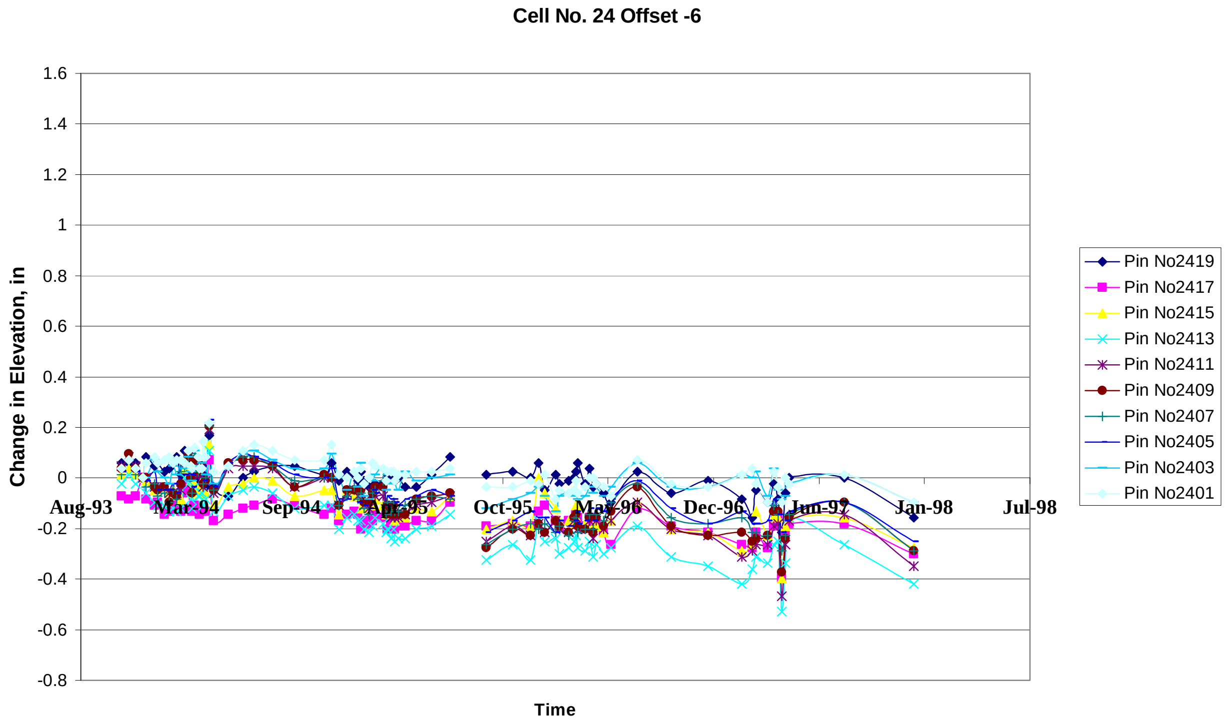
Change in Pin Elevations for Driving Lane of Cell 22



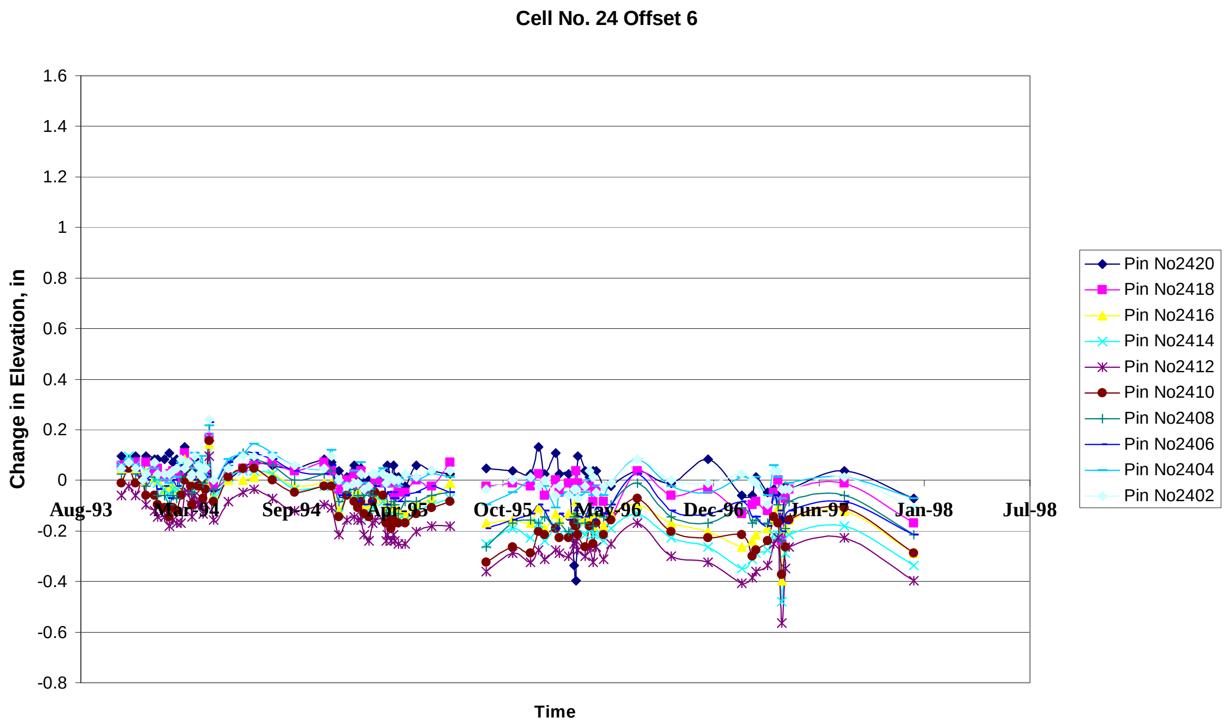
Change in Pin Elevations for Passing Lane of Cell 23



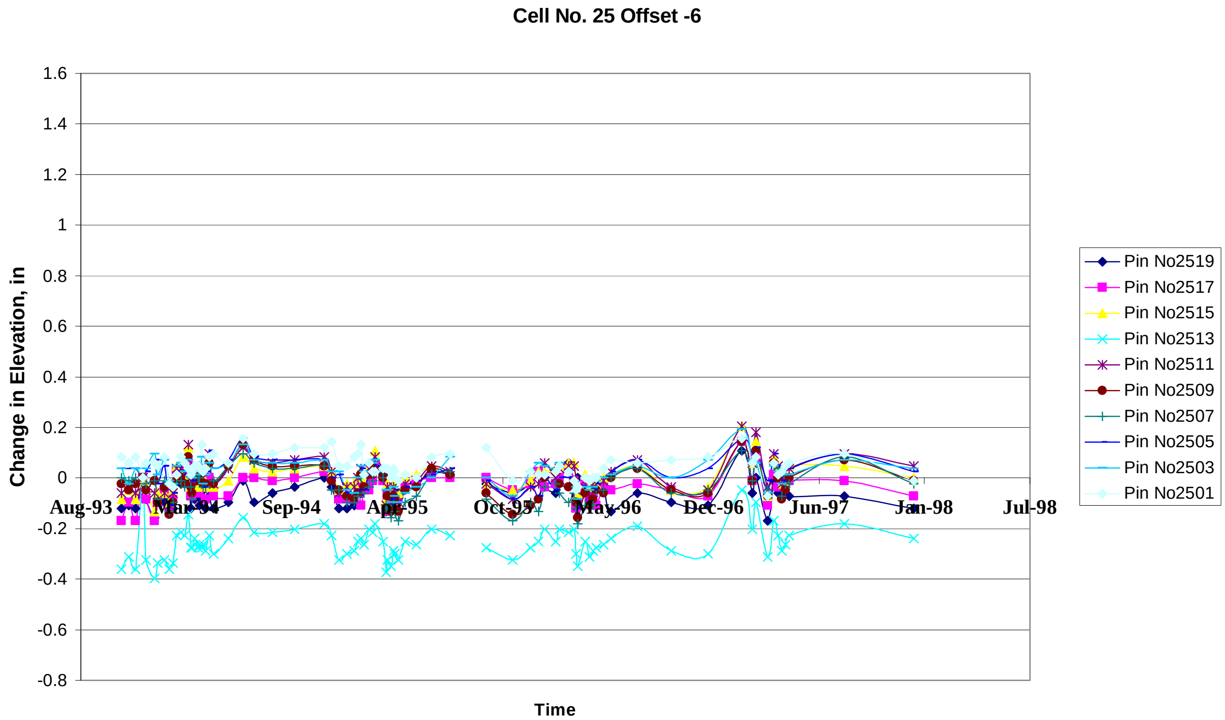
Change in Pin Elevations for Driving Lane of Cell 23



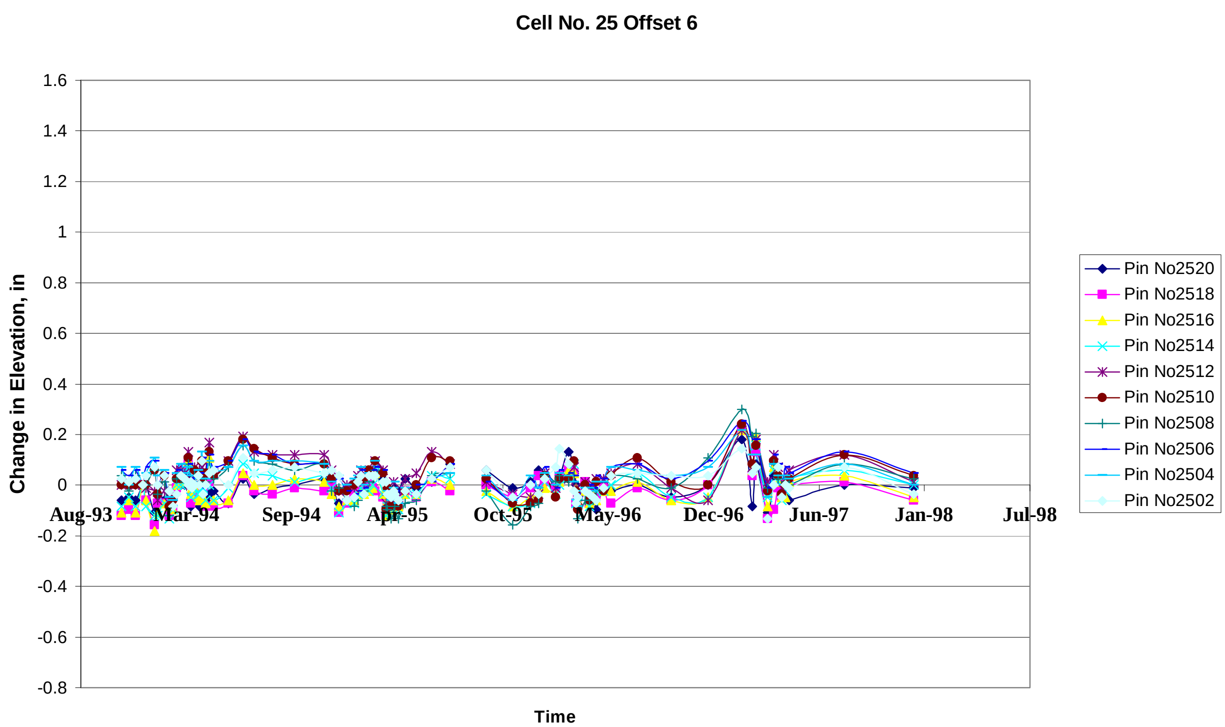
Change in Pin Elevations for 80K Lane of Cell 24



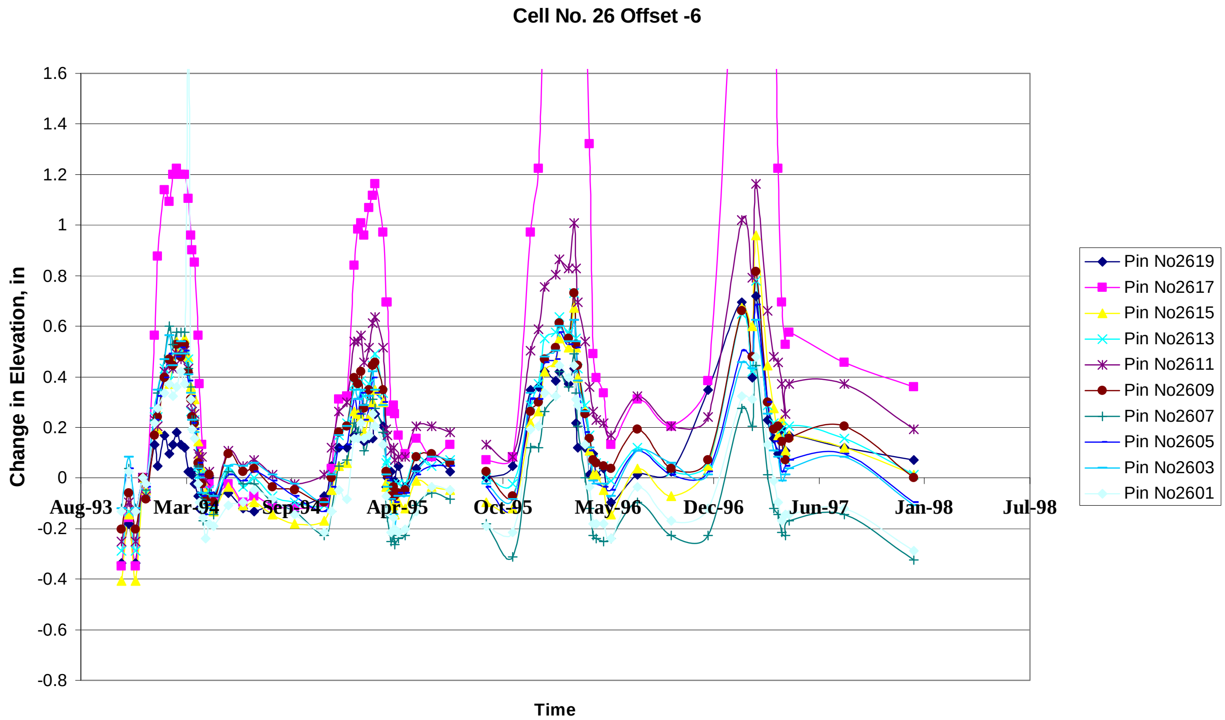
Change in Pin Elevations for 102K Lane of Cell 24



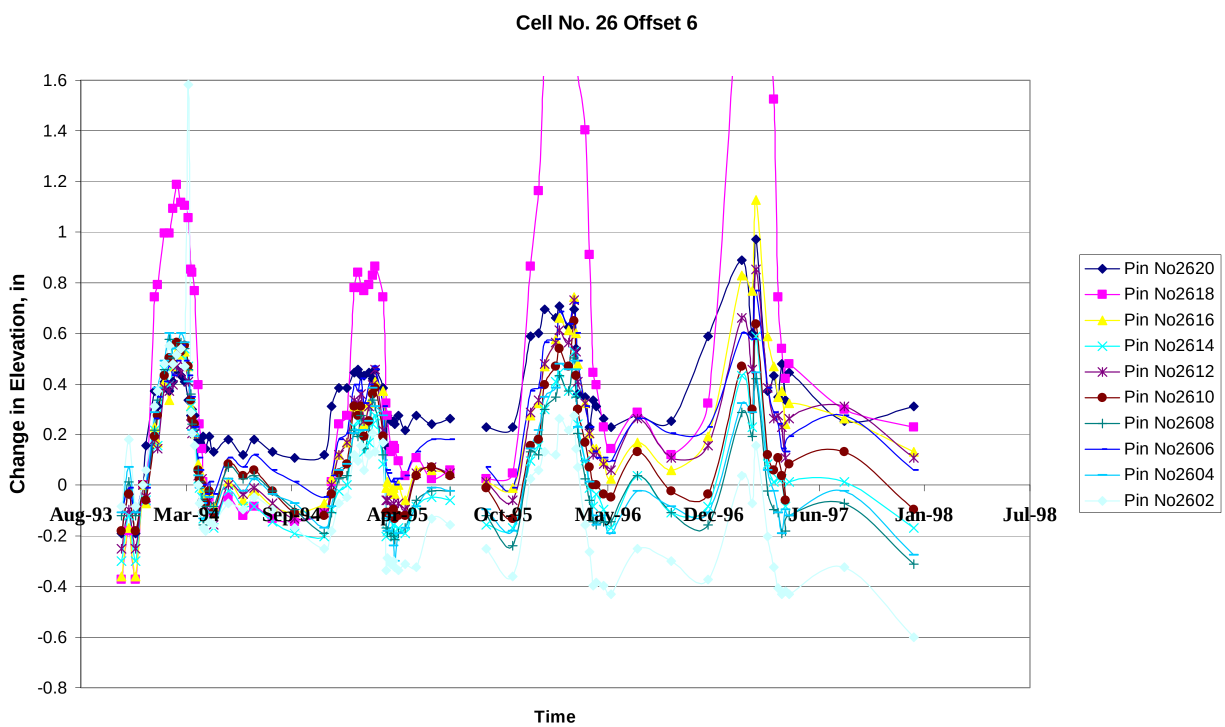
Change in Pin Elevations for 80K Lane of Cell 25



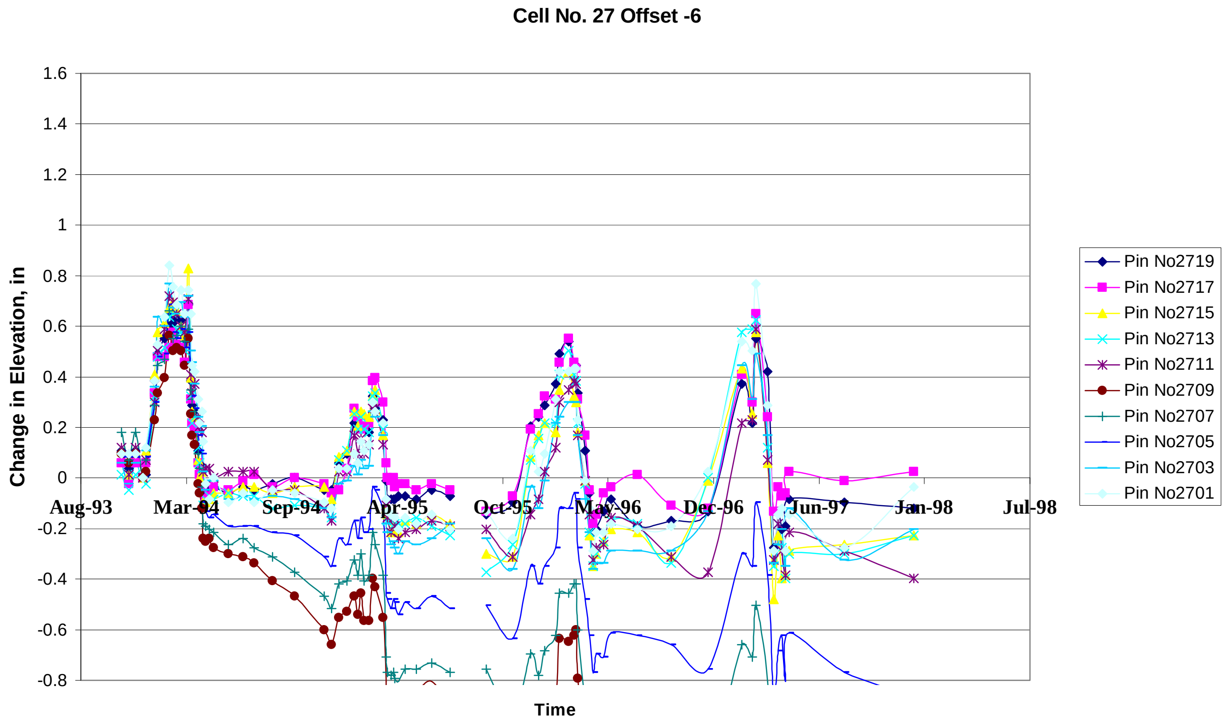
Change in Pin Elevations for 102K Lane of Cell 25



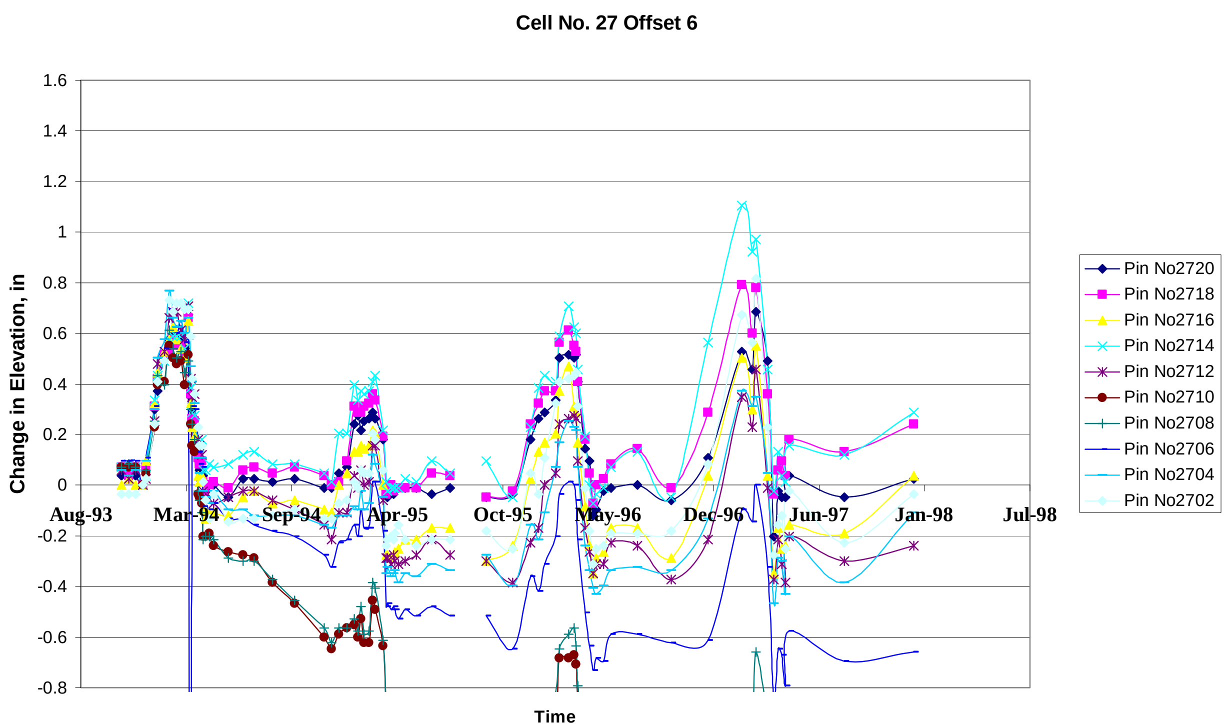
Change in Pin Elevations for 80K Lane of Cell 26



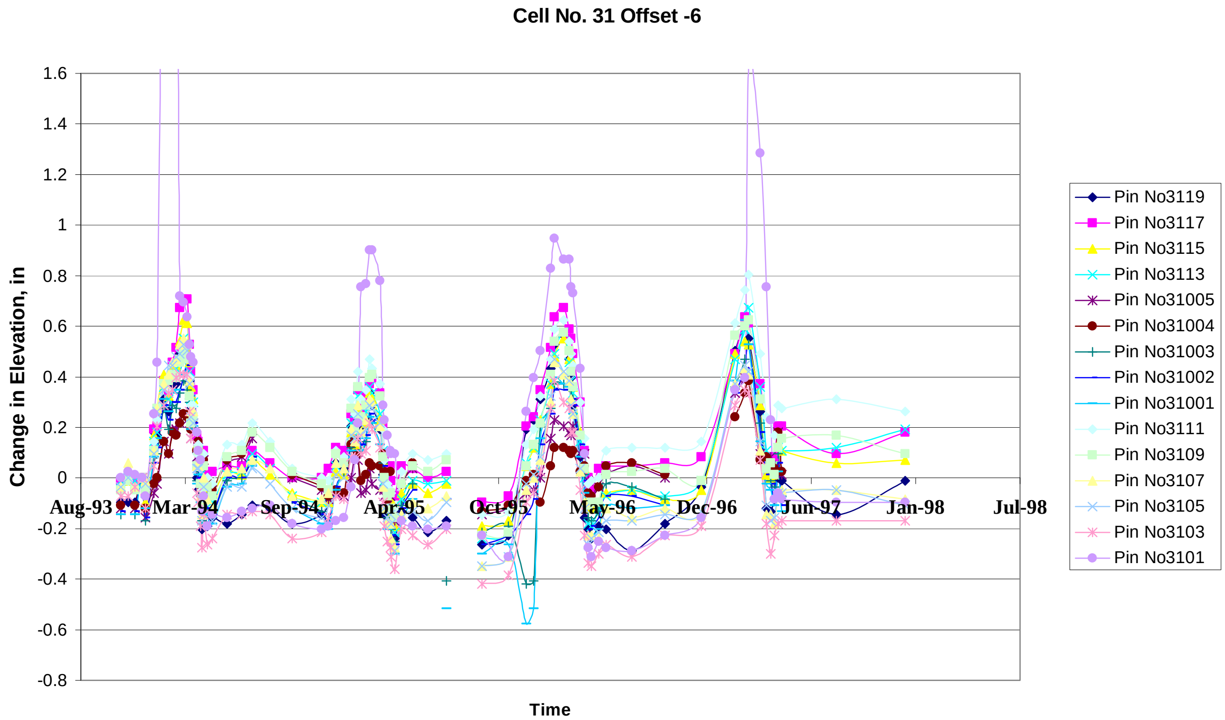
Change in Pin Elevations for 102K Lane of Cell 26



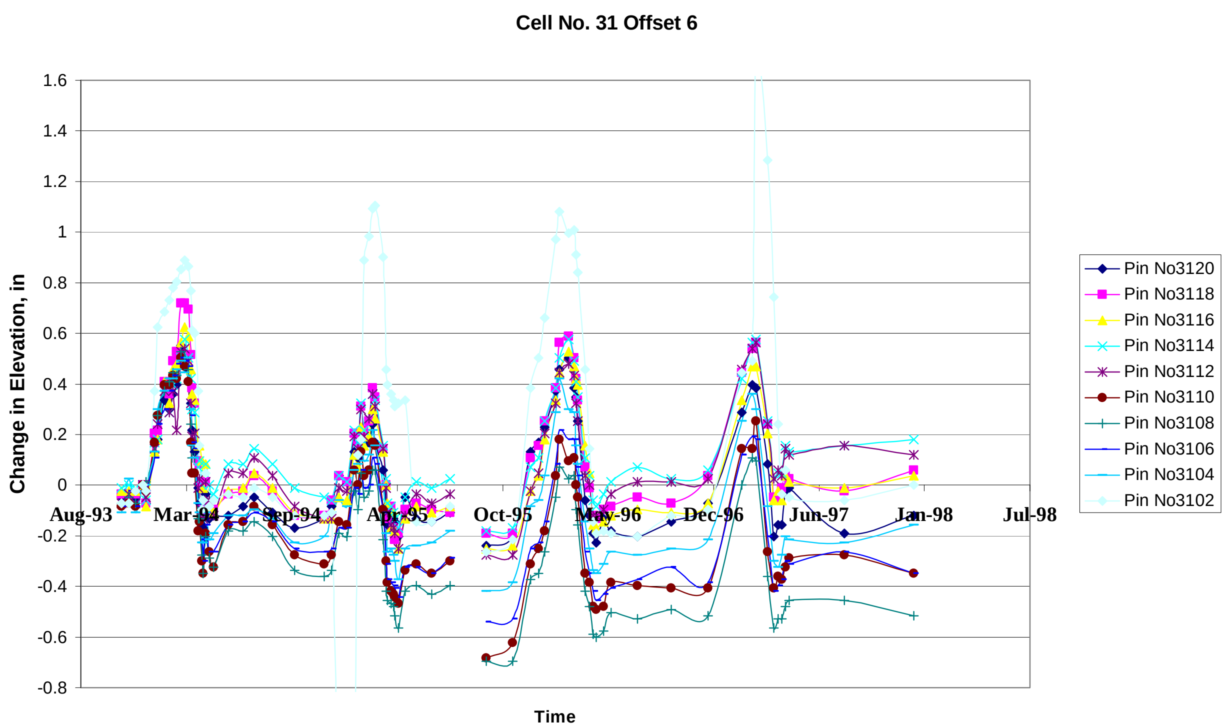
Change in Pin Elevations for 80K Lane of Cell 27



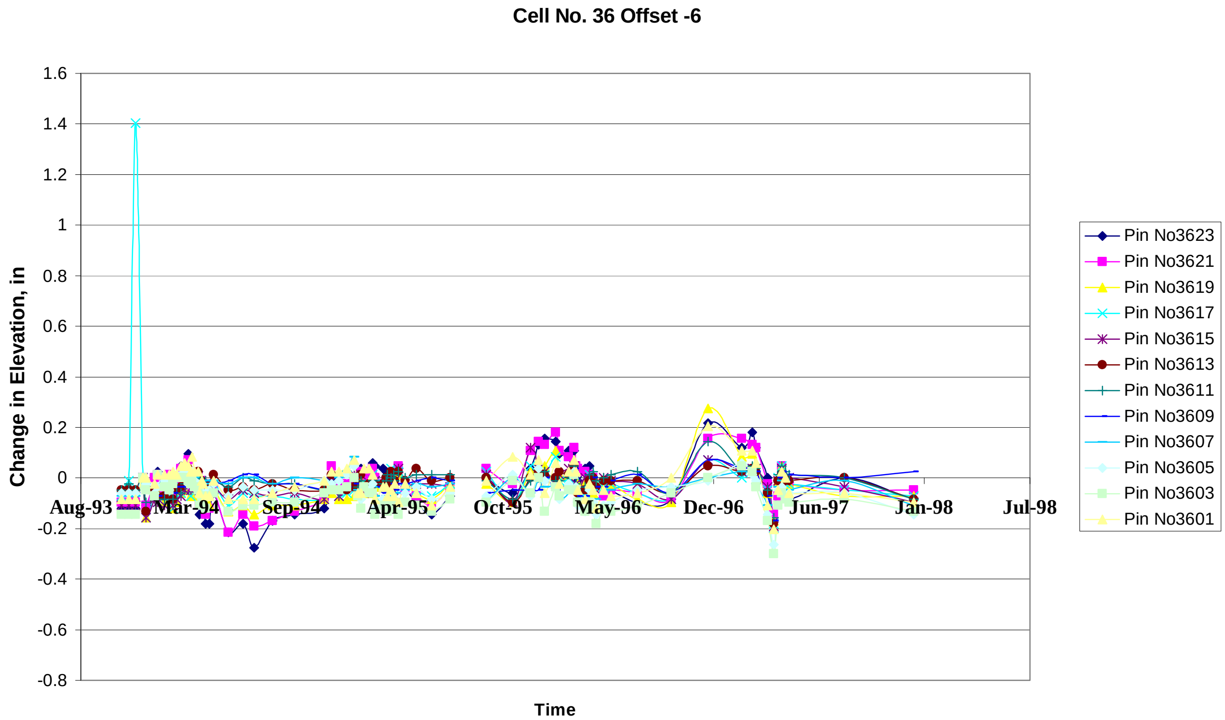
Change in Pin Elevations for 102K Lane of Cell 27



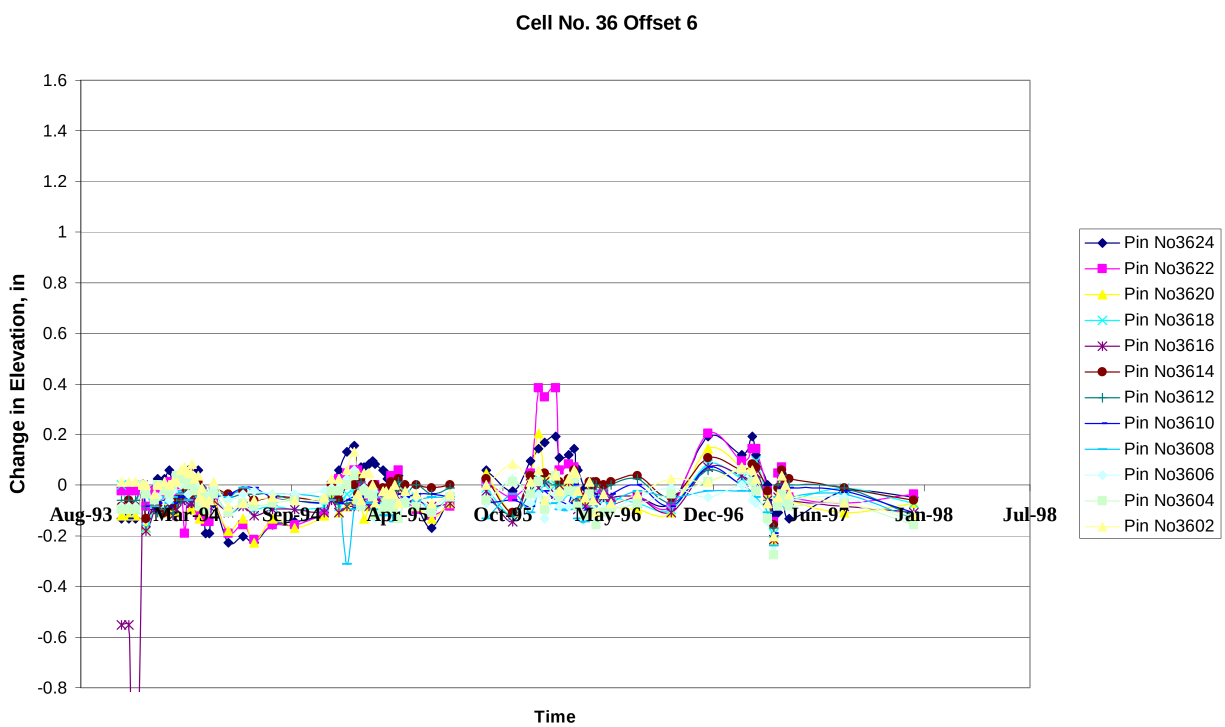
Change in Pin Elevations for 80K Lane of Cell 31



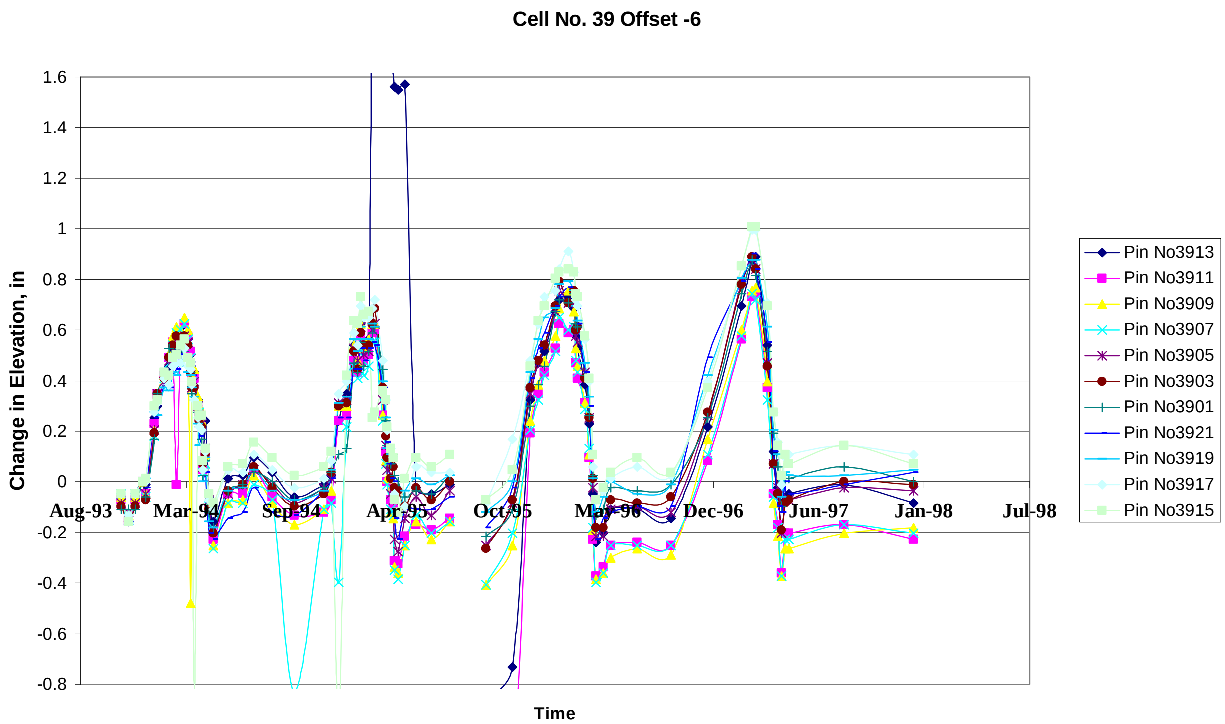
Change in Pin Elevations for 102K Lane of Cell 31



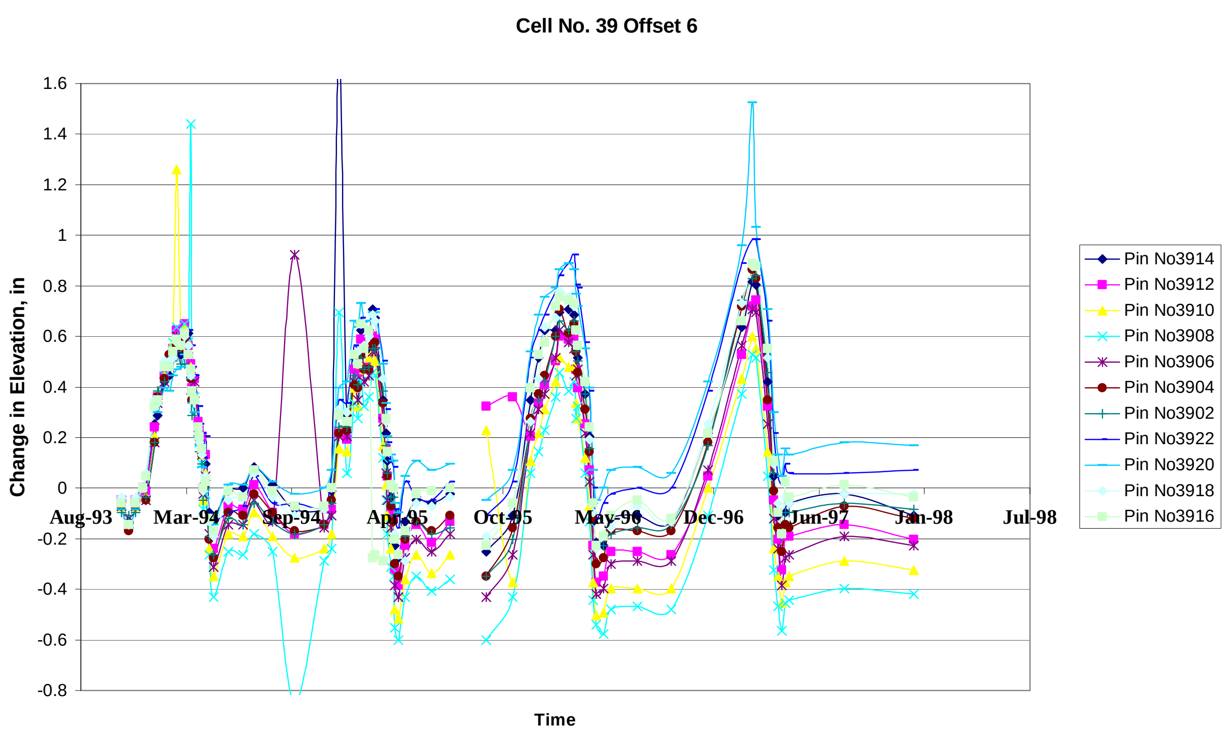
Change in Pin Elevations for 80K Lane of Cell 36



Change in Pin Elevations for 102K Lane of Cell 36



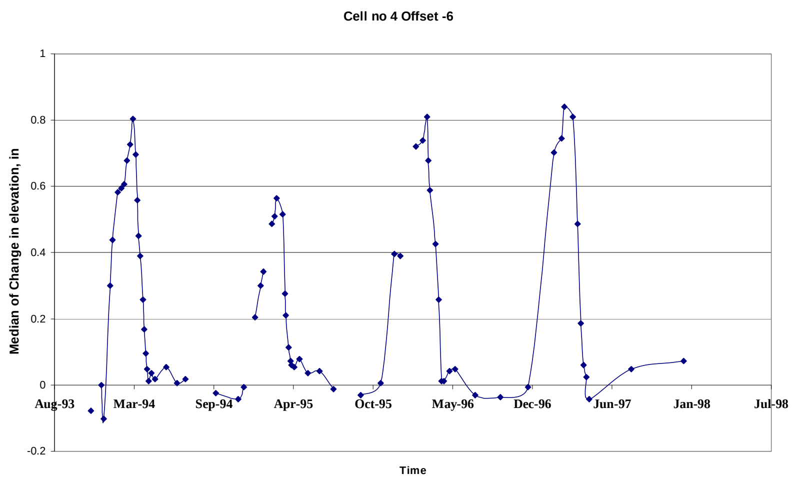
Change in Pin Elevations for 80K Lane of Cell 39

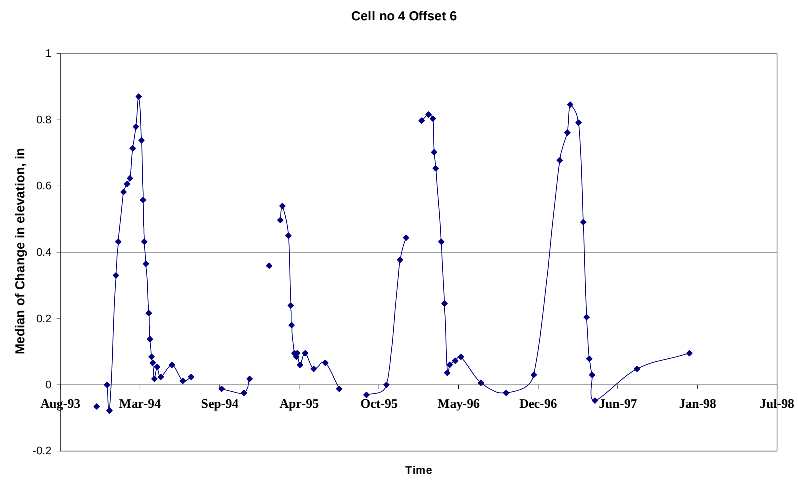


Change in Pin Elevations for 102K Lane of Cell 39

Appendix D

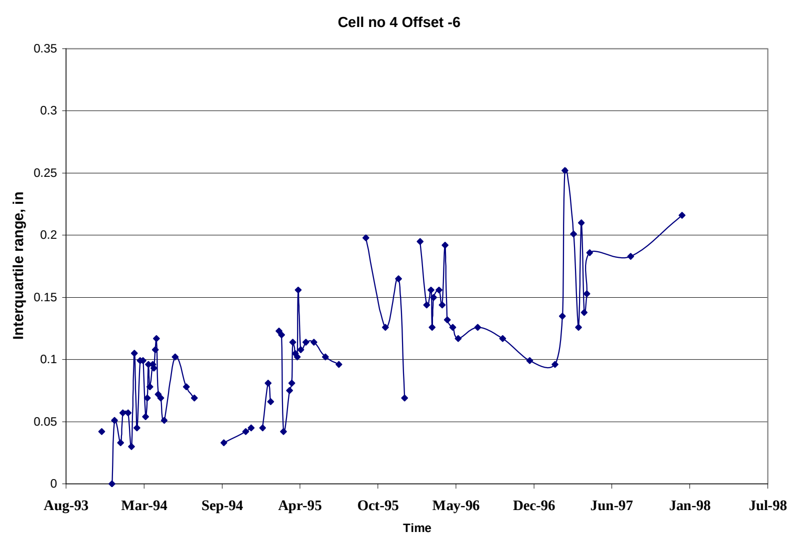
Median Value and Interquartile Range of Changes in Pin Values for Each Section

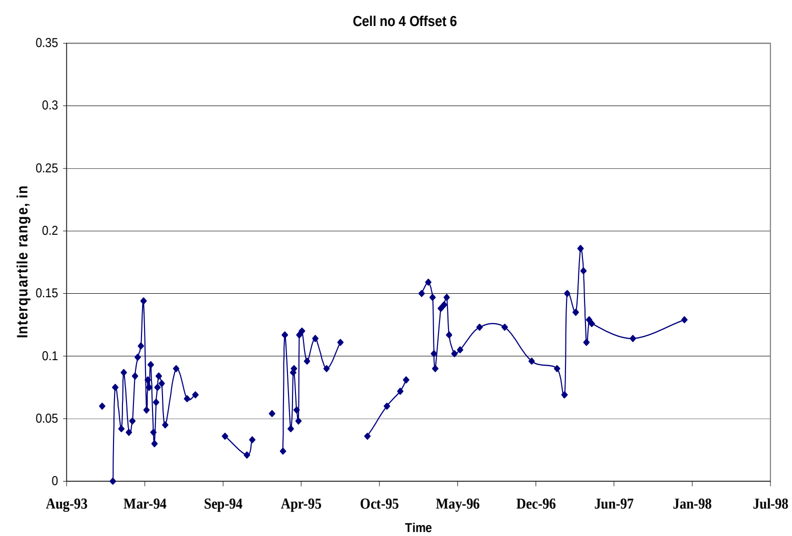




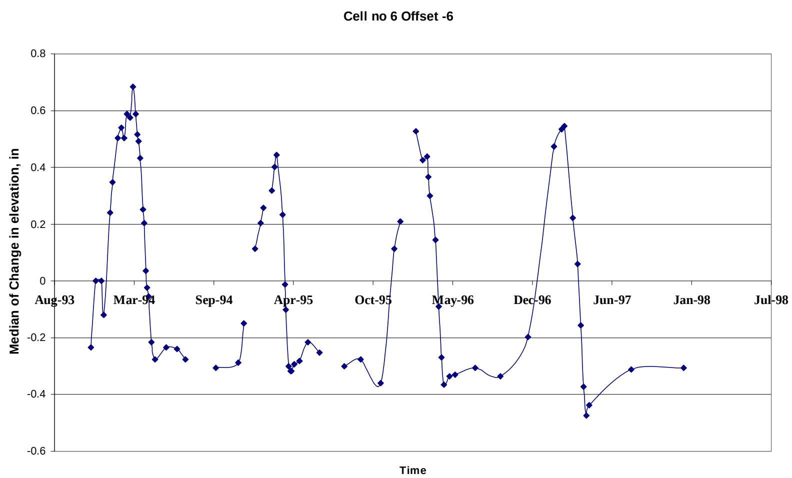
Passing

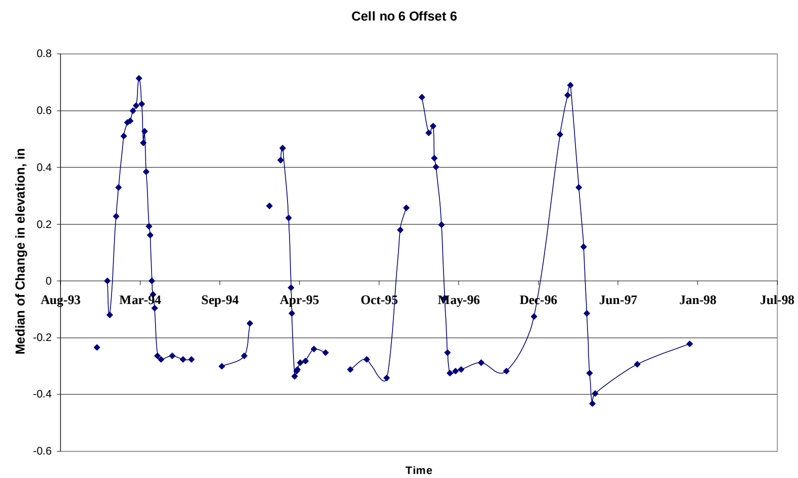
Driving





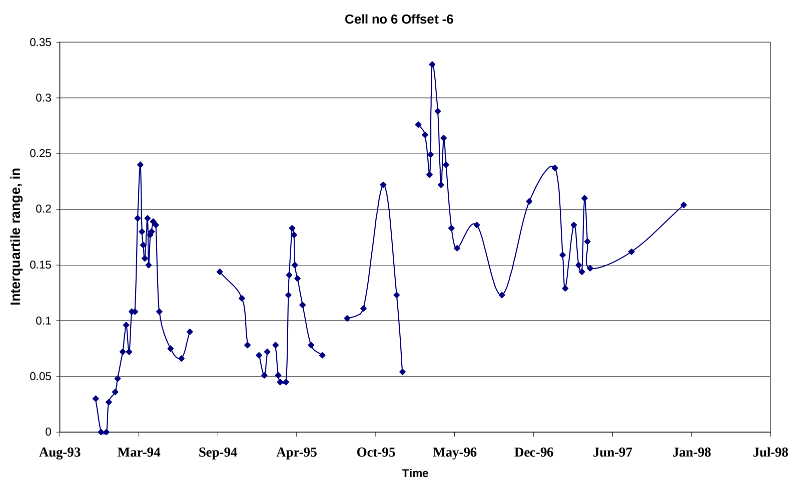
Median Change in Pin Elevation and Interquartile Range for Passing and Driving Lanes of Cell 4

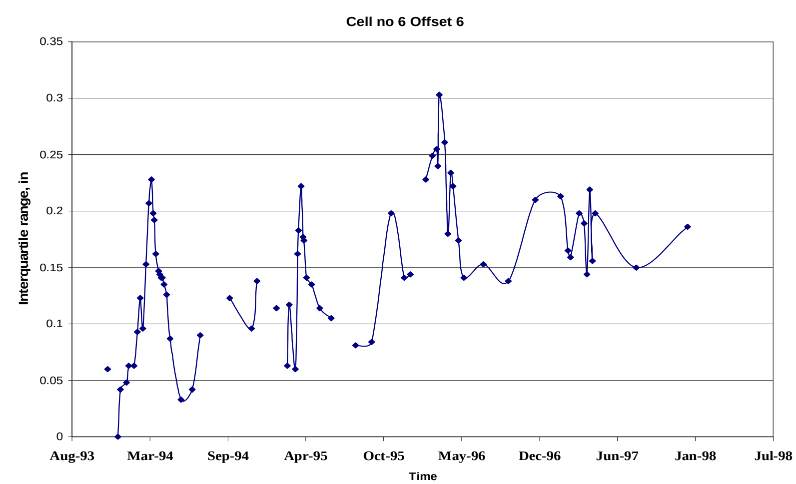




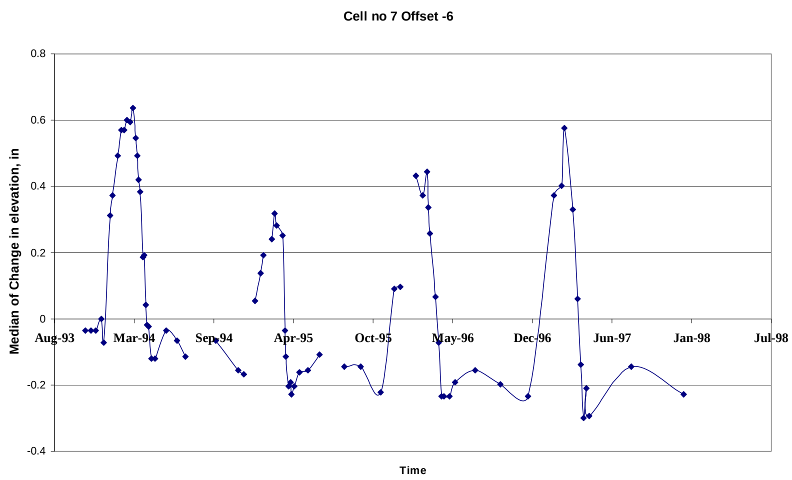
Passing

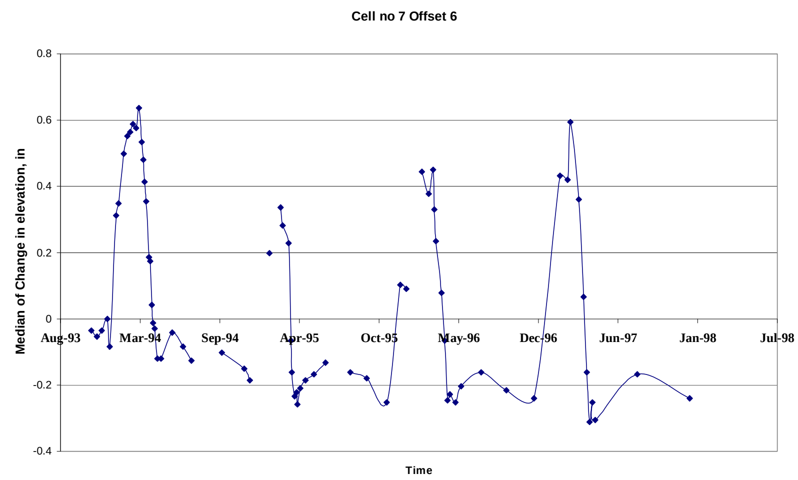
Driving





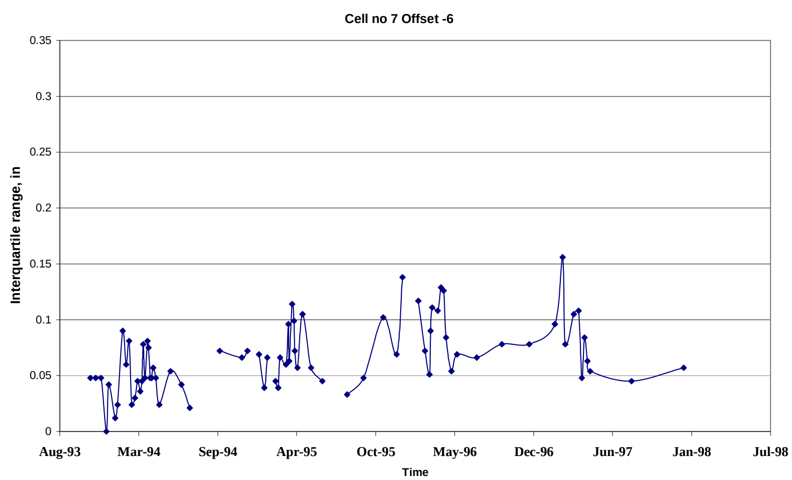
Median Change in Pin Elevation and Interquartile Range for Passing and Driving Lanes of Cell 6

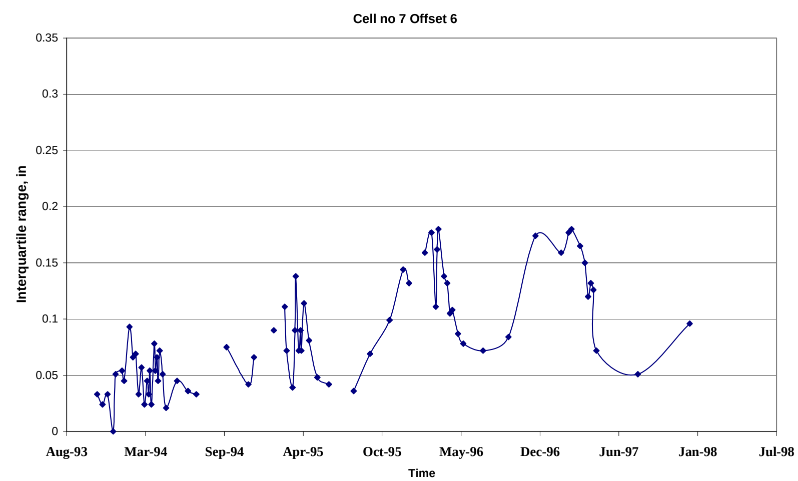




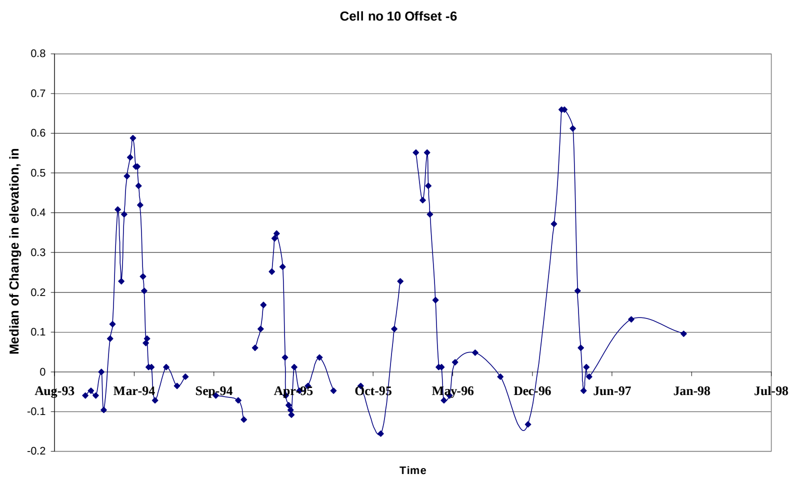
Passing

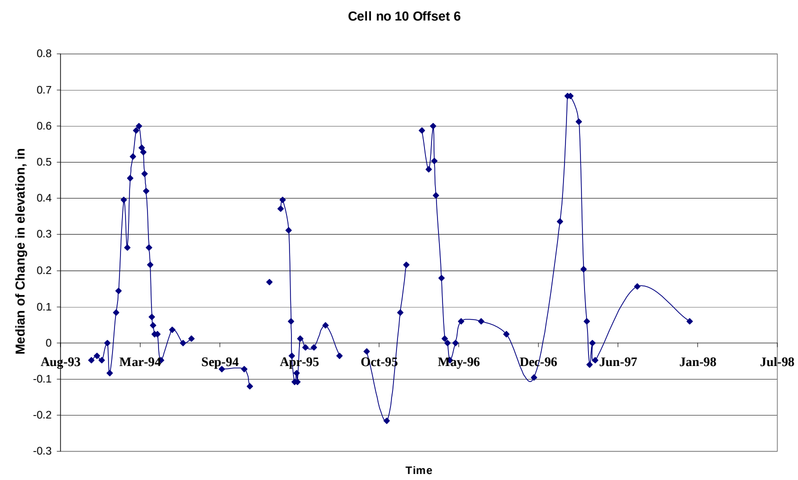
Driving





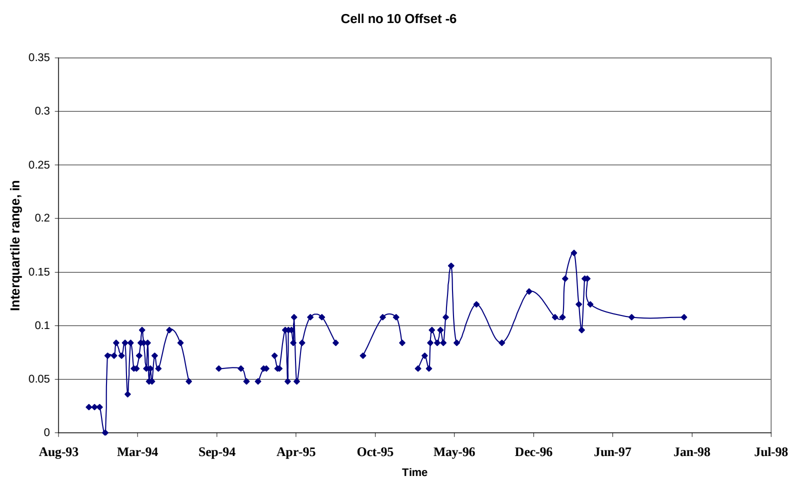
Median Change in Pin Elevation and Interquartile Range for Passing and Driving Lanes of Cell 7

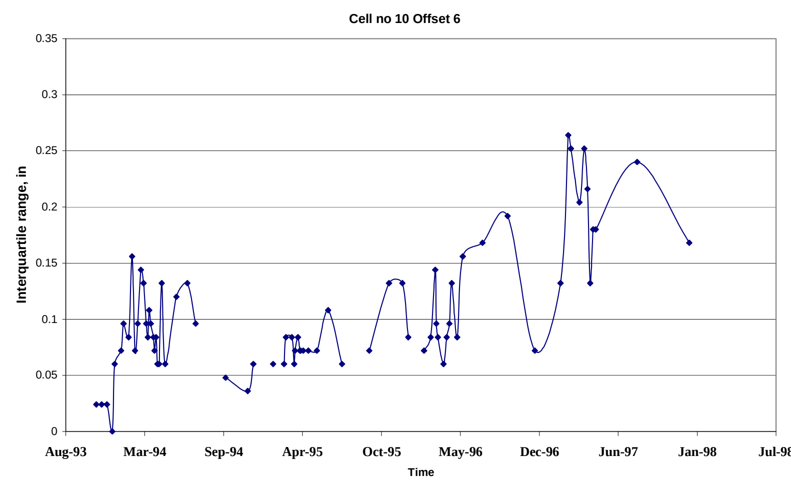




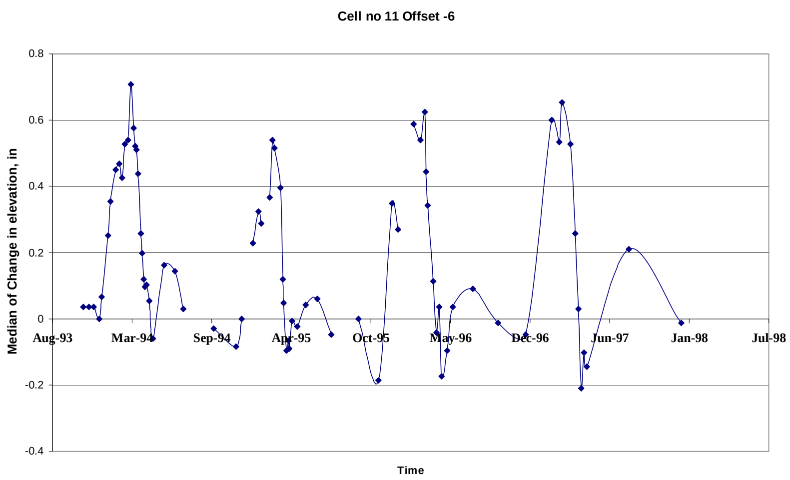
Passing

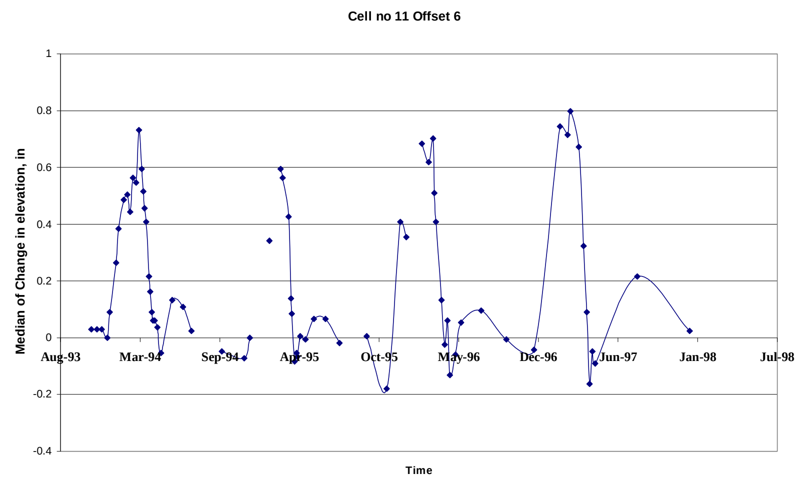
Driving



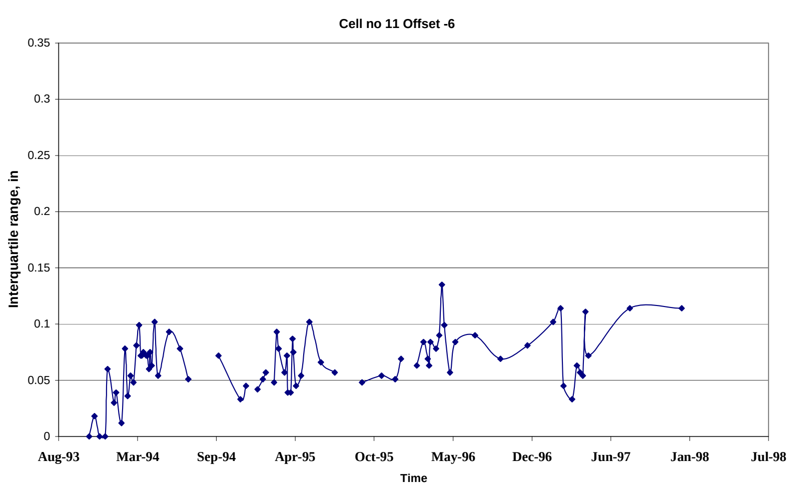


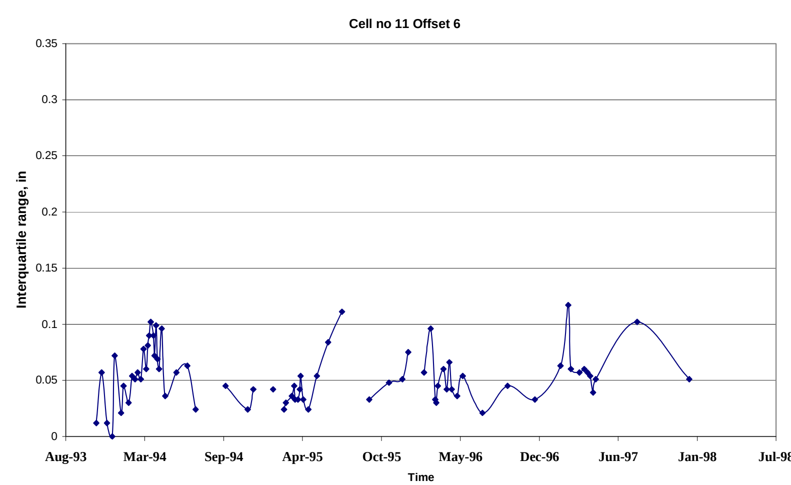
Median Change in Pin Elevation and Interquartile Range for Passing and Driving Lanes of Cell 10



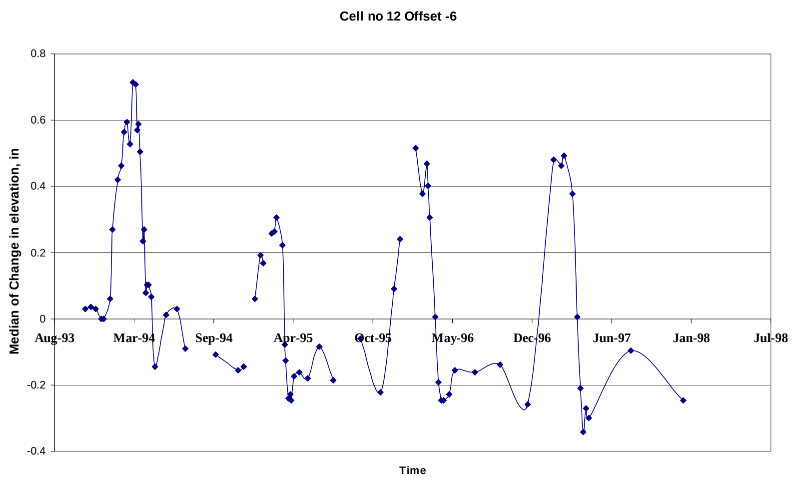


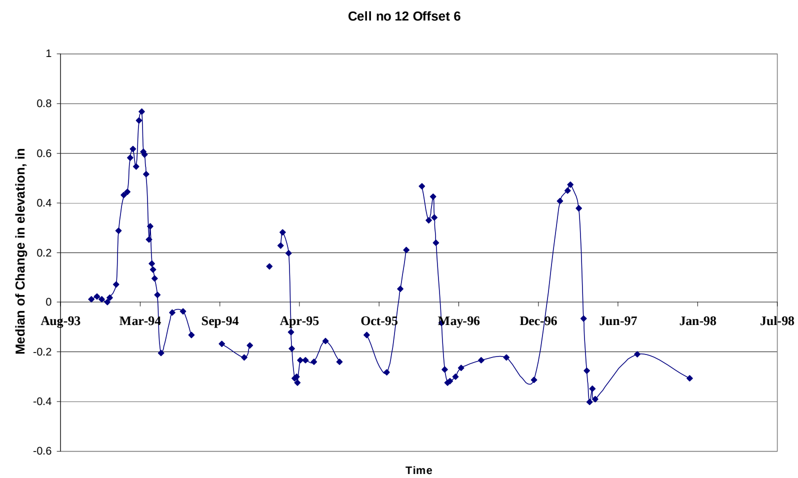
Passing **Driving**





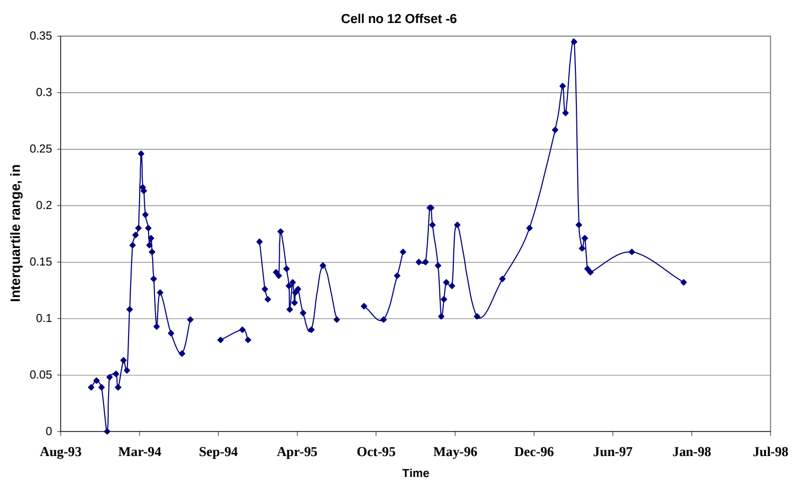
Median Change in Pin Elevation and Interquartile Range for Passing and Driving Lanes of Cell 11

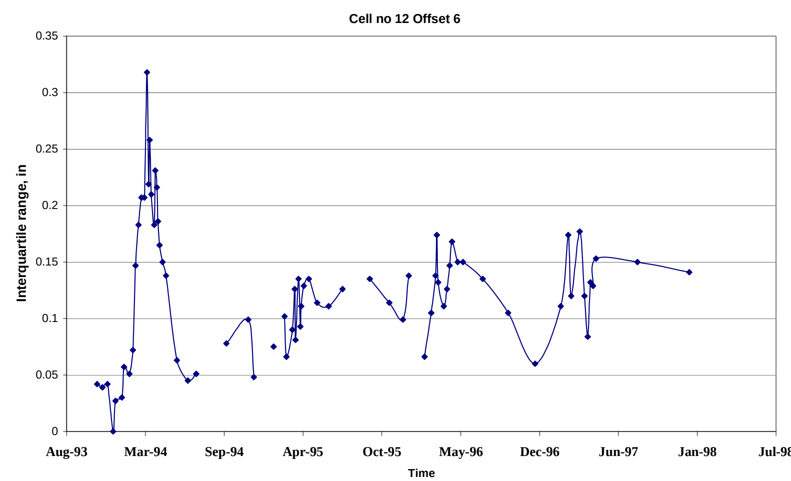




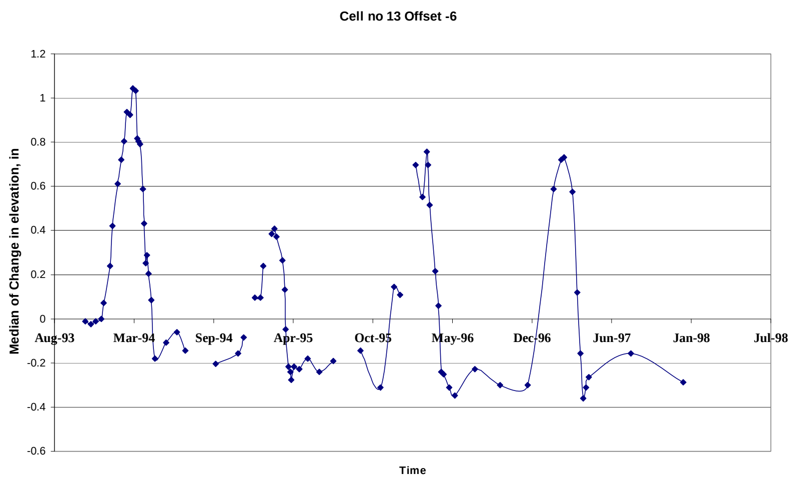
Passing

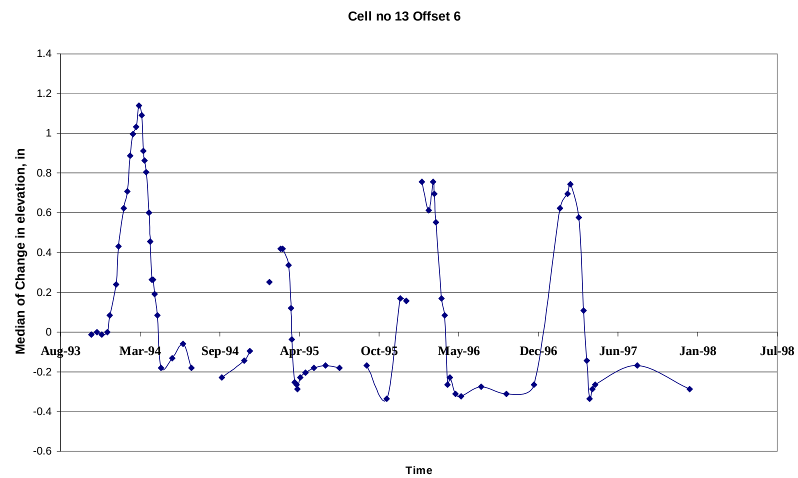
Driving





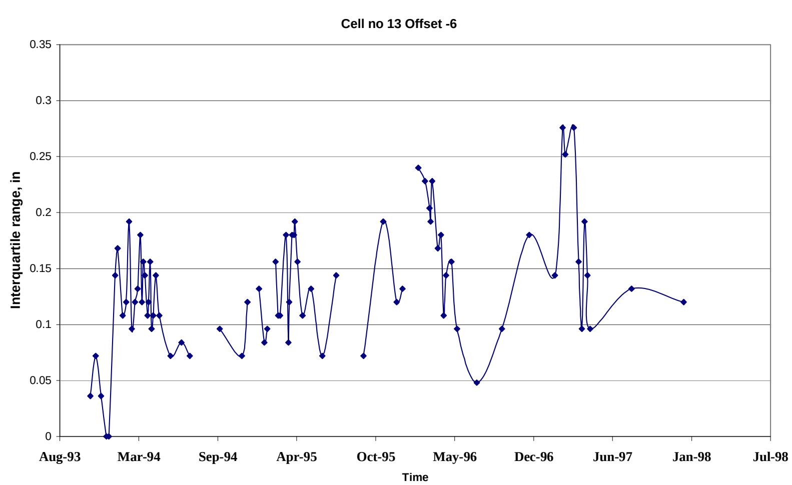
Median Change in Pin Elevation and Interquartile Range for Passing and Driving Lanes of Cell 12

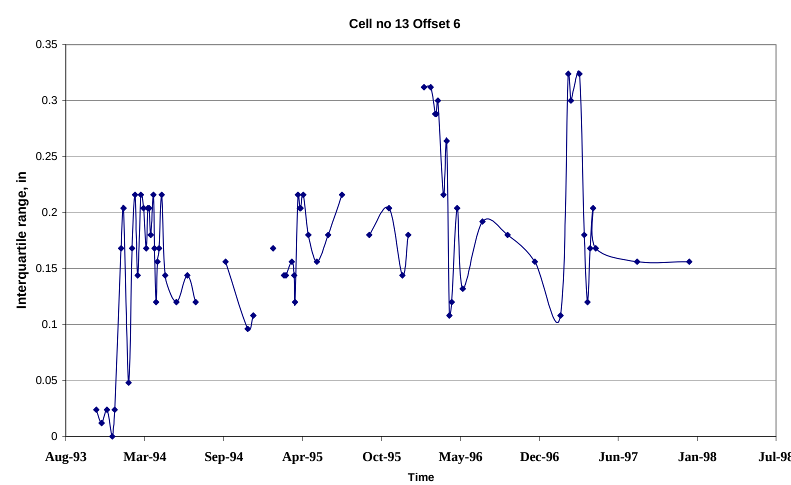




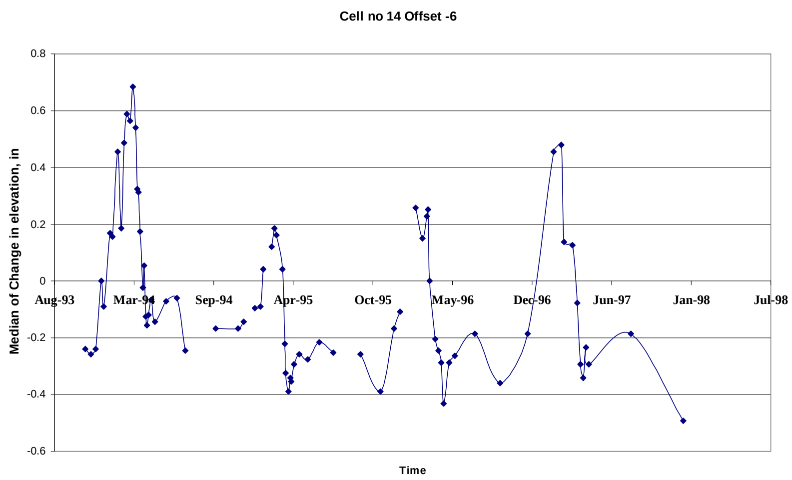
Passing

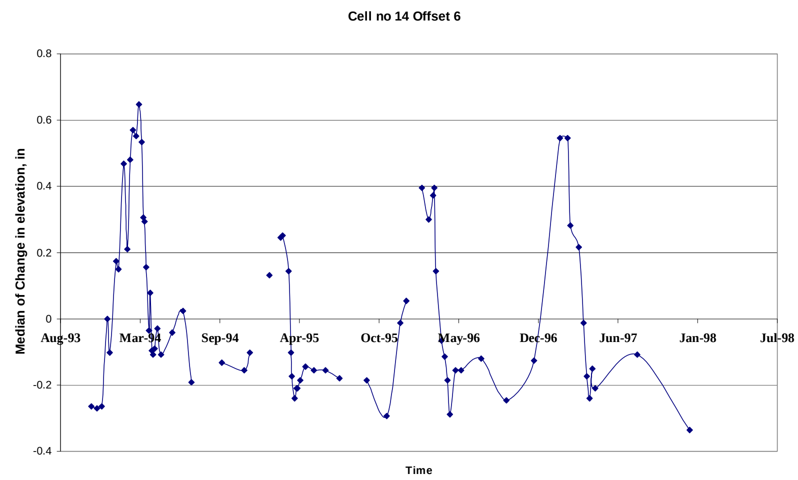
Driving





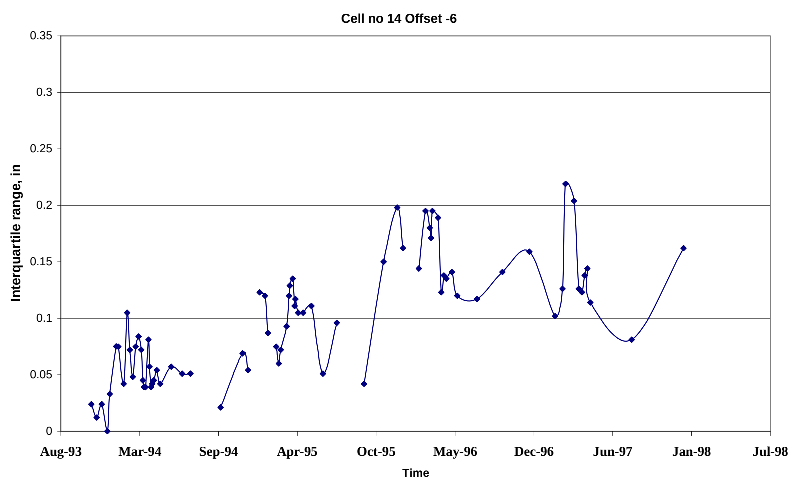
Median Change in Pin Elevation and Interquartile Range for Passing and Driving Lanes of Cell 13

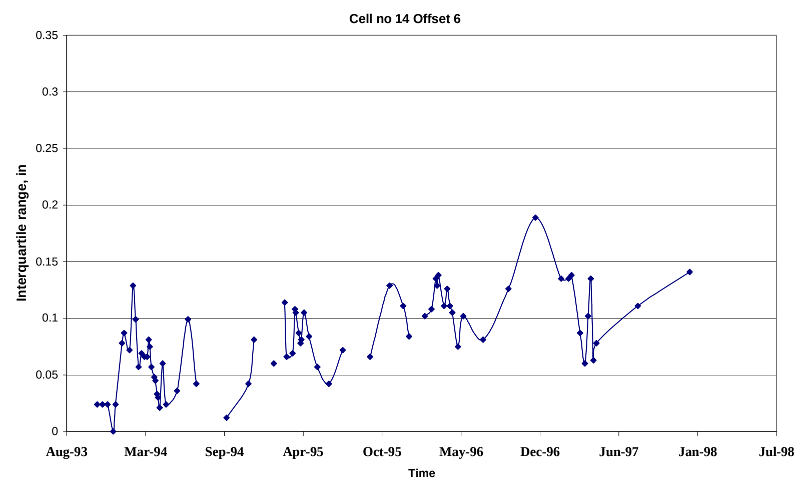




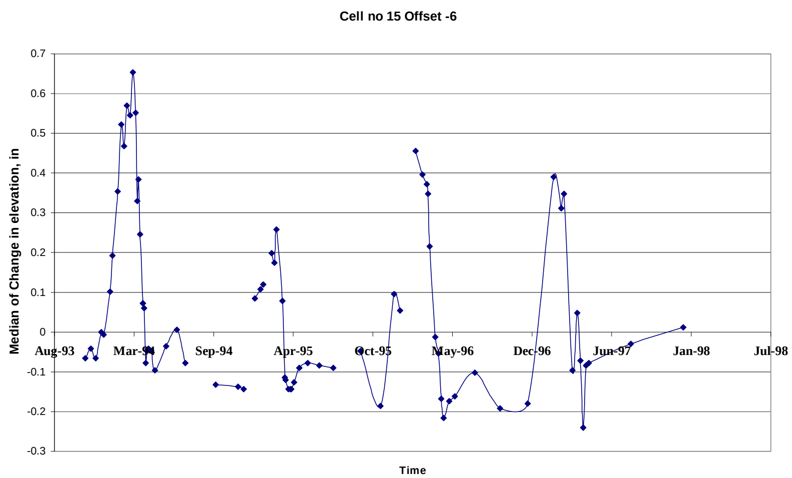
Passing

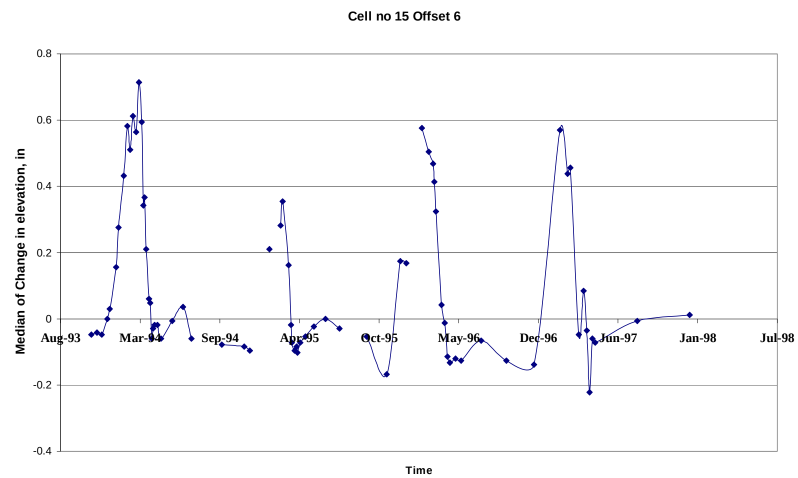
Driving





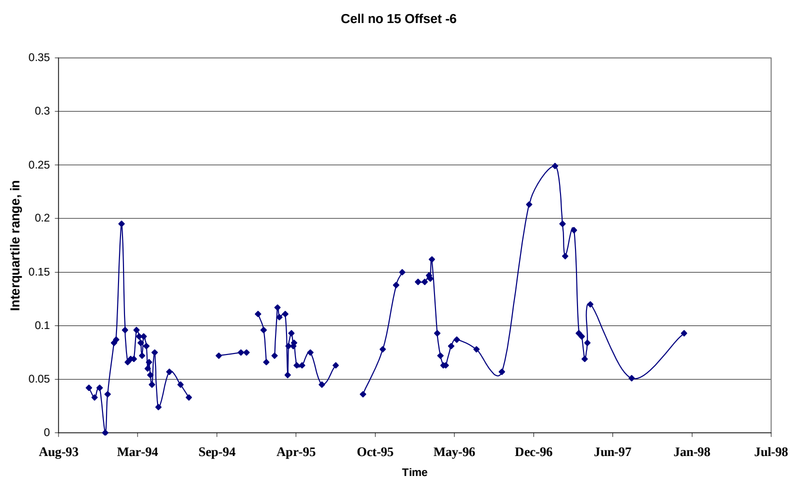
Median Change in Pin Elevation and Interquartile Range for Passing and Driving Lanes of Cell 14

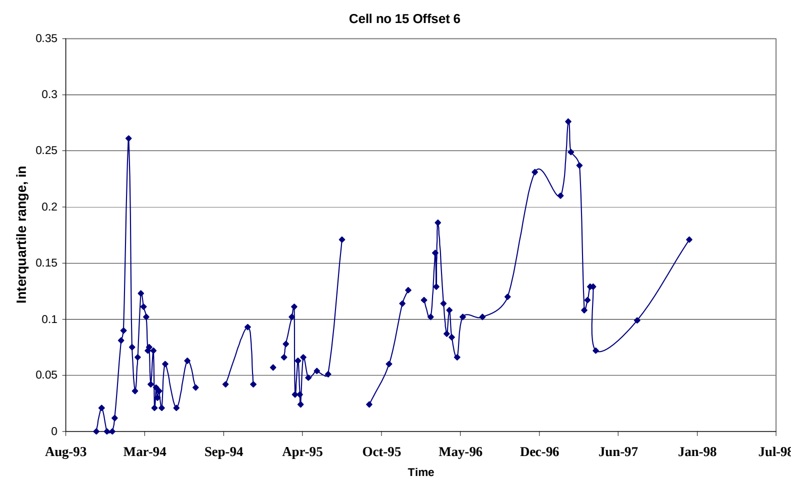




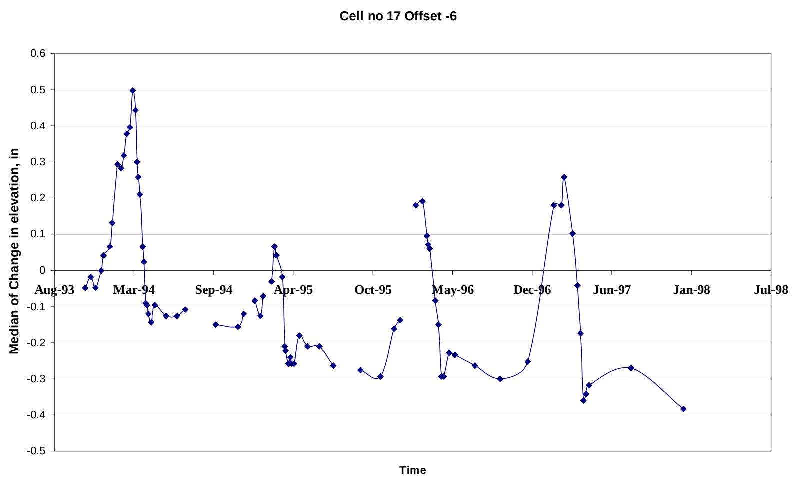
Passing

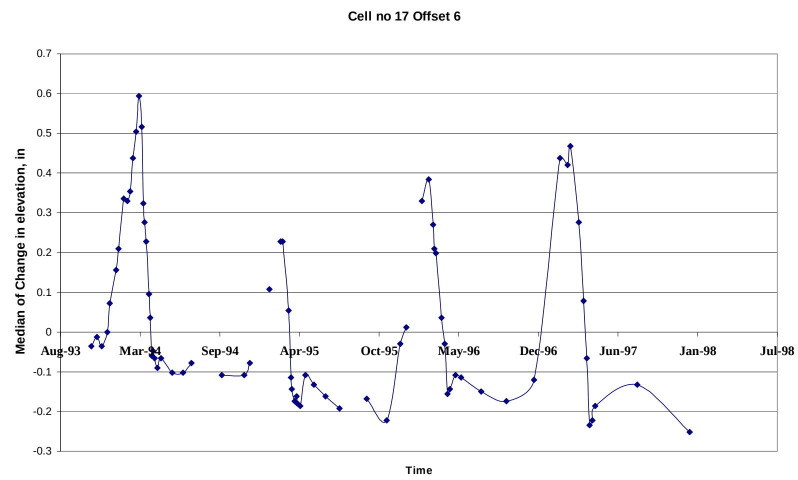
Driving





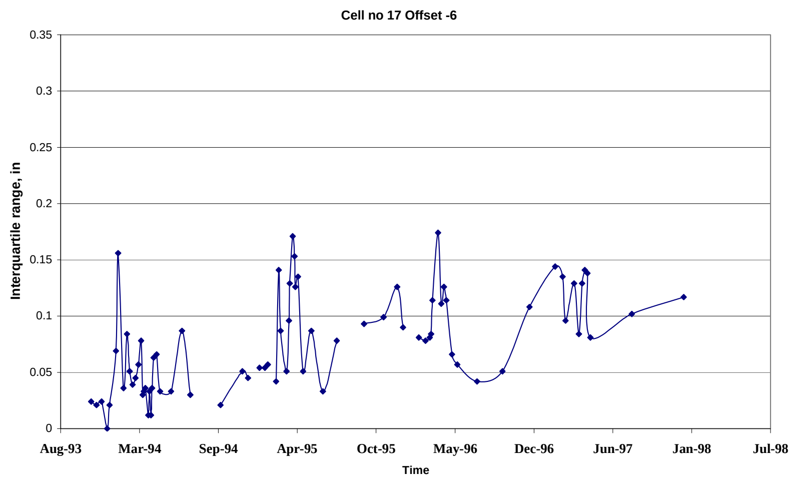
Median Change in Pin Elevation and Interquartile Range for Passing and Driving Lanes of Cell 15

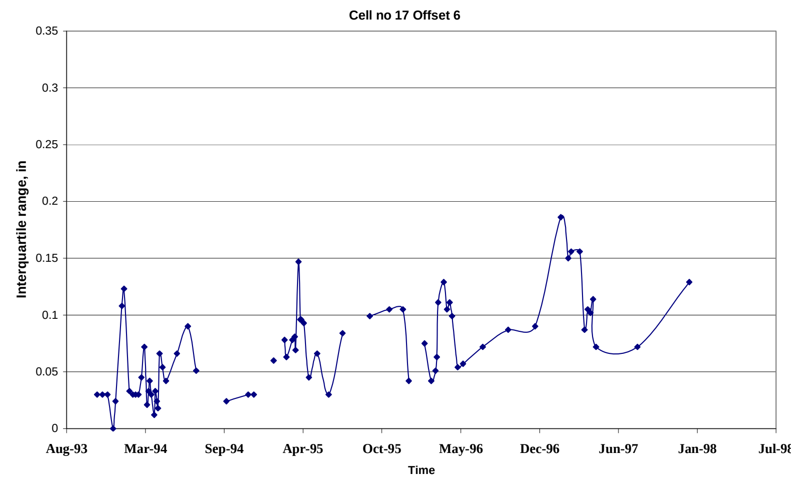




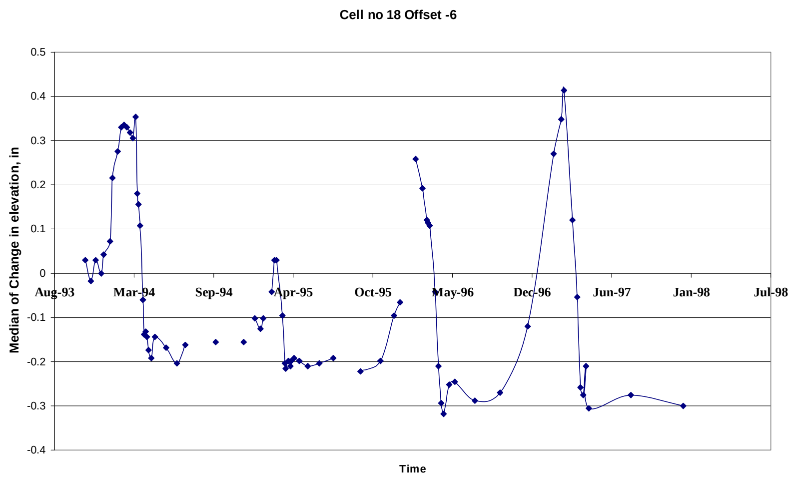
Passing

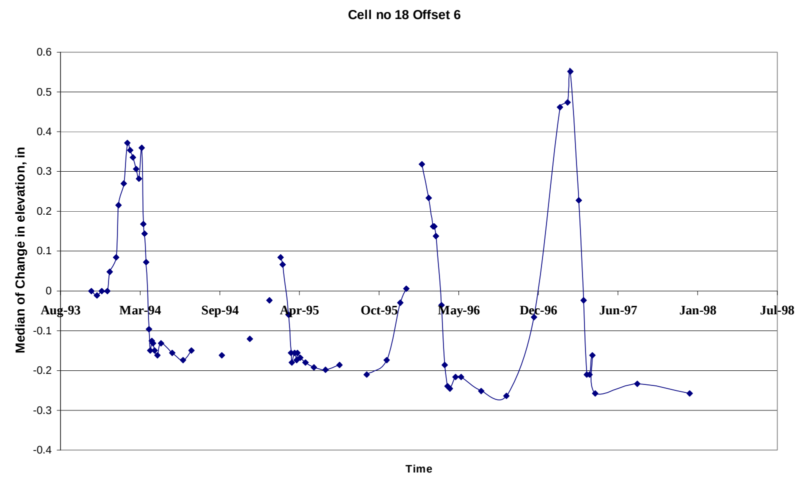
Driving





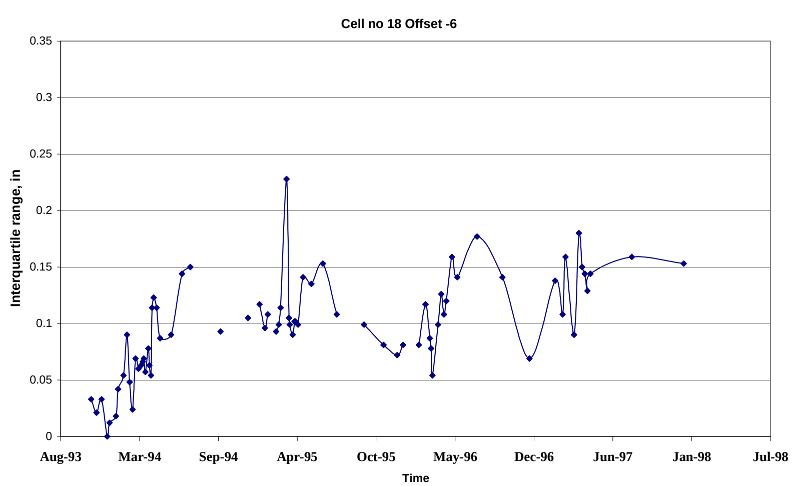
Median Change in Pin Elevation and Interquartile Range for Passing and Driving Lanes of Cell 17

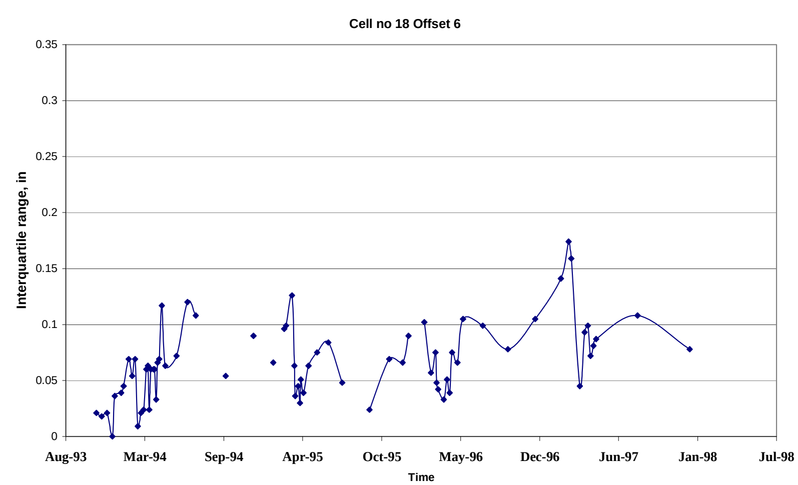




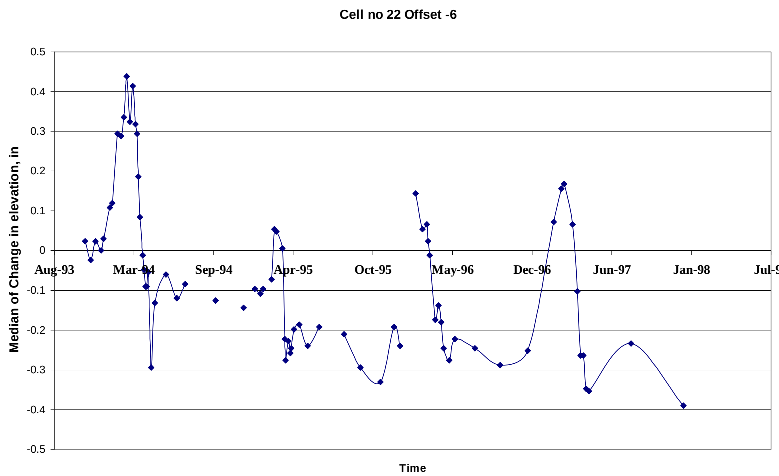
Passing

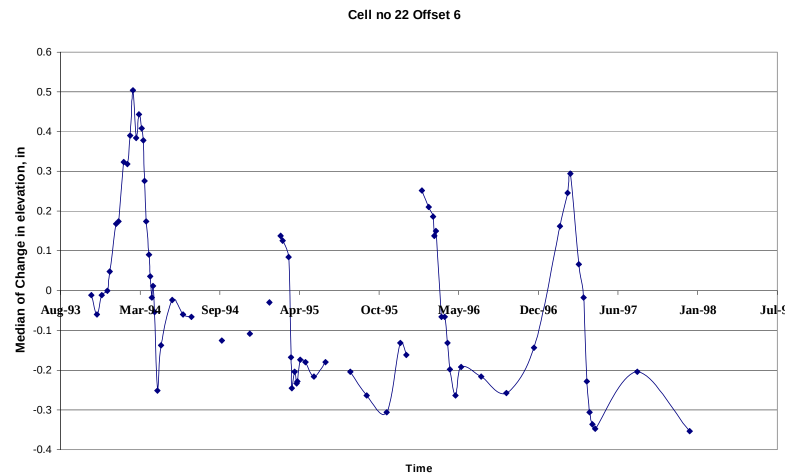
Driving



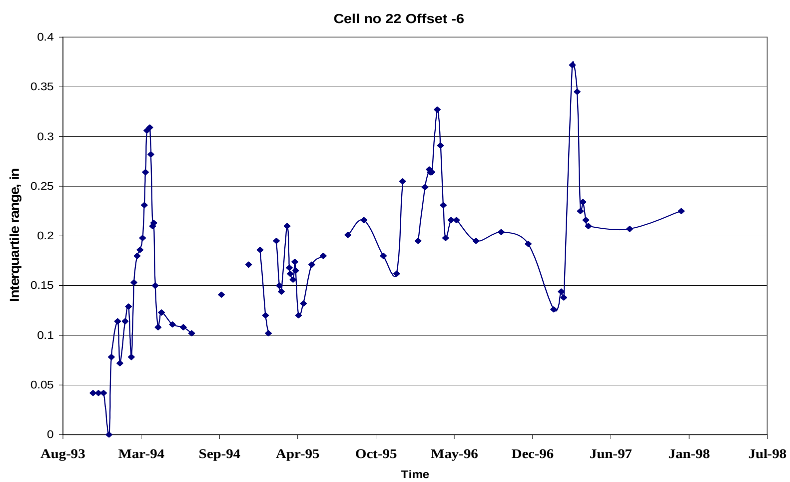


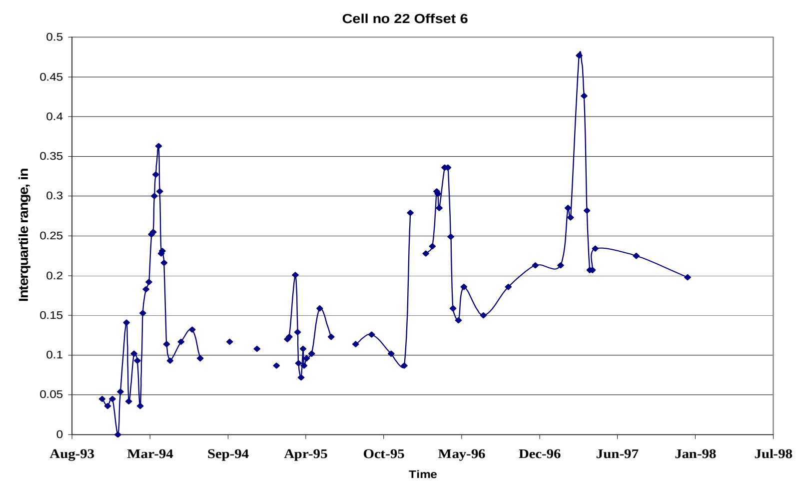
Median Change in Pin Elevation and Interquartile Range for Passing and Driving Lanes of Cell 18



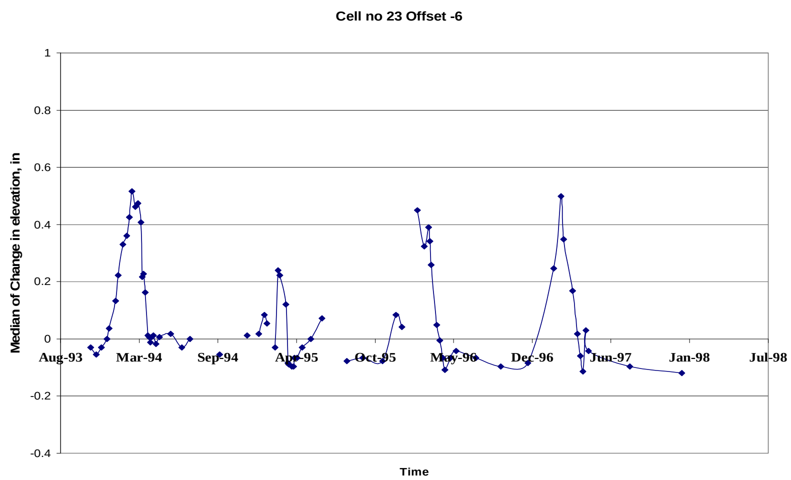


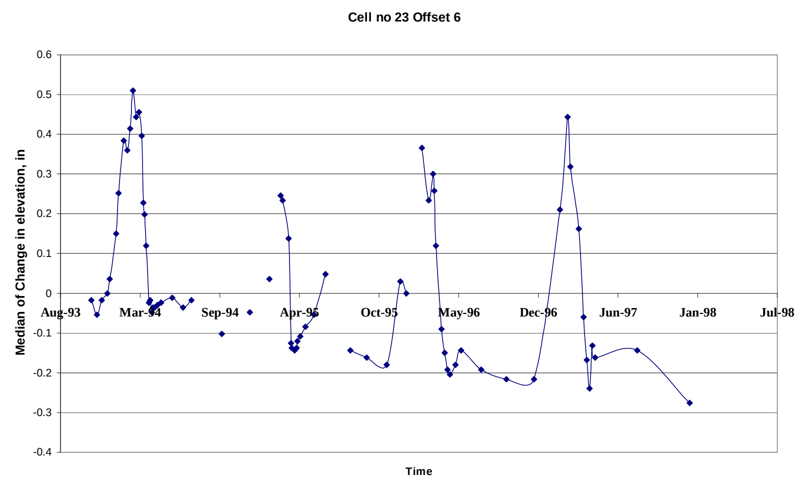
Passing **Driving**





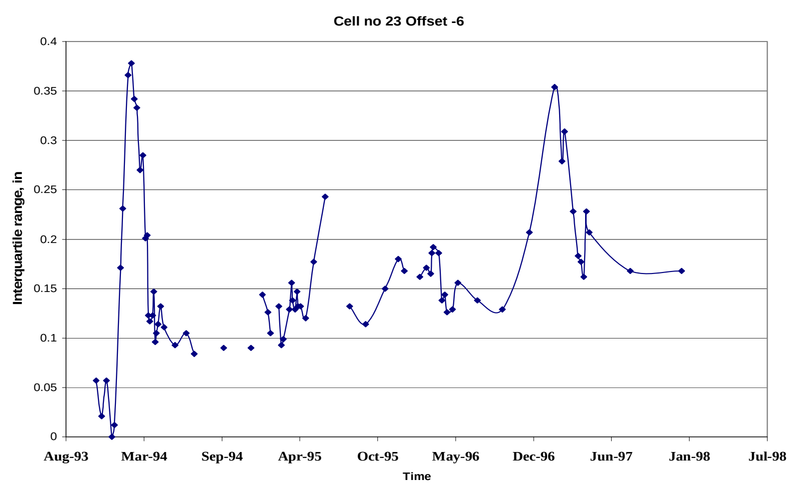
Median Change in Pin Elevation and Interquartile Range for Passing and Driving Lanes of Cell 22

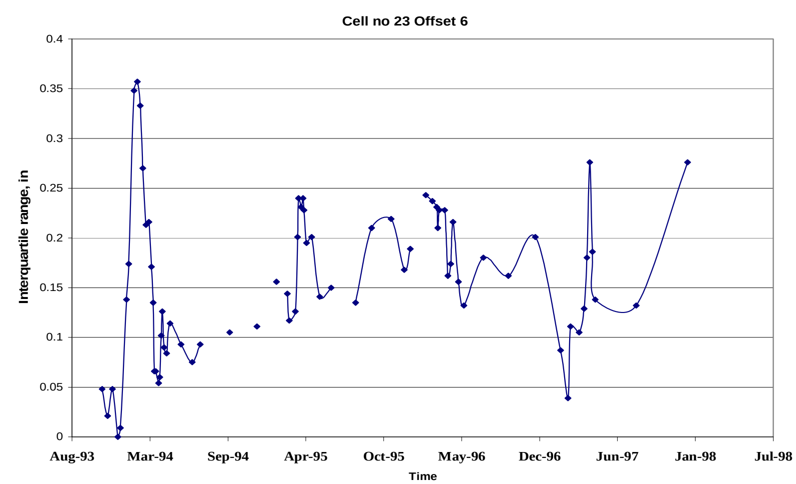




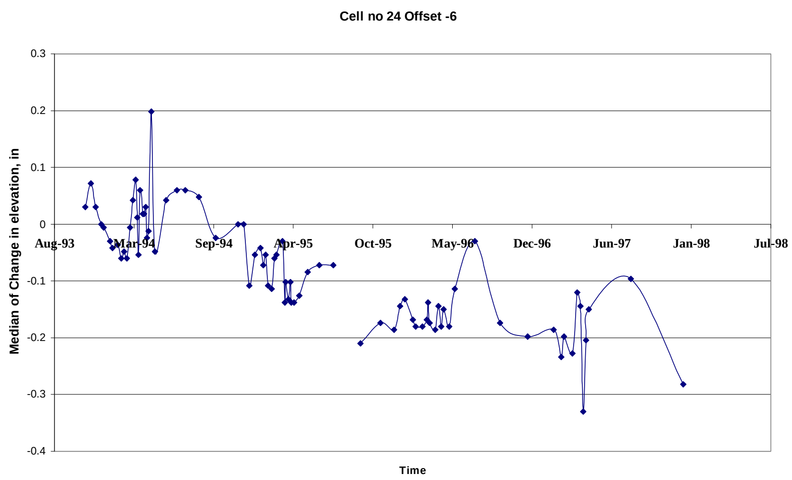
Passing

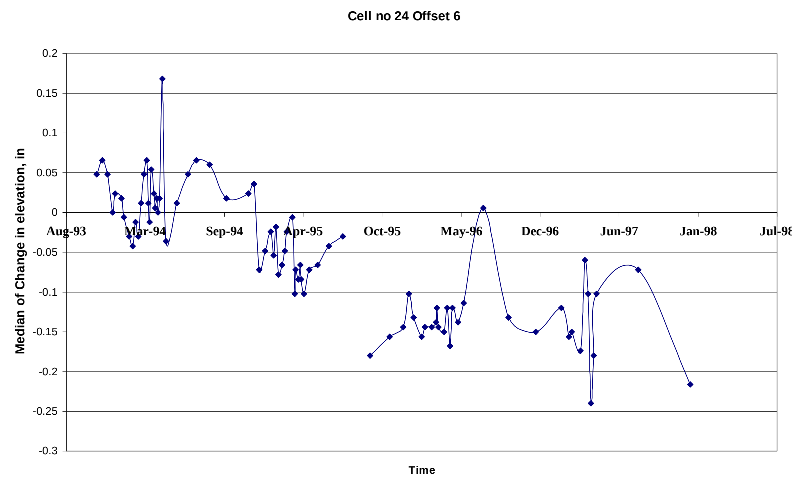
Driving





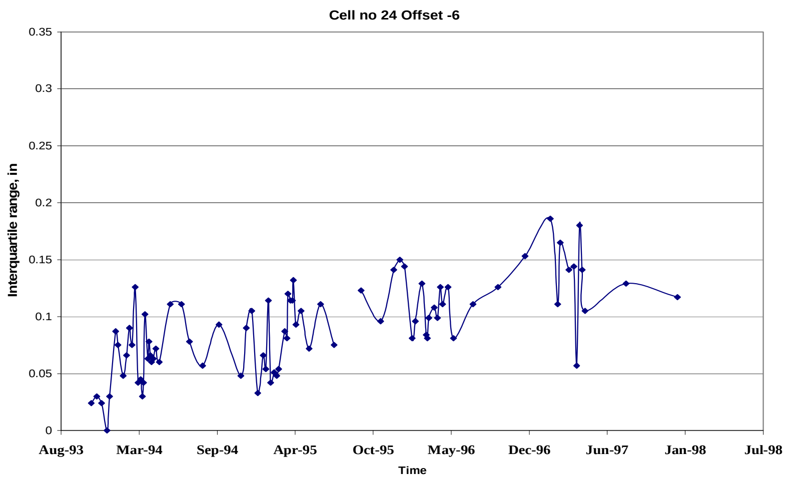
Median Change in Pin Elevation and Interquartile Range for Passing and Driving Lanes of Cell 23

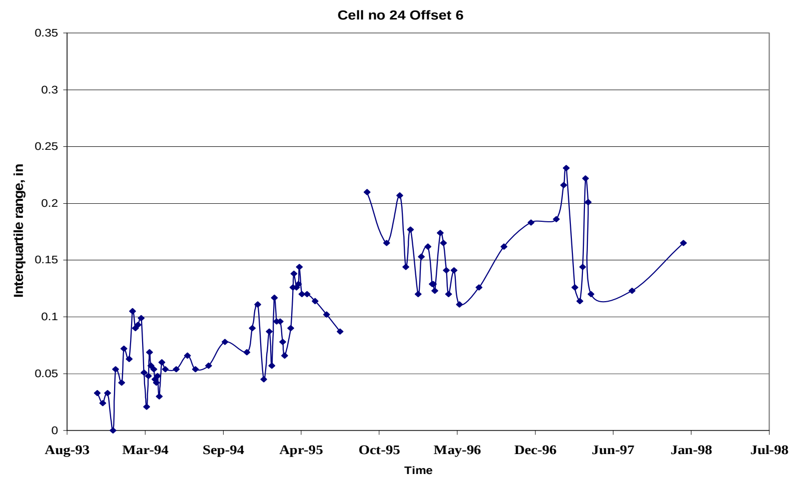




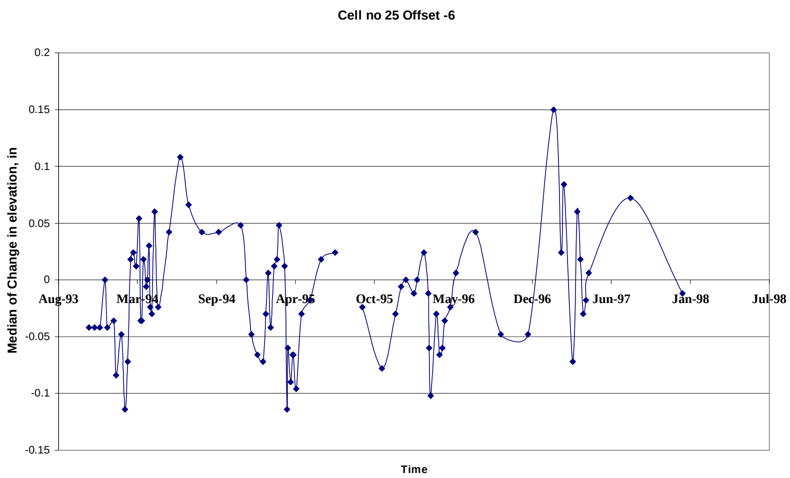
Passing

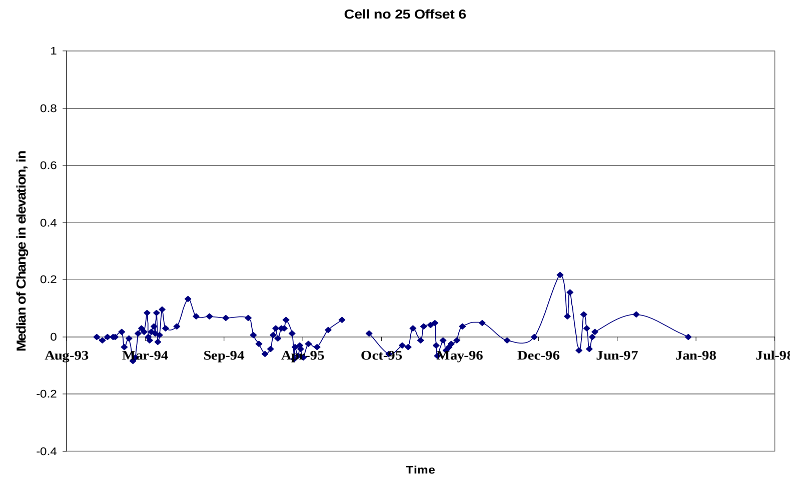
Driving





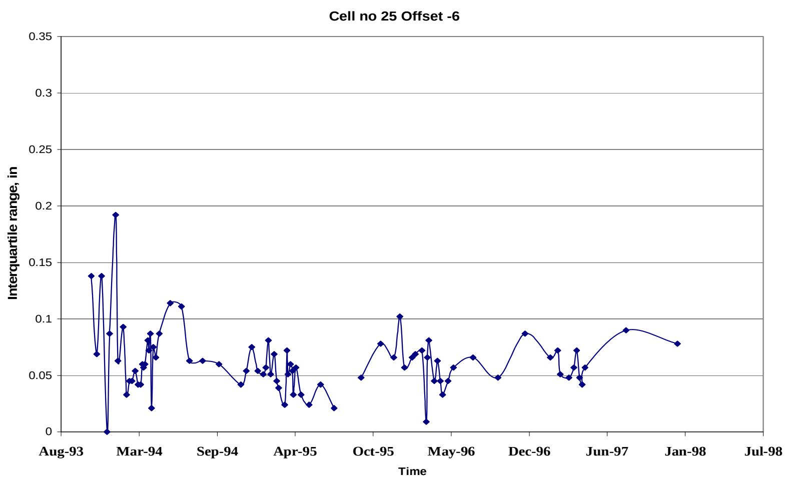
Median Change in Pin Elevation and Interquartile Range for 80K and 102K Lanes of Cell 24

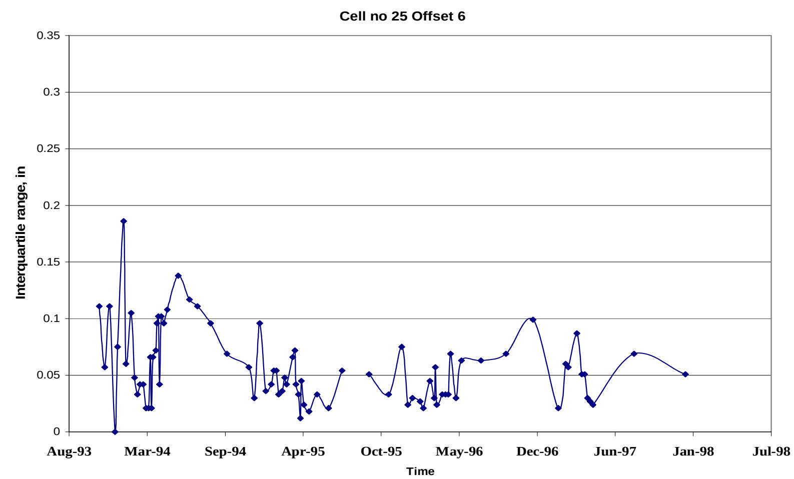




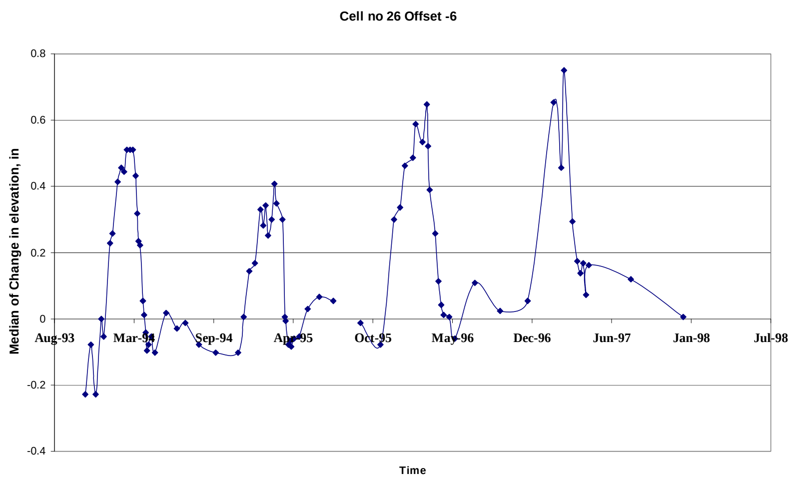
Passing

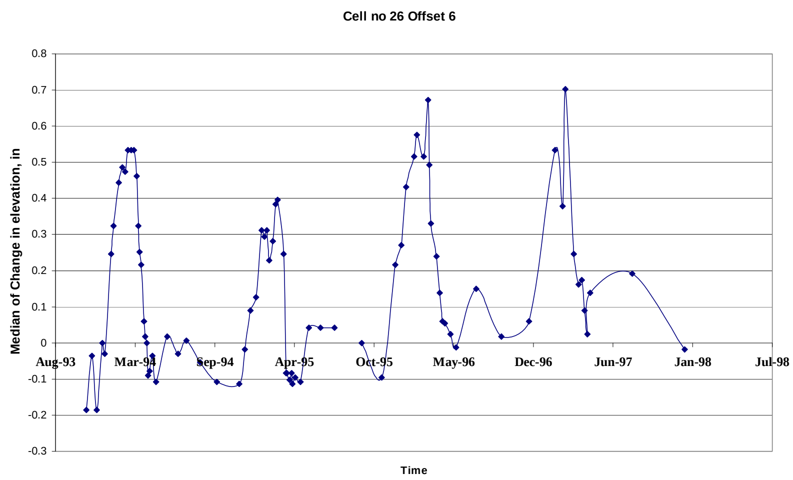
Driving





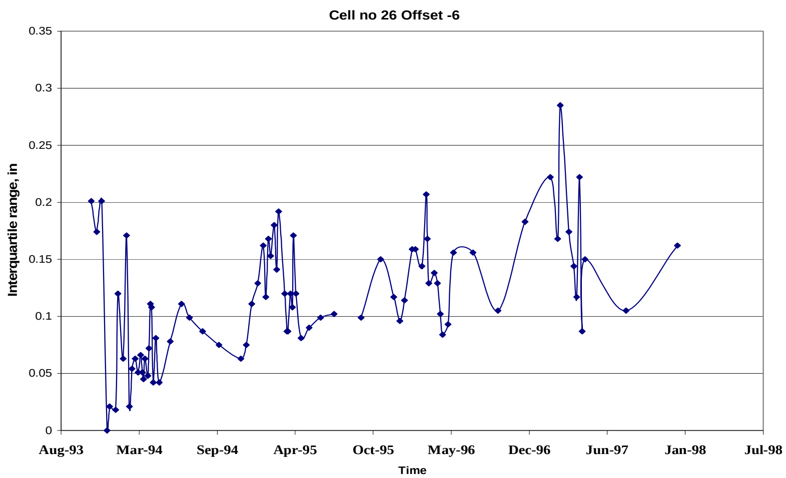
Median Change in Pin Elevation and Interquartile Range for 80K and 102K Lanes of Cell 25

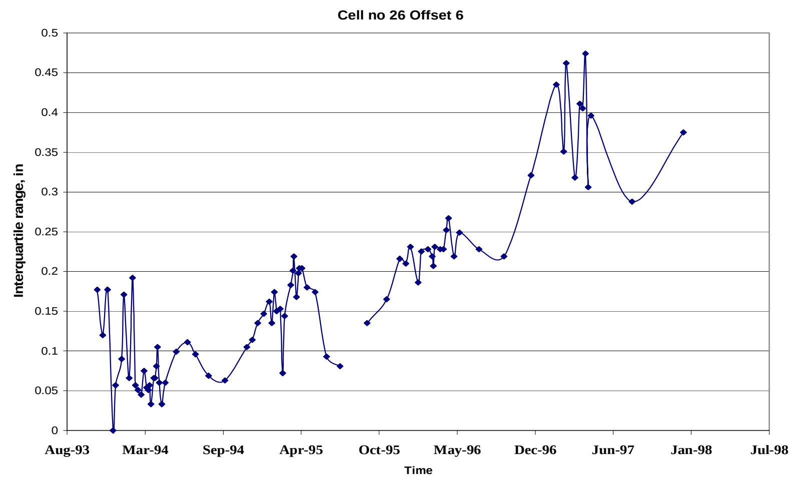




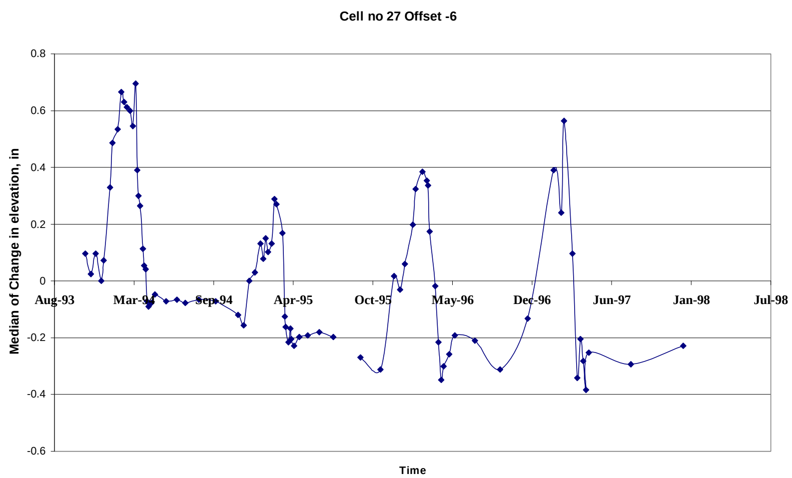
Passing

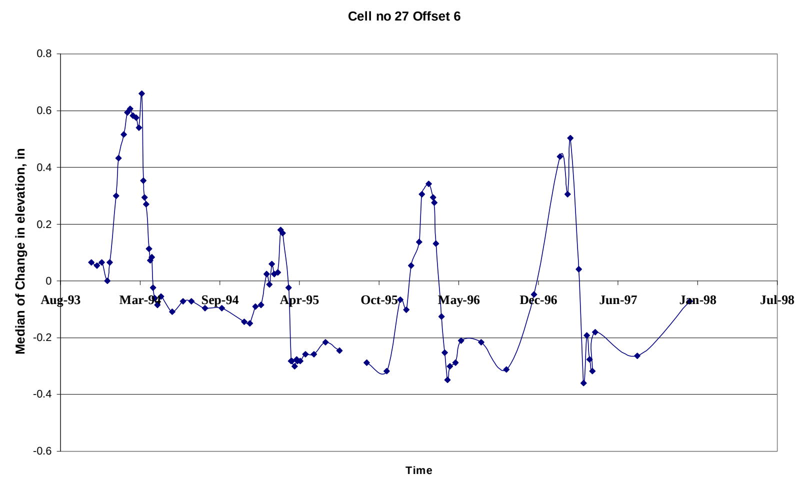
Driving





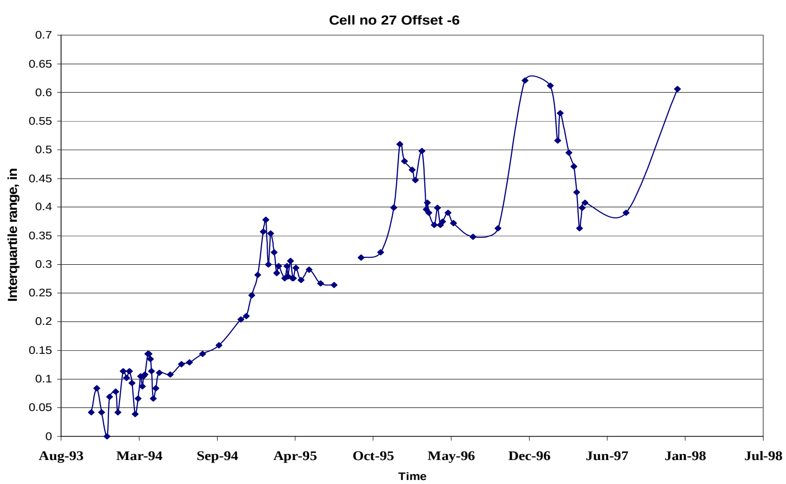
Median Change in Pin Elevation and Interquartile Range for 80K and 102K Lanes of Cell 26

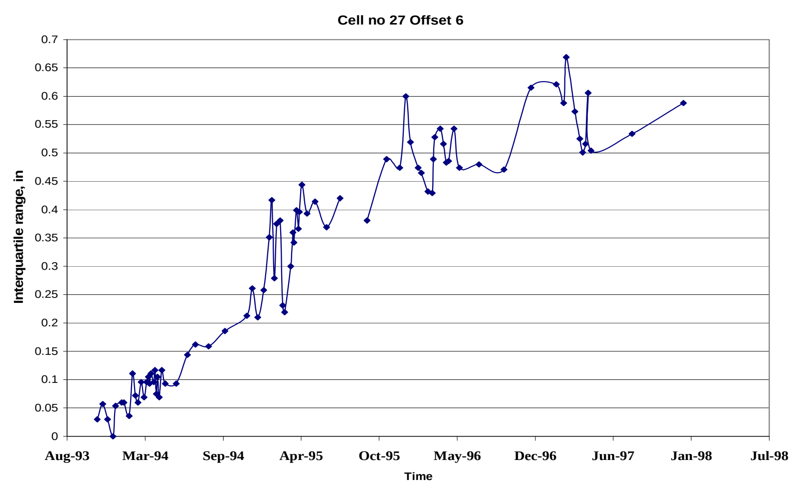




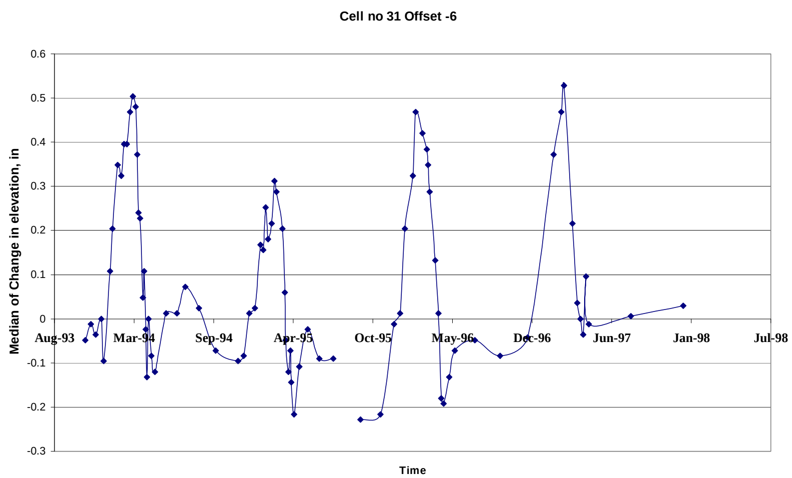
Passing

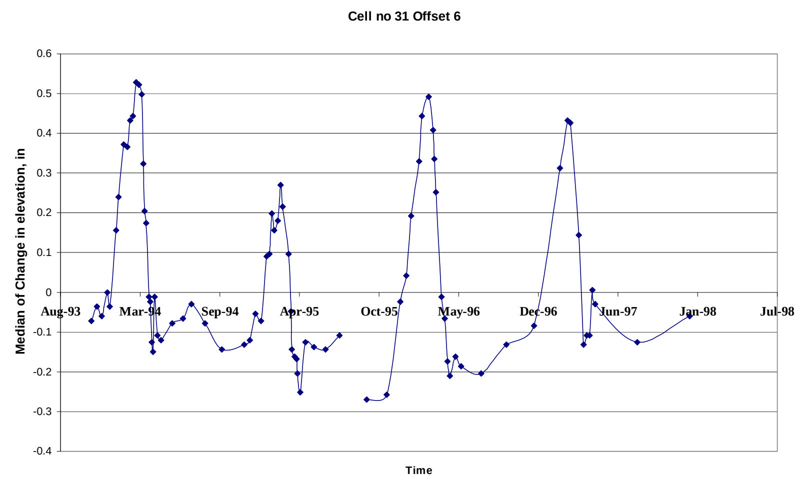
Driving





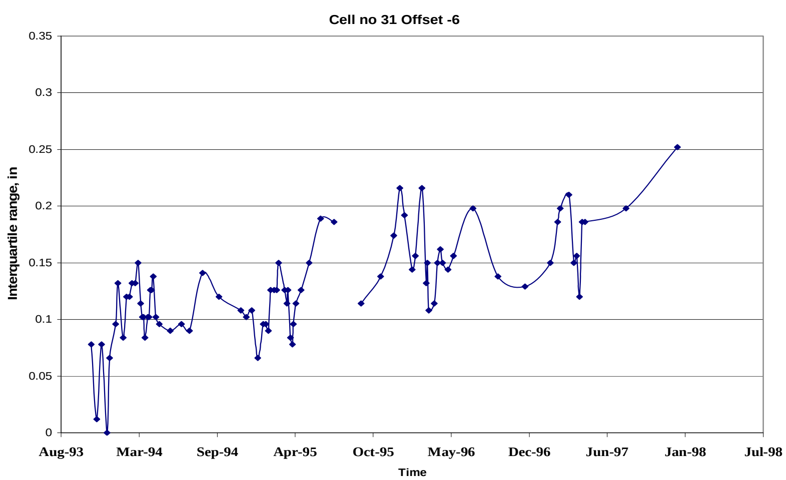
Median Change in Pin Elevation and Interquartile Range for 80K and 102K Lanes of Cell 27

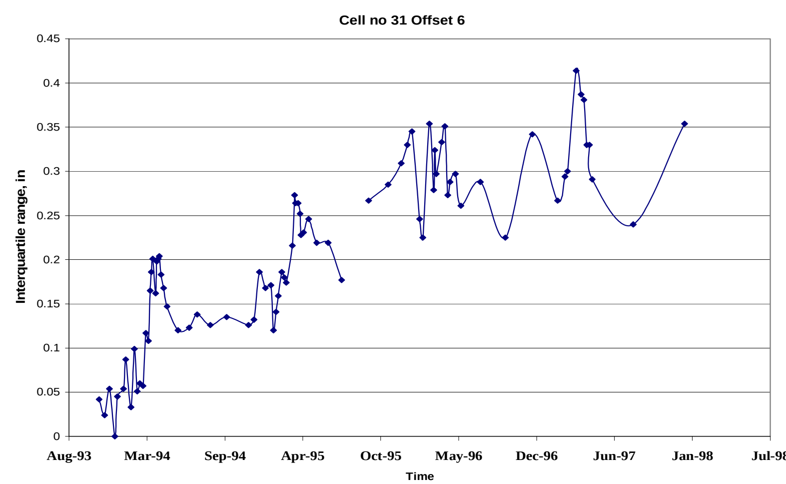




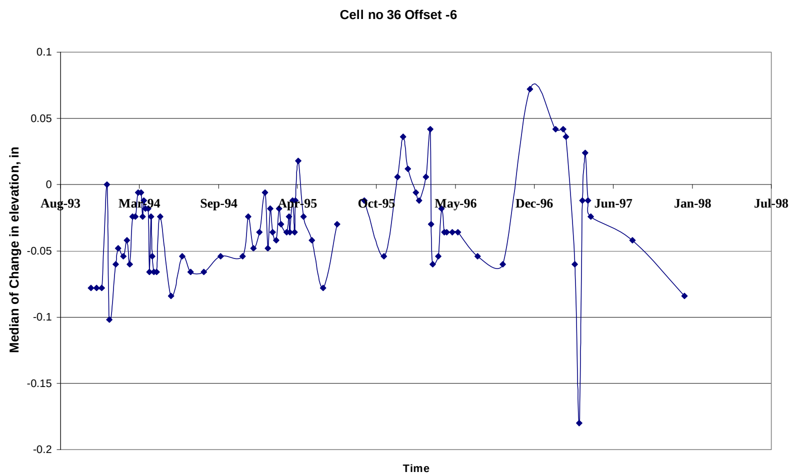
Passing

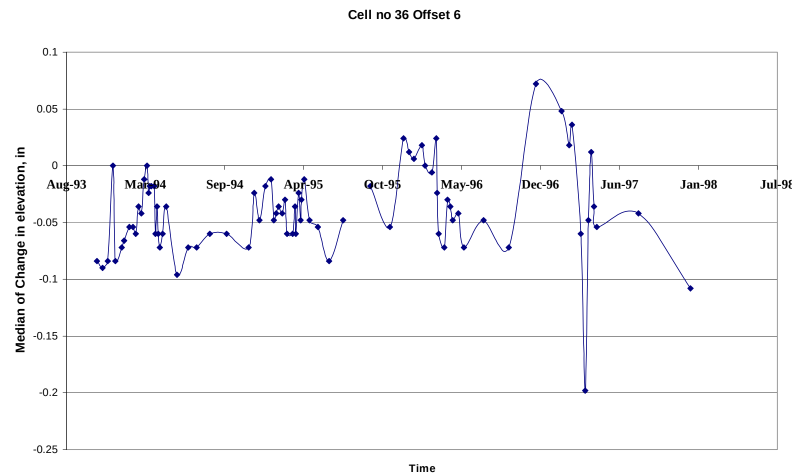
Driving





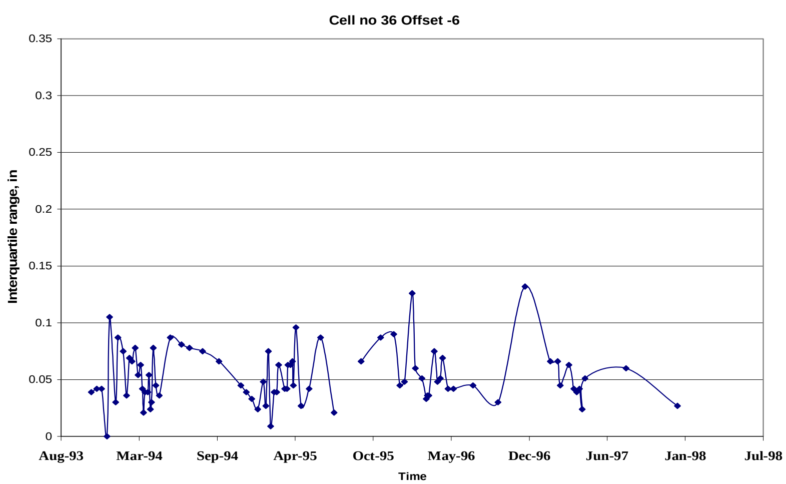
Median Change in Pin Elevation and Interquartile Range for 80K and 102K Lanes of Cell 31

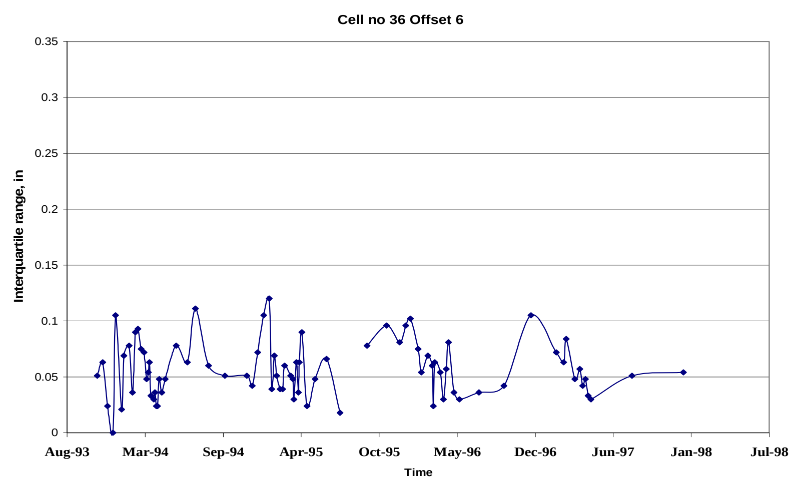




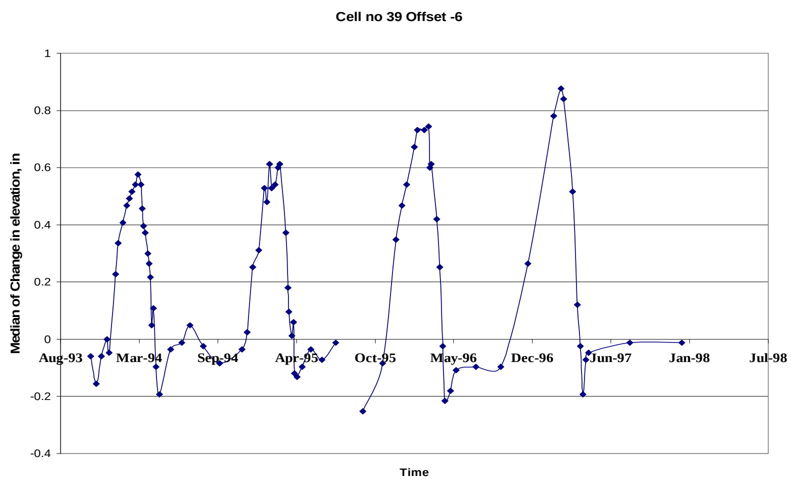
Passing

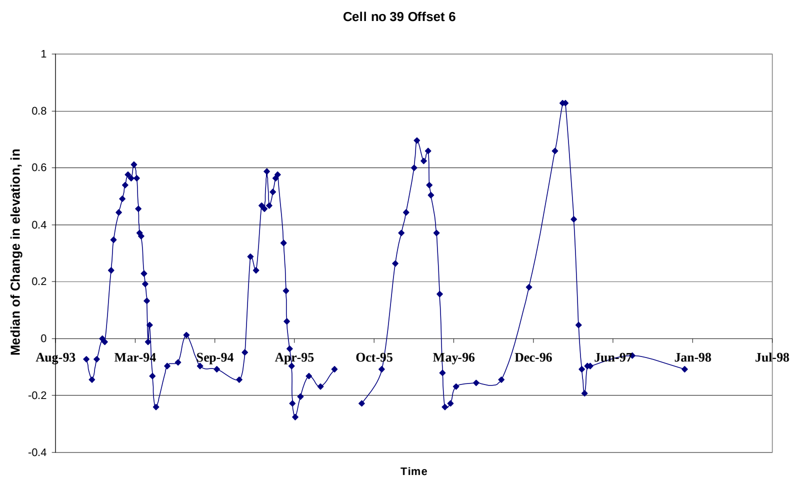
Driving





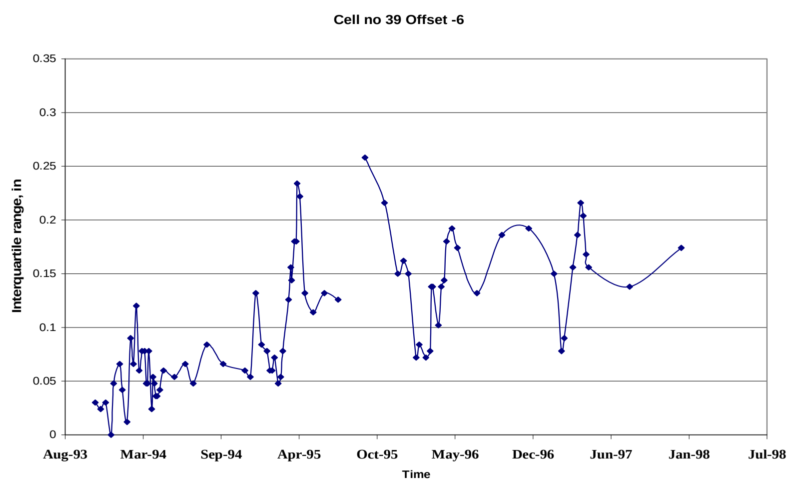
Median Change in Pin Elevation and Interquartile Range for 80K and 102K Lanes of Cell 36

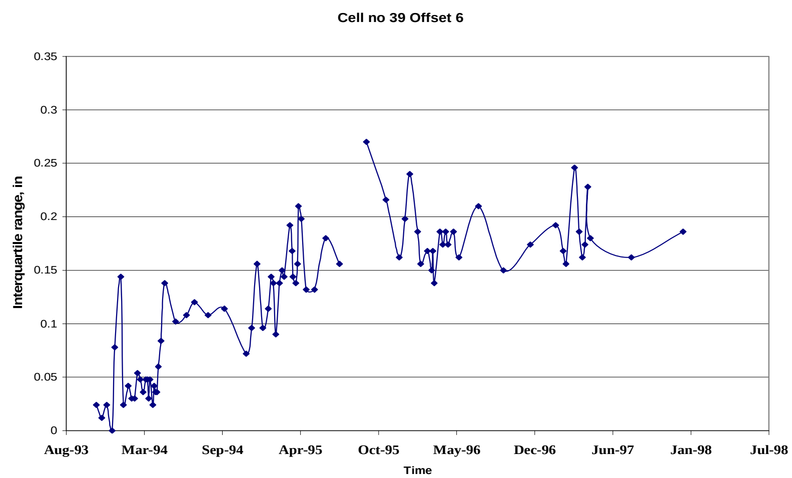




Passing

Driving

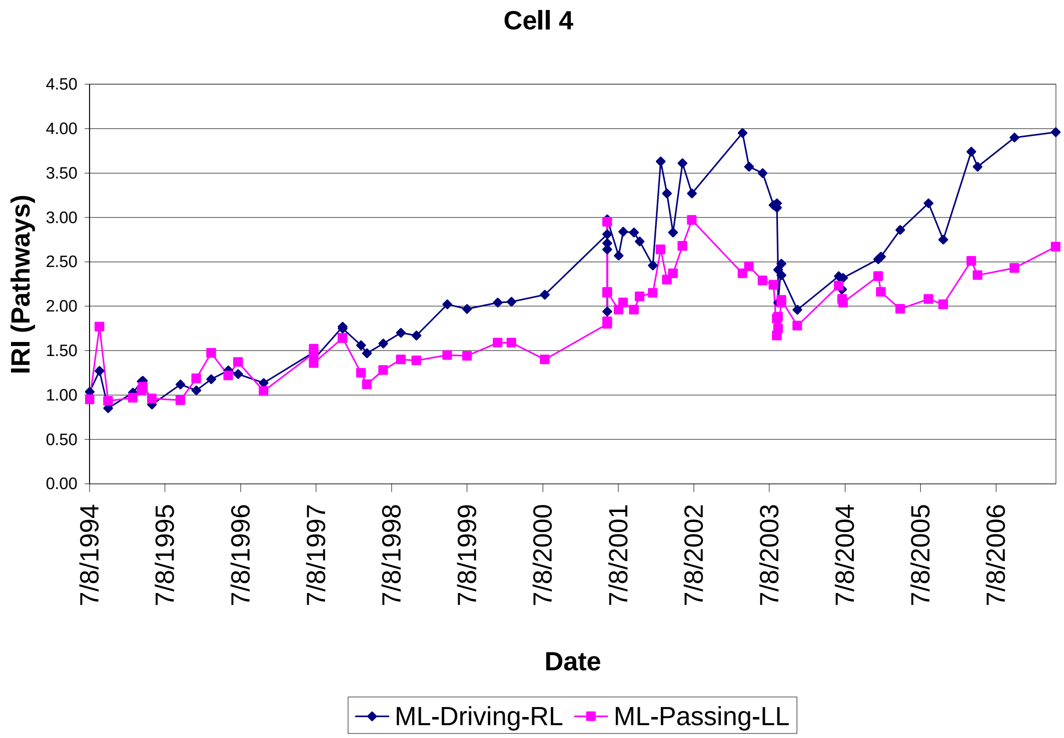




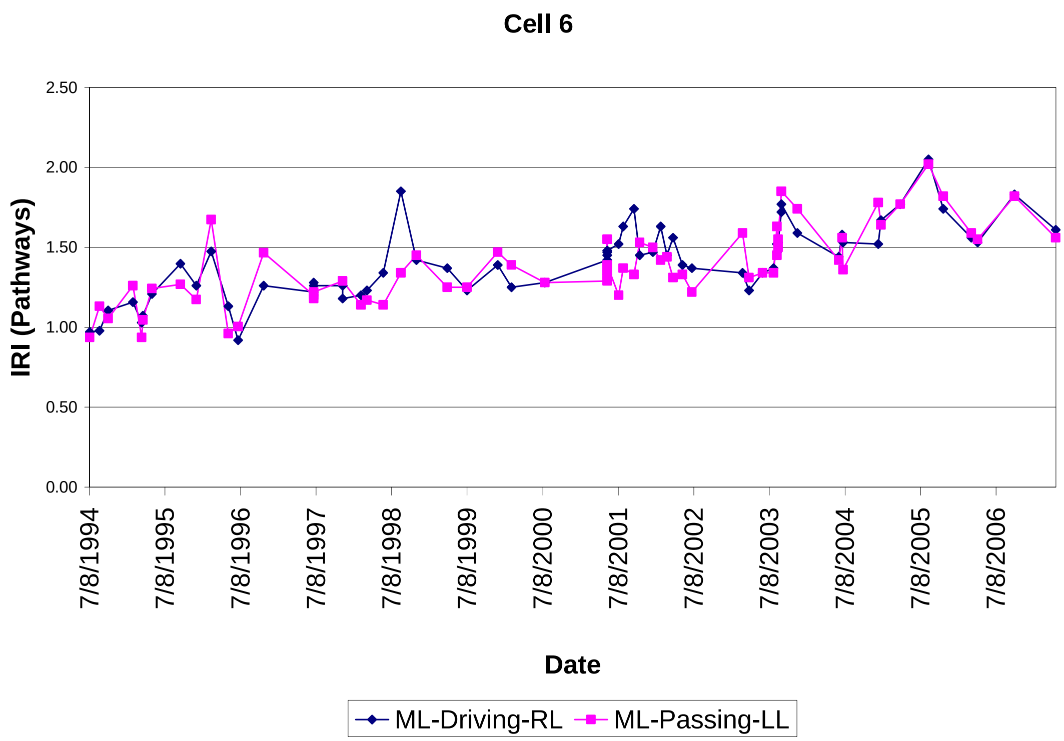
Median Change in Pin Elevation and Interquartile Range for 80K and 102K Lanes of Cell 39

Appendix E

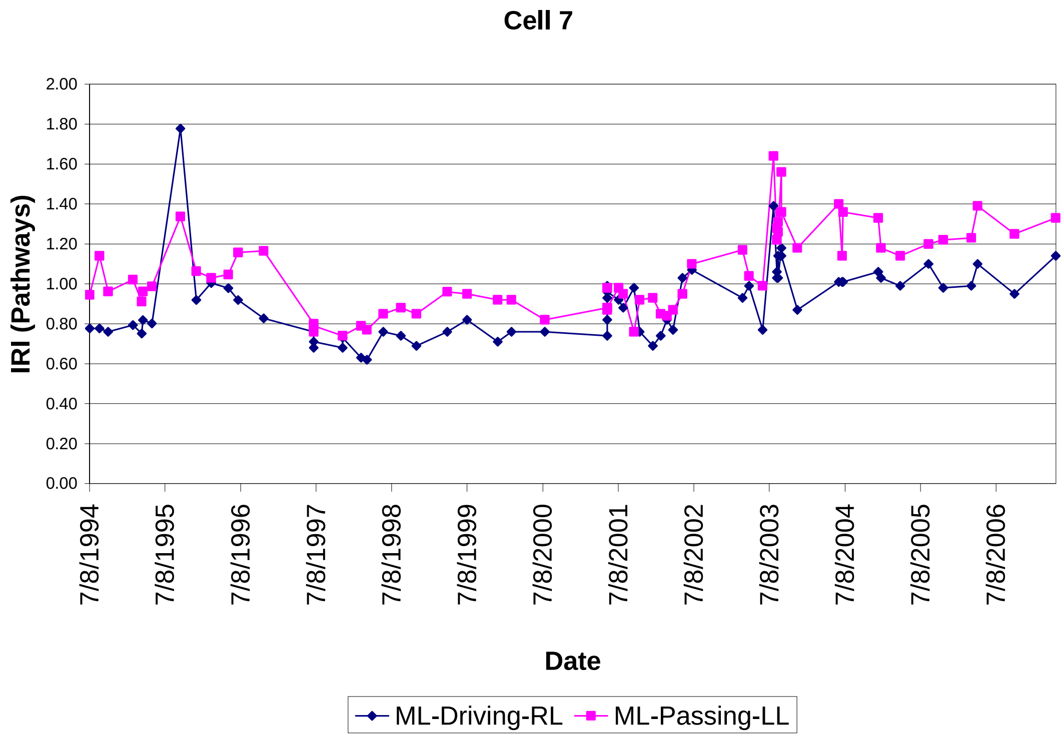
Yearly Changes in IRI

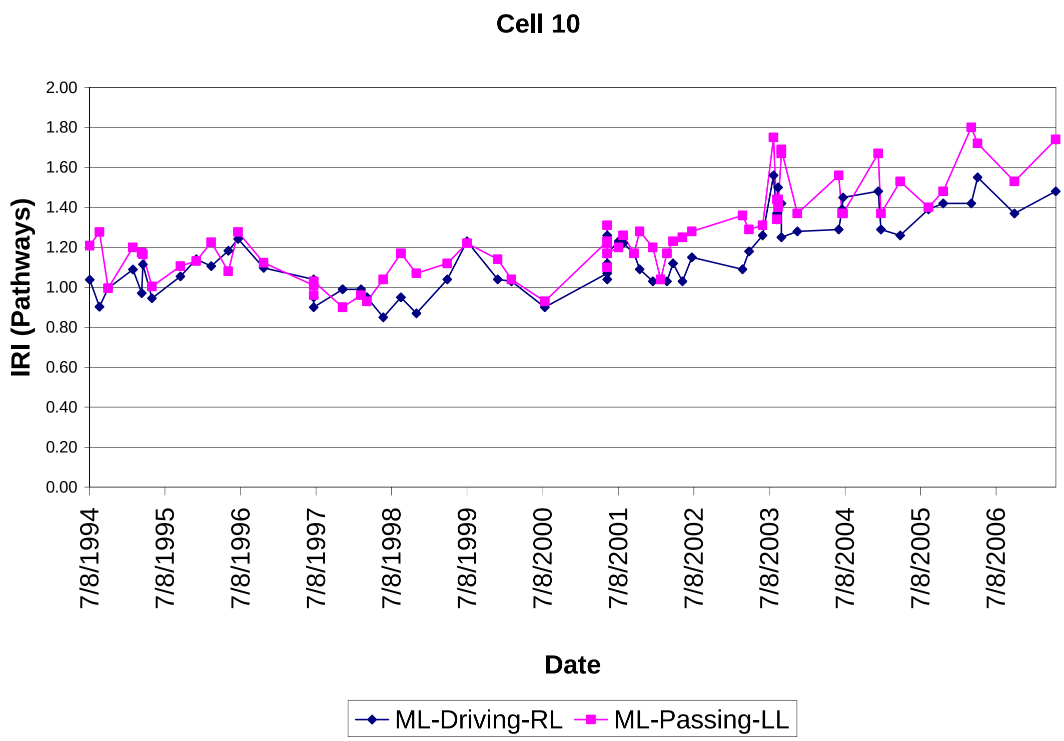


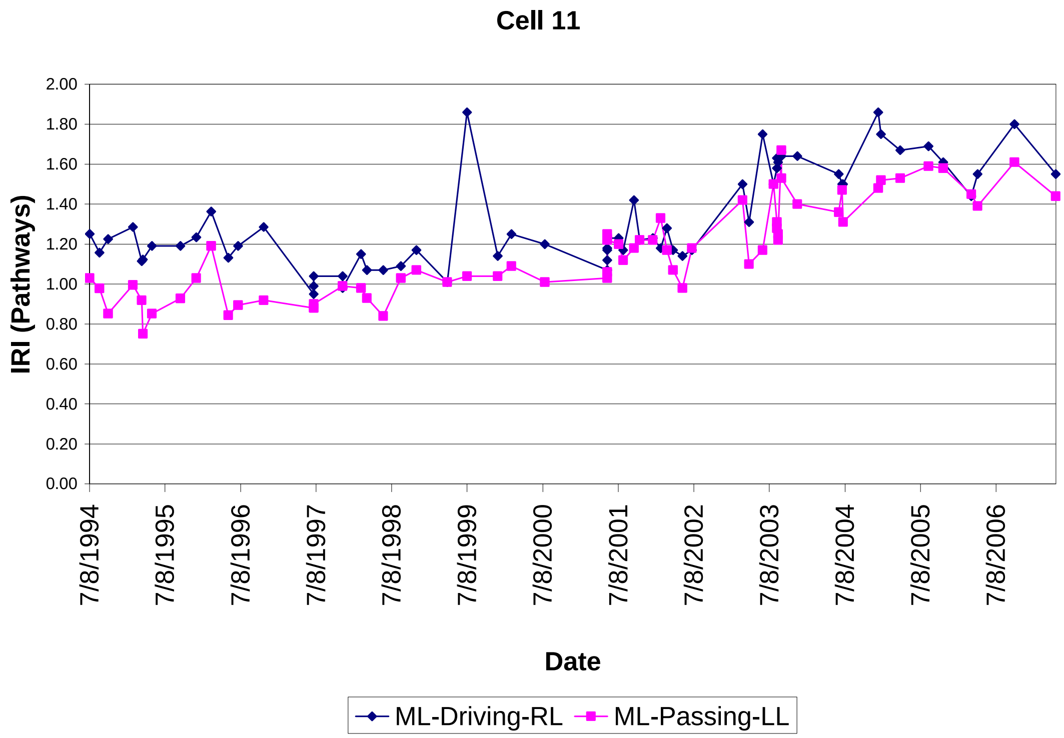
Cell 4
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
IRI (Pathways)
7/8/1994
7/8/1995
7/8/1996
7/8/1997
7/8/1998
7/8/1999
7/8/2000
7/8/2001
7/8/2002
7/8/2003
7/8/2004
7/8/2005
7/8/2006
Date
ML-Driving-RL
ML-Passing-LL

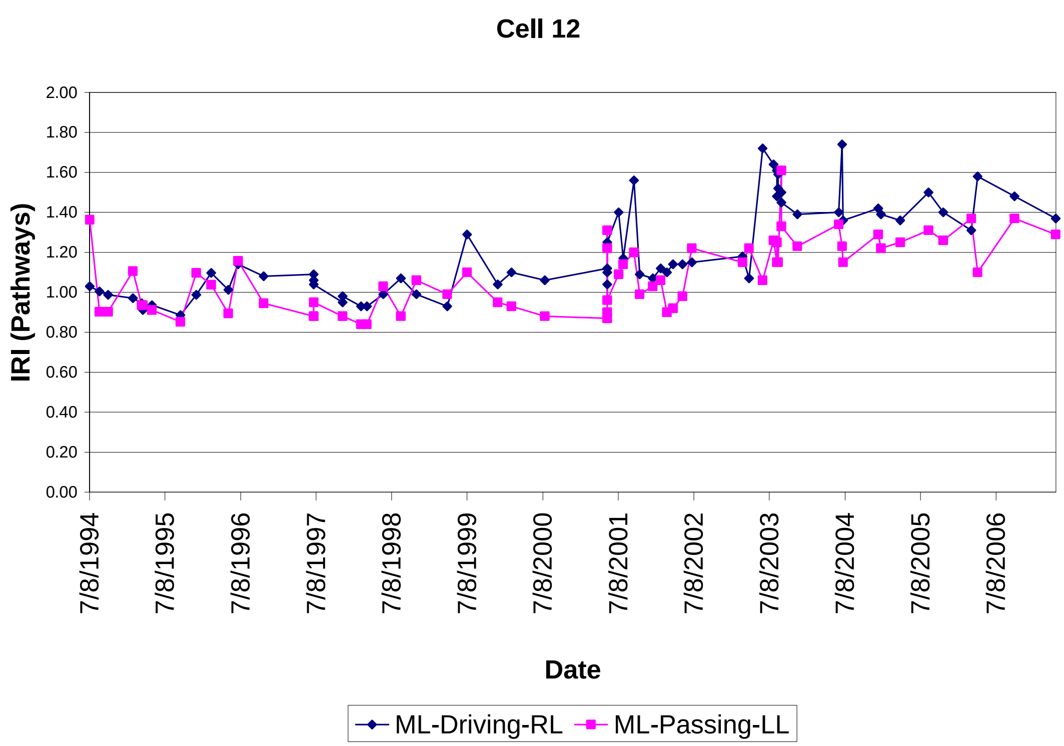


Cell 6
2.50
2.00
1.50
1.00
0.50
0.00
IRI (Pathways)
7/8/1994
7/8/1995
7/8/1996
7/8/1997
7/8/1998
7/8/1999
7/8/2000
7/8/2001
7/8/2002
7/8/2003
7/8/2004
7/8/2005
7/8/2006
Date
ML-Driving-RL
ML-Passing-LL

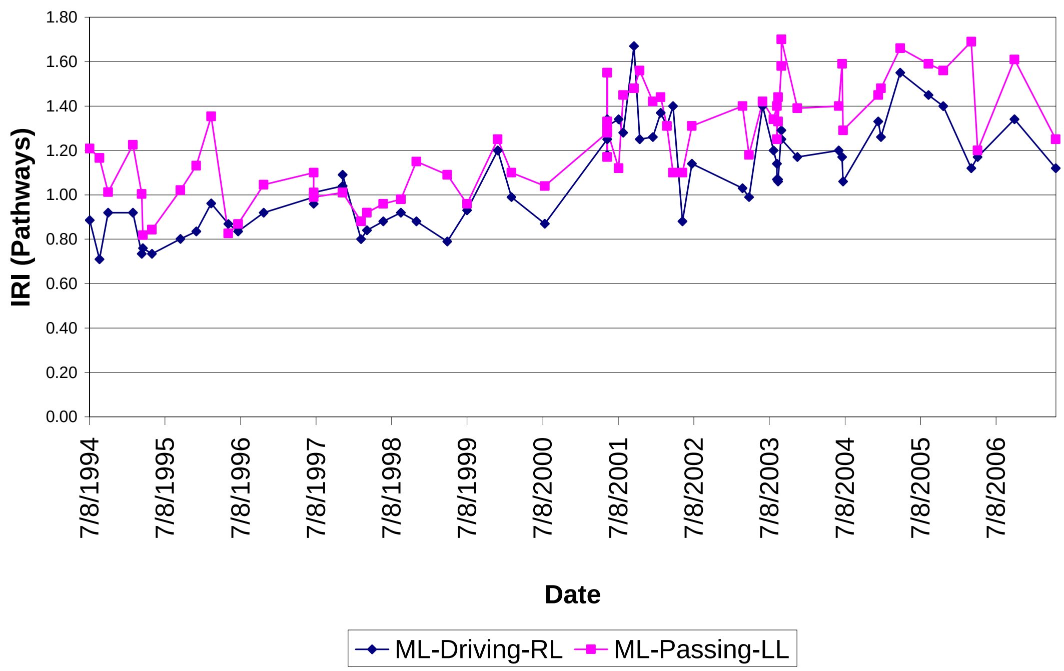

Cell 7
IRI (Pathways)
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
7/8/1994
7/8/1995
7/8/1996
7/8/1997
7/8/1998
7/8/1999
7/8/2000
7/8/2001
7/8/2002
7/8/2003
7/8/2004
7/8/2005
7/8/2006
Date
ML-Driving-RL
ML-Passing-LL


Cell 10
IRI (Pathways)
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
7/8/1994
7/8/1995
7/8/1996
7/8/1997
7/8/1998
7/8/1999
7/8/2000
7/8/2001
7/8/2002
7/8/2003
7/8/2004
7/8/2005
7/8/2006
Date
ML-Driving-RL
ML-Passing-LL

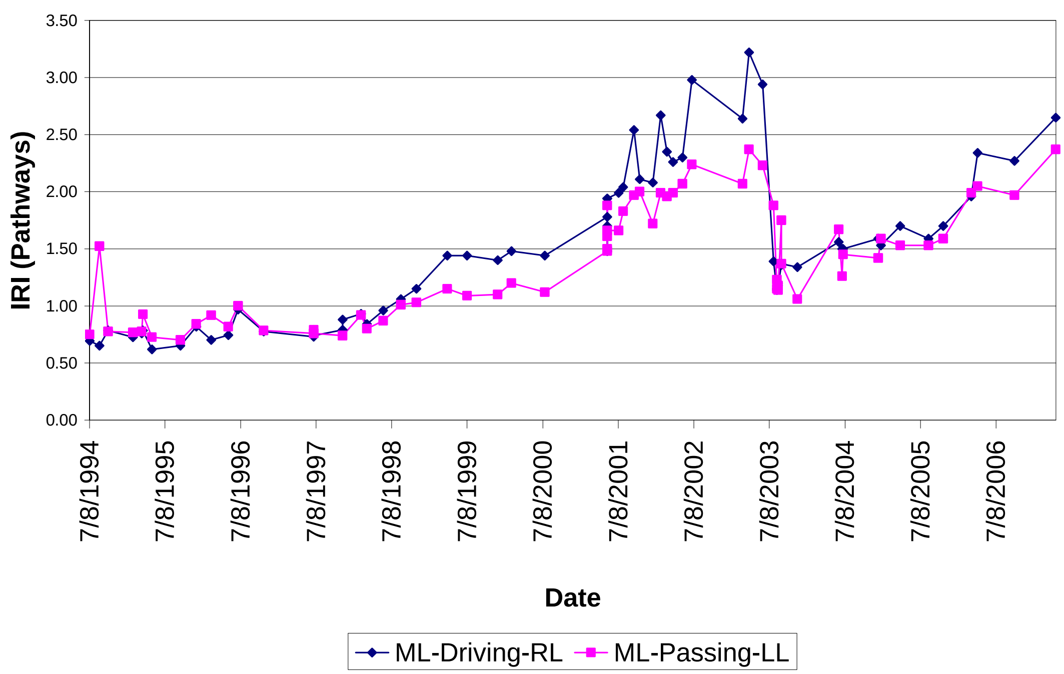

Cell 11
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
IRI (Pathways)
7/8/1994
7/8/1995
7/8/1996
7/8/1997
7/8/1998
7/8/1999
7/8/2000
7/8/2001
7/8/2002
7/8/2003
7/8/2004
7/8/2005
7/8/2006
Date
ML-Driving-RL
ML-Passing-LL

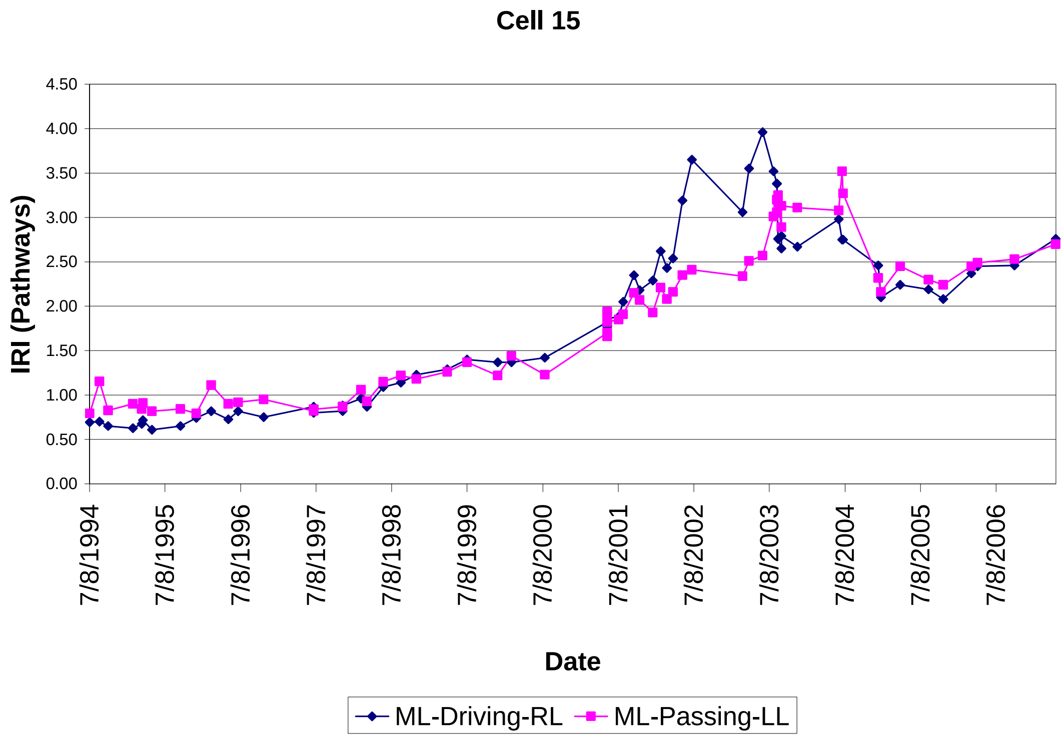

Cell 12
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
IRI (Pathways)
7/8/1994
7/8/1995
7/8/1996
7/8/1997
7/8/1998
7/8/1999
7/8/2000
7/8/2001
7/8/2002
7/8/2003
7/8/2004
7/8/2005
7/8/2006
Date
ML-Driving-RL
ML-Passing-LL

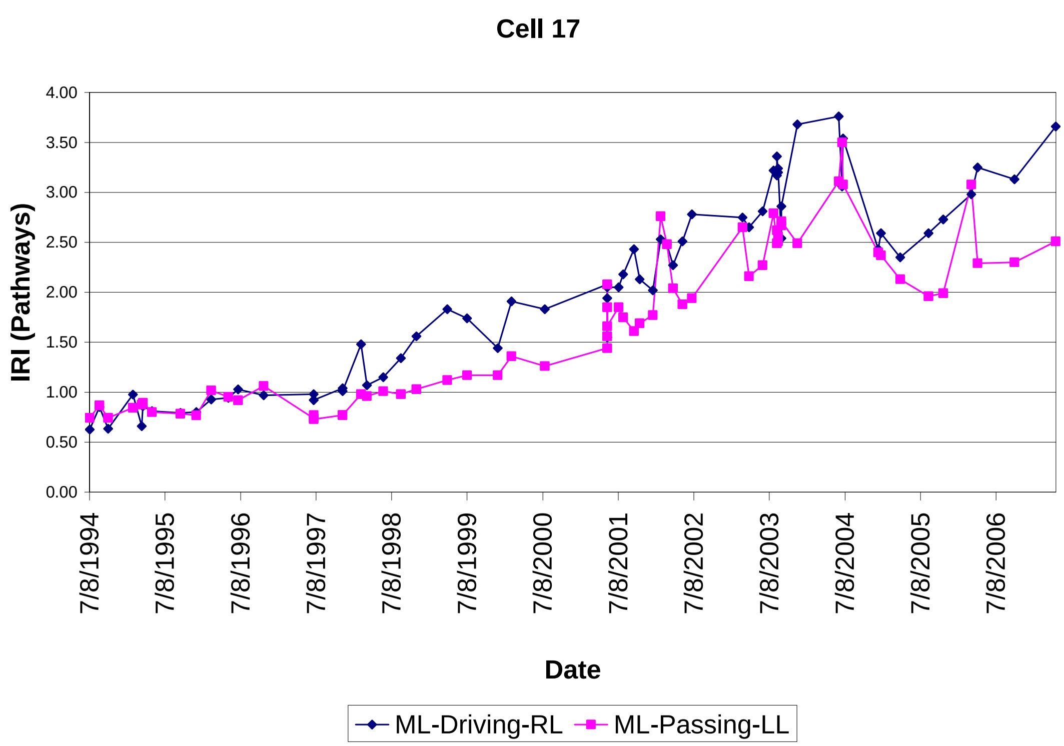
Cell 13

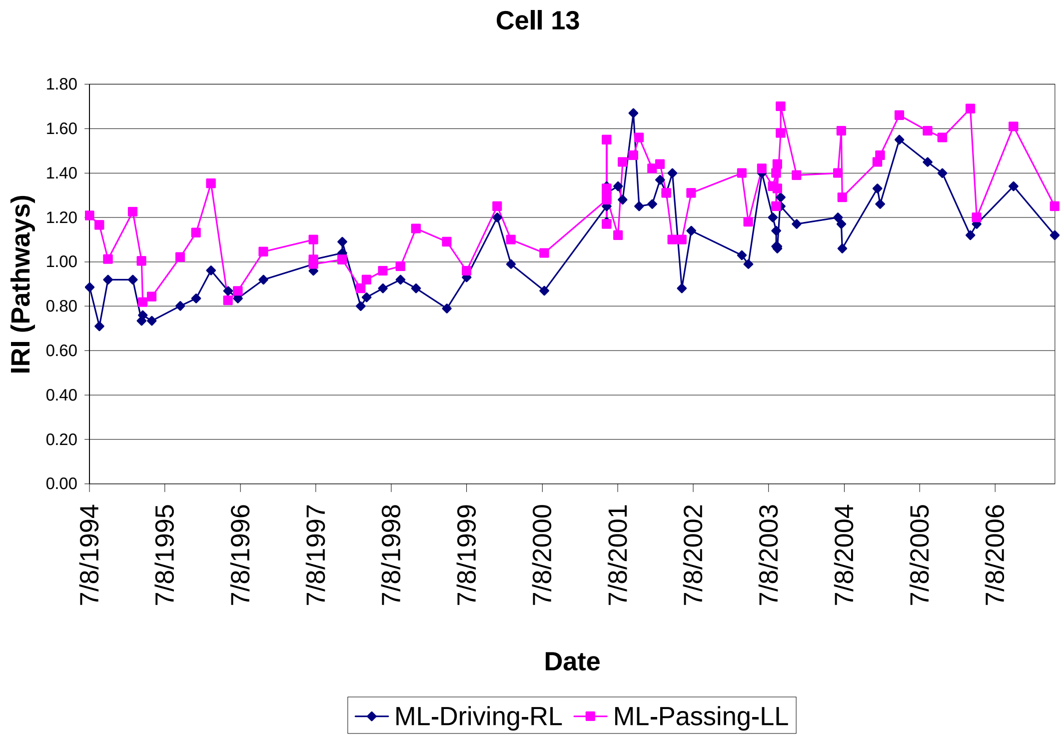


Cell 14

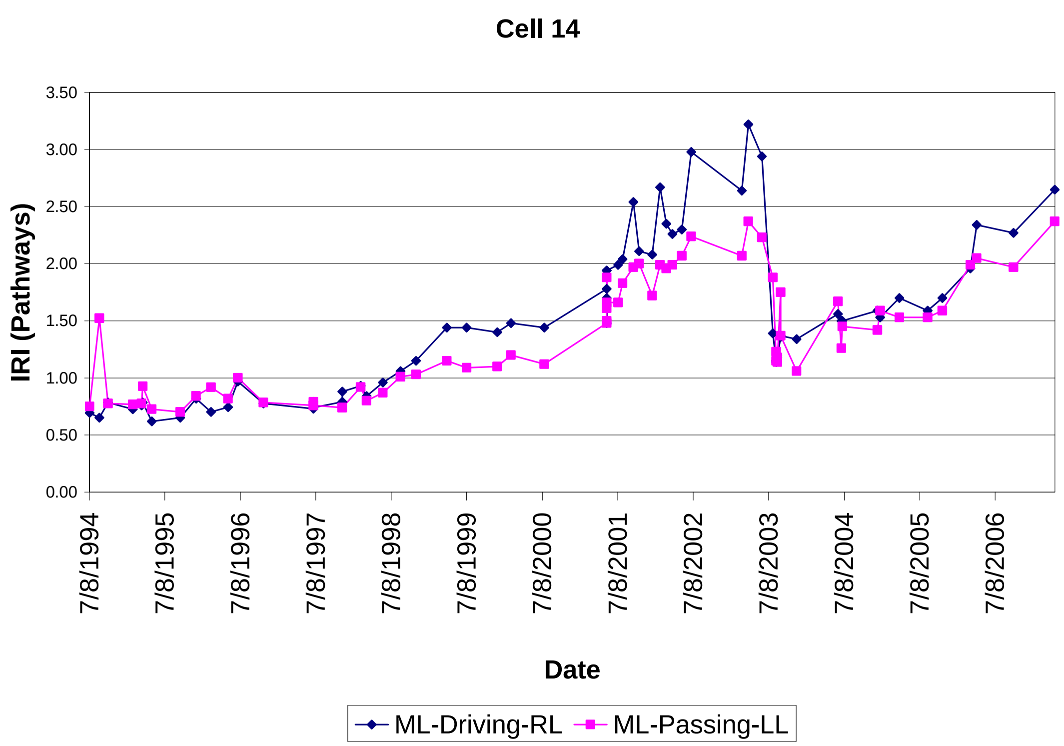



Cell 15
IRI (Pathways)
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
7/8/1994
7/8/1995
7/8/1996
7/8/1997
7/8/1998
7/8/1999
7/8/2000
7/8/2001
7/8/2002
7/8/2003
7/8/2004
7/8/2005
7/8/2006
Date
ML-Driving-RL
ML-Passing-LL

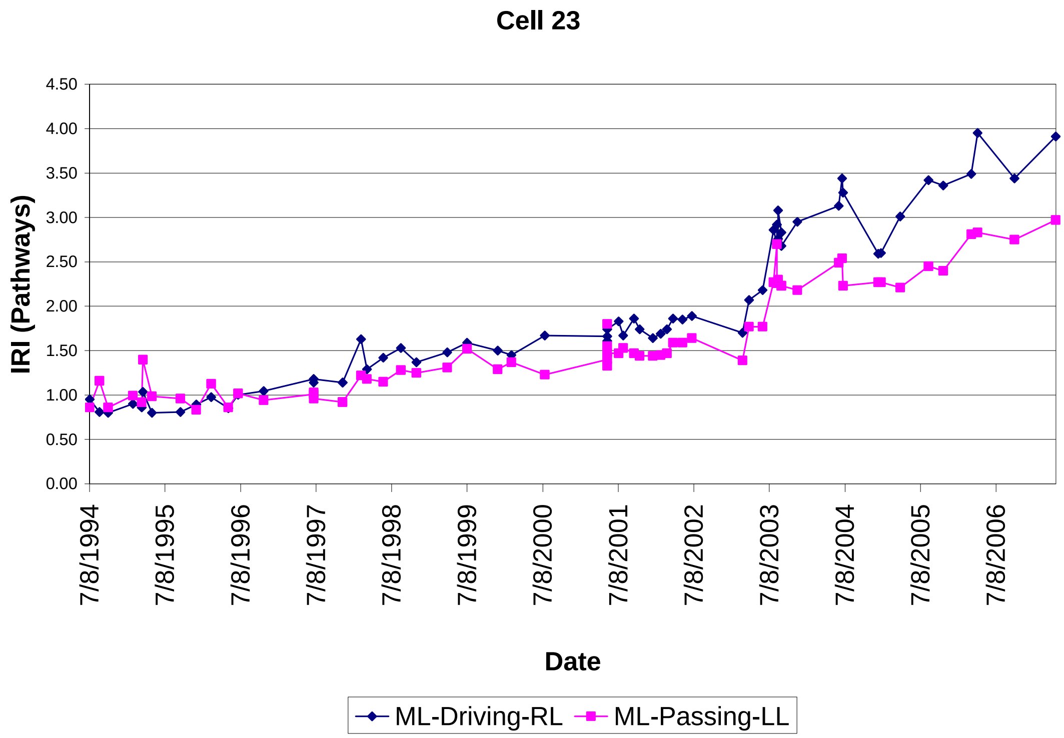

Cell 17
IRI (Pathways)
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
7/8/1994
7/8/1995
7/8/1996
7/8/1997
7/8/1998
7/8/1999
7/8/2000
7/8/2001
7/8/2002
7/8/2003
7/8/2004
7/8/2005
7/8/2006
Date
ML-Driving-RL
ML-Passing-LL

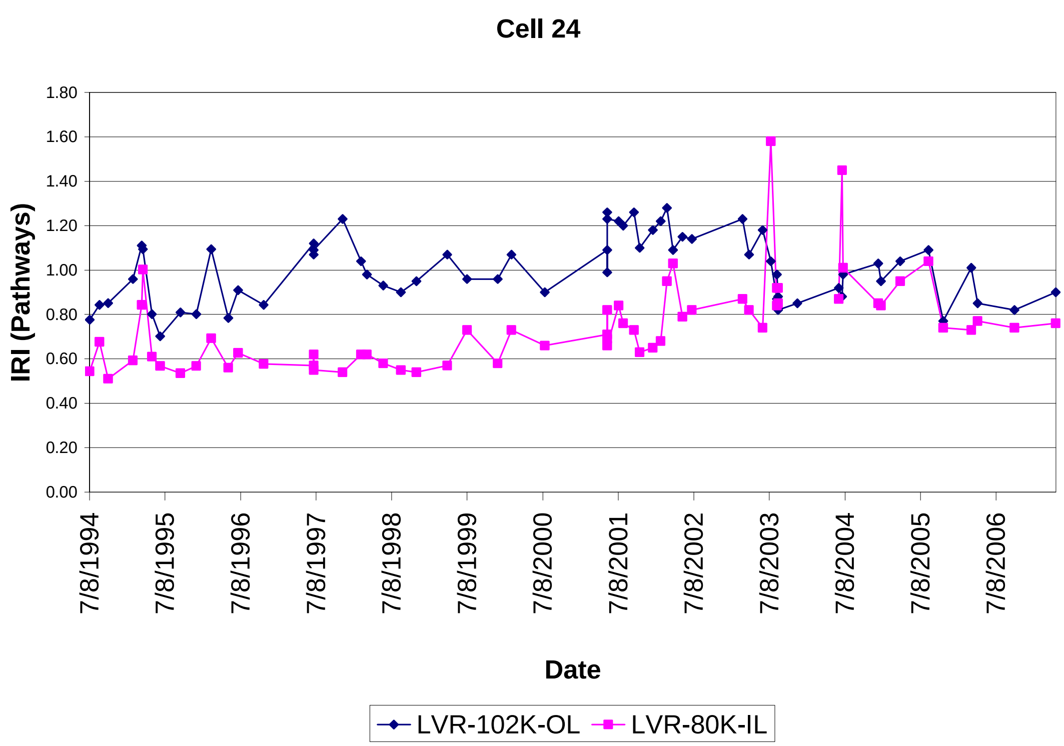


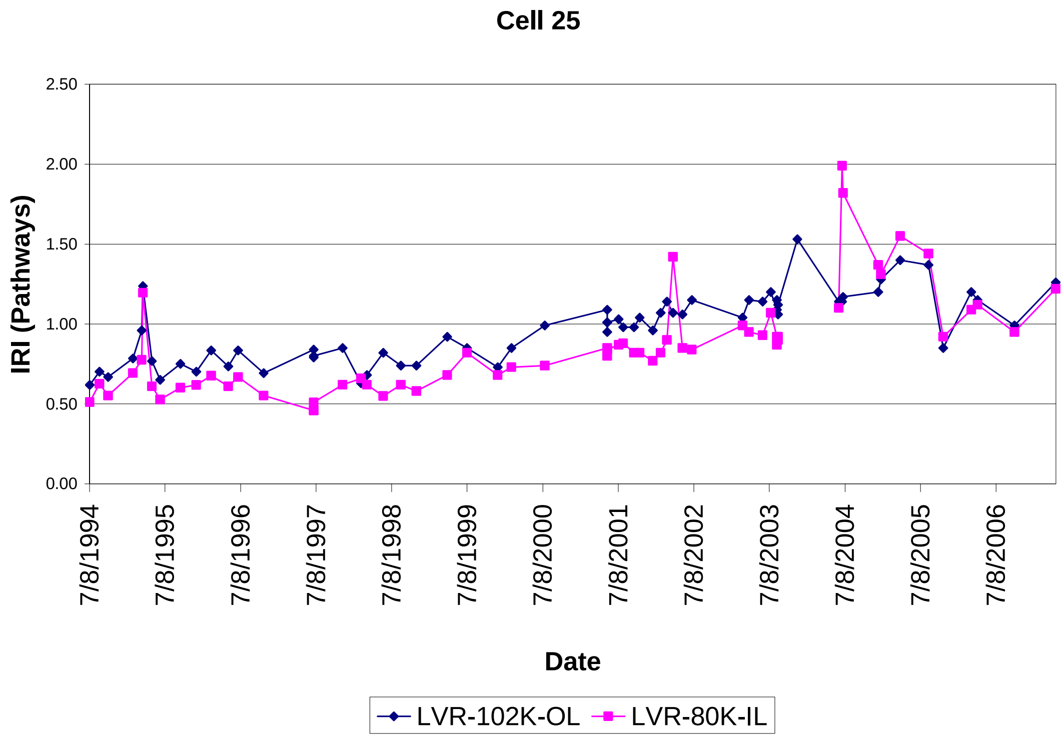
Cell 13
IRI (Pathways)
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
7/8/1994
7/8/1995
7/8/1996
7/8/1997
7/8/1998
7/8/1999
7/8/2000
7/8/2001
7/8/2002
7/8/2003
7/8/2004
7/8/2005
7/8/2006
Date
ML-Driving-RL
ML-Passing-LL



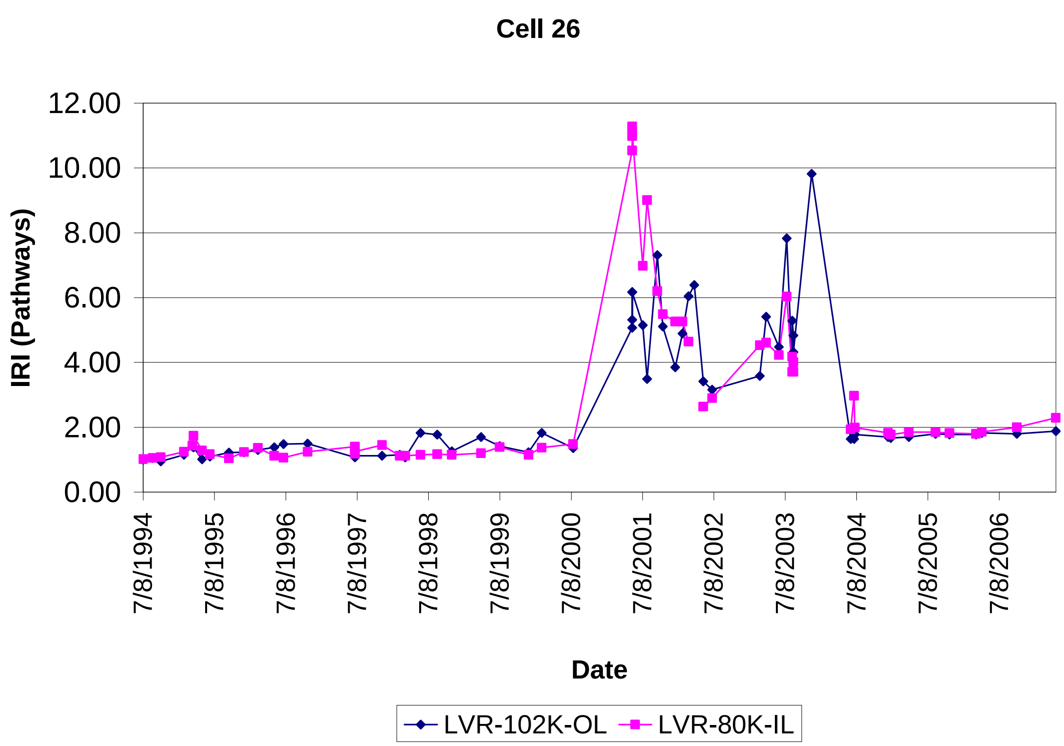
Cell 14
IRI (Pathways)
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
7/8/1994
7/8/1995
7/8/1996
7/8/1997
7/8/1998
7/8/1999
7/8/2000
7/8/2001
7/8/2002
7/8/2003
7/8/2004
7/8/2005
7/8/2006
Date
ML-Driving-RL
ML-Passing-LL


Cell 23
IRI (Pathways)
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
7/8/1994
7/8/1995
7/8/1996
7/8/1997
7/8/1998
7/8/1999
7/8/2000
7/8/2001
7/8/2002
7/8/2003
7/8/2004
7/8/2005
7/8/2006
Date
ML-Driving-RL
ML-Passing-LL

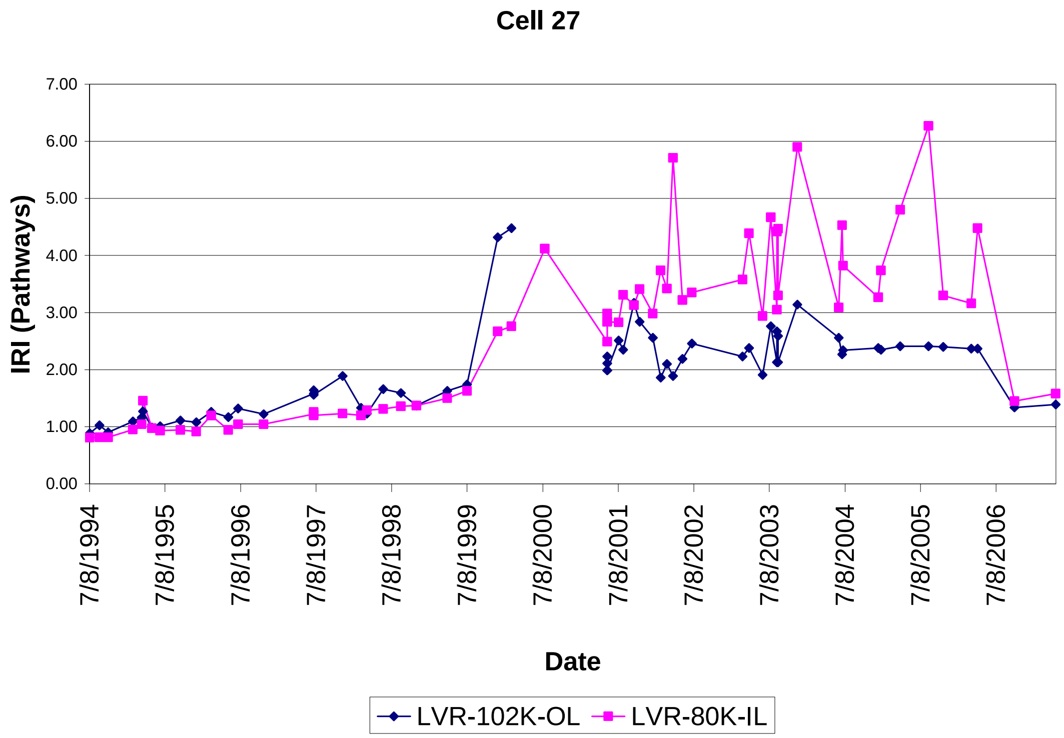

Cell 24
IRI (Pathways)
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
7/8/1994
7/8/1995
7/8/1996
7/8/1997
7/8/1998
7/8/1999
7/8/2000
7/8/2001
7/8/2002
7/8/2003
7/8/2004
7/8/2005
7/8/2006
Date
LVR-102K-OL
LVR-80K-IL

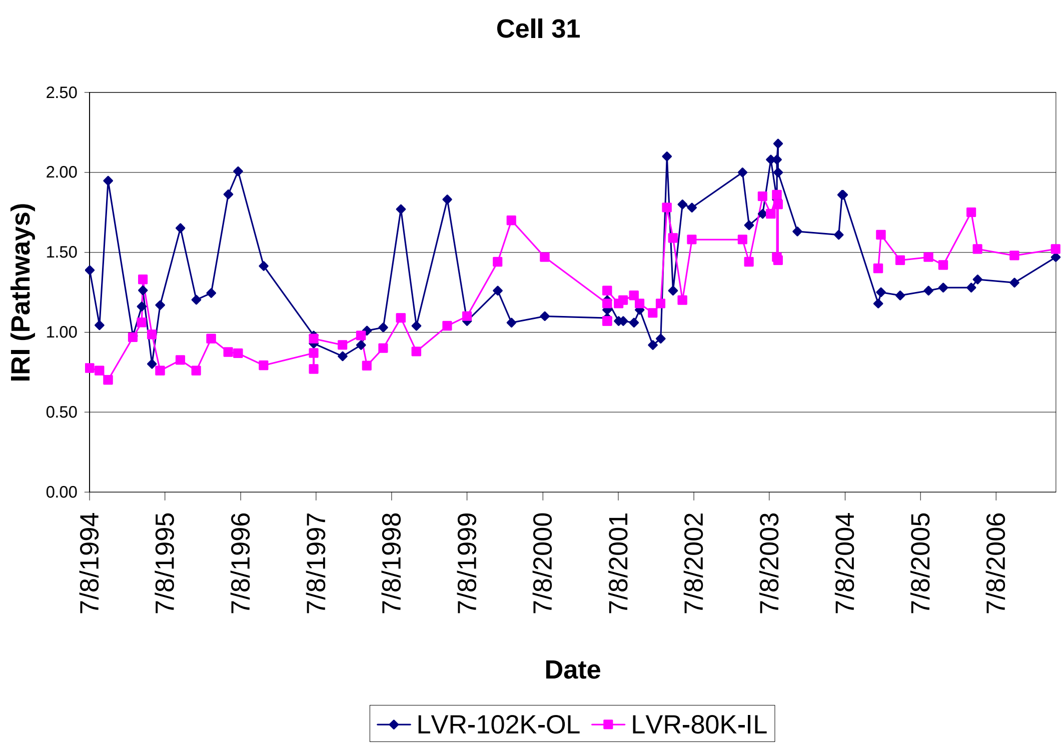


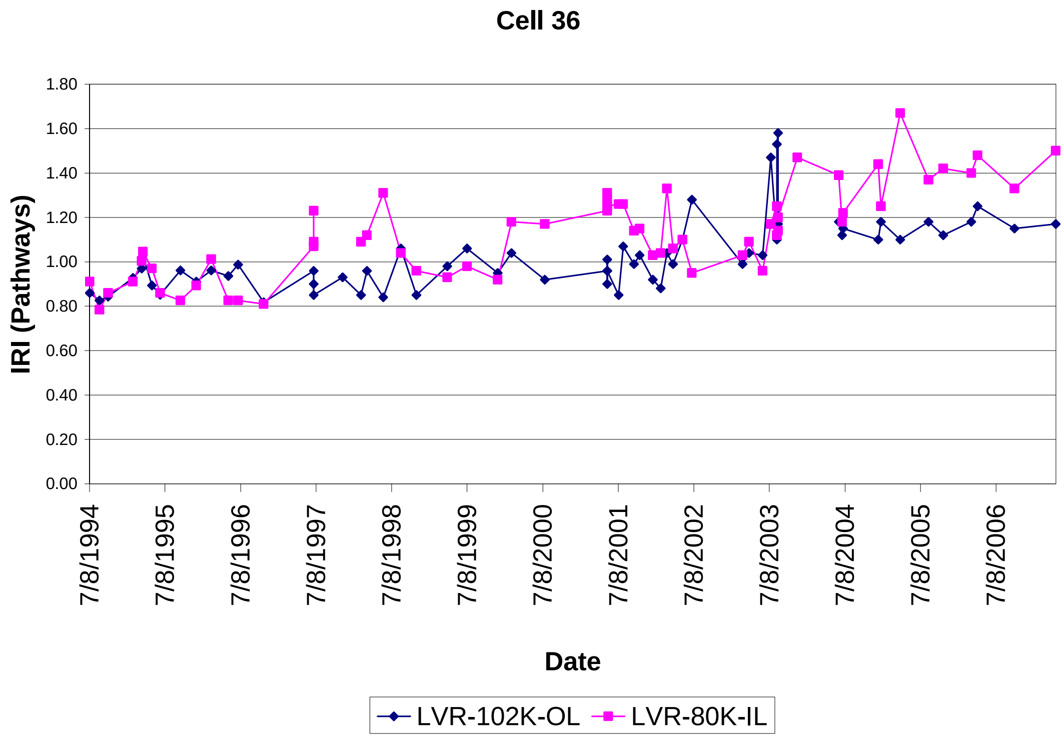
Cell 25
2.50
2.00
1.50
1.00
0.50
0.00
IRI (Pathways)
7/8/1994
7/8/1995
7/8/1996
7/8/1997
7/8/1998
7/8/1999
7/8/2000
7/8/2001
7/8/2002
7/8/2003
7/8/2004
7/8/2005
7/8/2006
Date
LVR-102K-OL
LVR-80K-IL



Cell 26
12.00
10.00
8.00
6.00
4.00
2.00
0.00
IRI (Pathways)
7/8/1994
7/8/1995
7/8/1996
7/8/1997
7/8/1998
7/8/1999
7/8/2000
7/8/2001
7/8/2002
7/8/2003
7/8/2004
7/8/2005
7/8/2006
Date
LVR-102K-OL
LVR-80K-IL


Cell 27
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
IRI (Pathways)
7/8/1994
7/8/1995
7/8/1996
7/8/1997
7/8/1998
7/8/1999
7/8/2000
7/8/2001
7/8/2002
7/8/2003
7/8/2004
7/8/2005
7/8/2006
Date
LVR-102K-OL
LVR-80K-IL

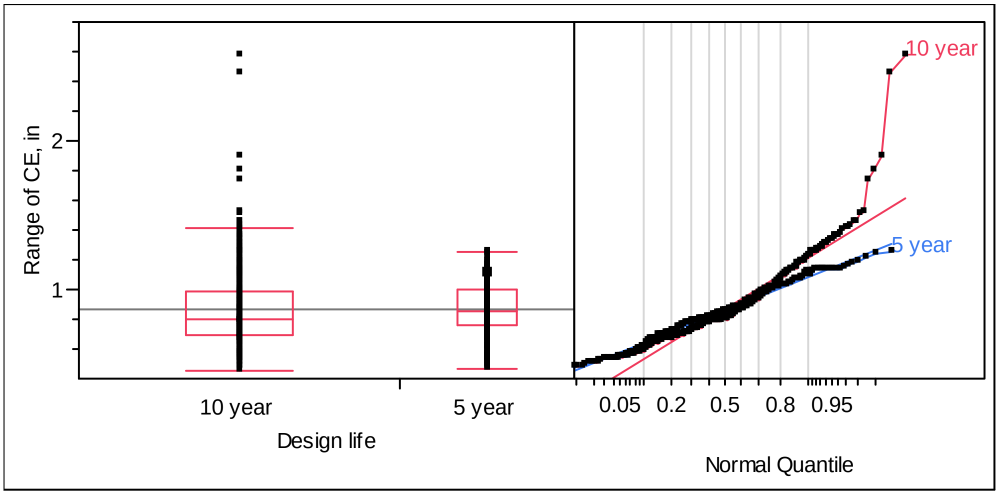

Cell 31
2.50
2.00
1.50
1.00
0.50
0.00
IRI (Pathways)
7/8/1994
7/8/1995
7/8/1996
7/8/1997
7/8/1998
7/8/1999
7/8/2000
7/8/2001
7/8/2002
7/8/2003
7/8/2004
7/8/2005
7/8/2006
Date
LVR-102K-OL
LVR-80K-IL


Cell 36
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
IRI (Pathways)
7/8/1994
7/8/1995
7/8/1996
7/8/1997
7/8/1998
7/8/1999
7/8/2000
7/8/2001
7/8/2002
7/8/2003
7/8/2004
7/8/2005
7/8/2006
Date
LVR-102K-OL
LVR-80K-IL

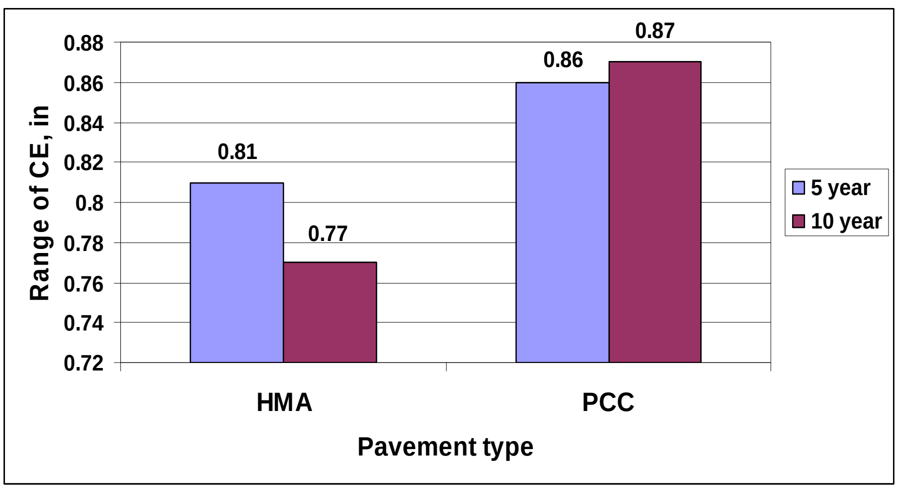
Appendix F

Visual Analysis Plots for Selected Design Features

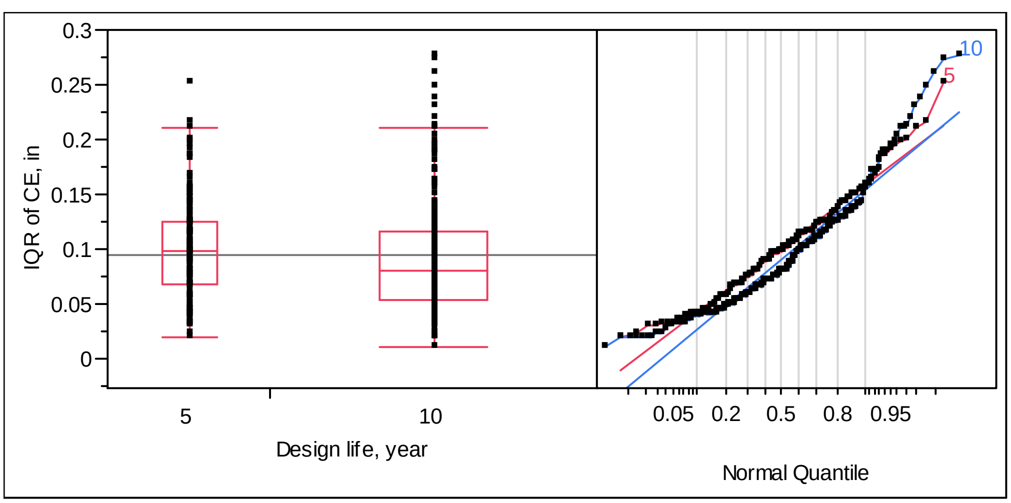
1) Design Life



YRCE Plot

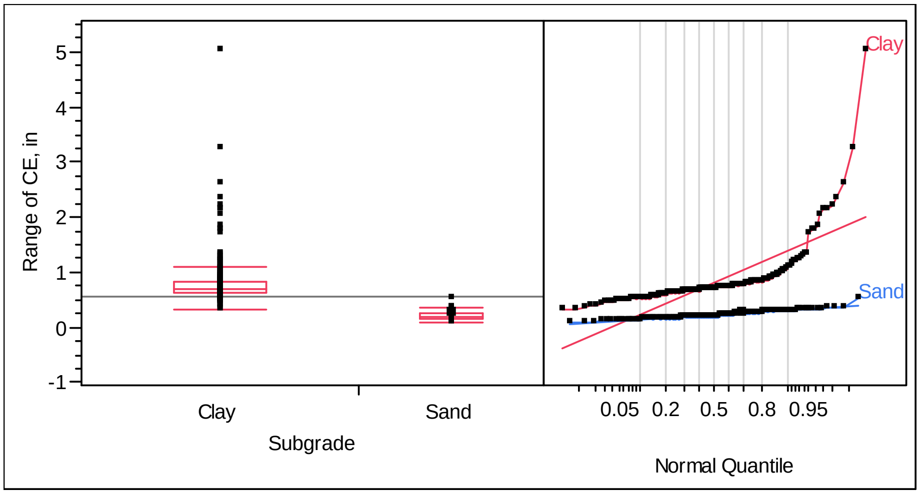


Mean YRCE values

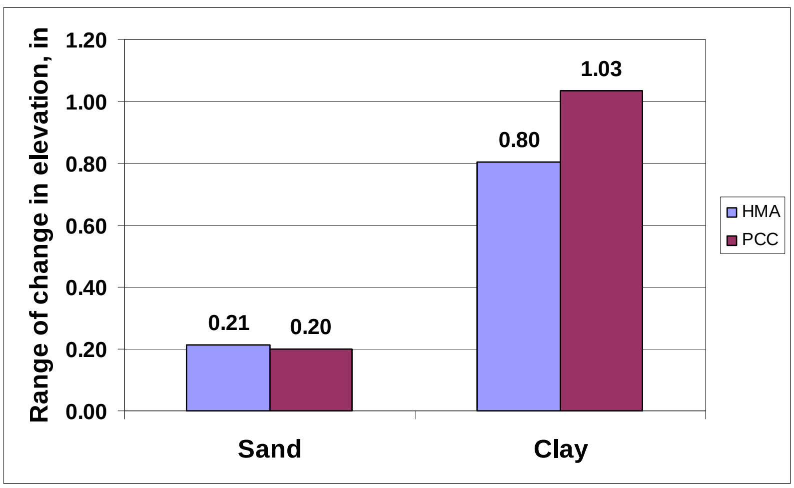


IQR Plot

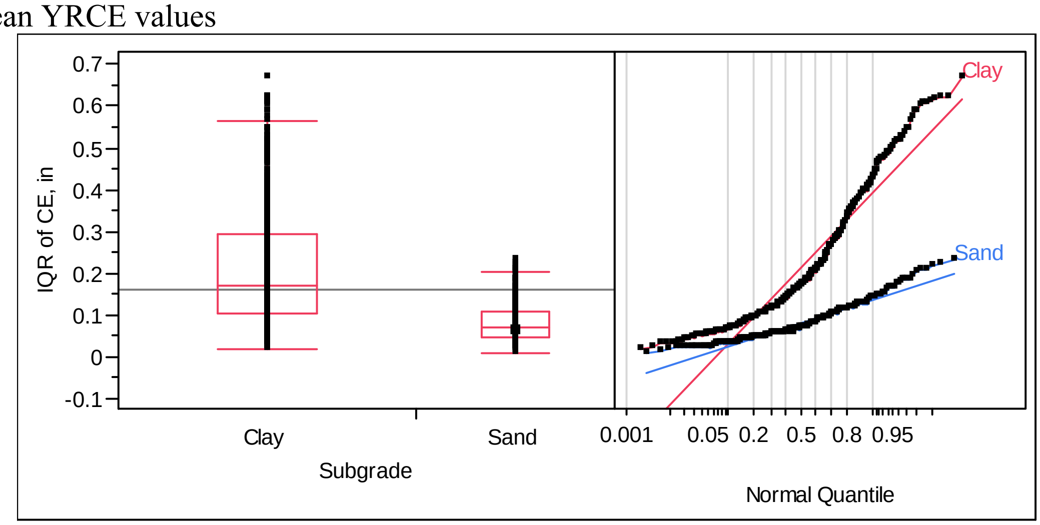
2) Subgrade Type



YRCE Plots for HMA LVR cells



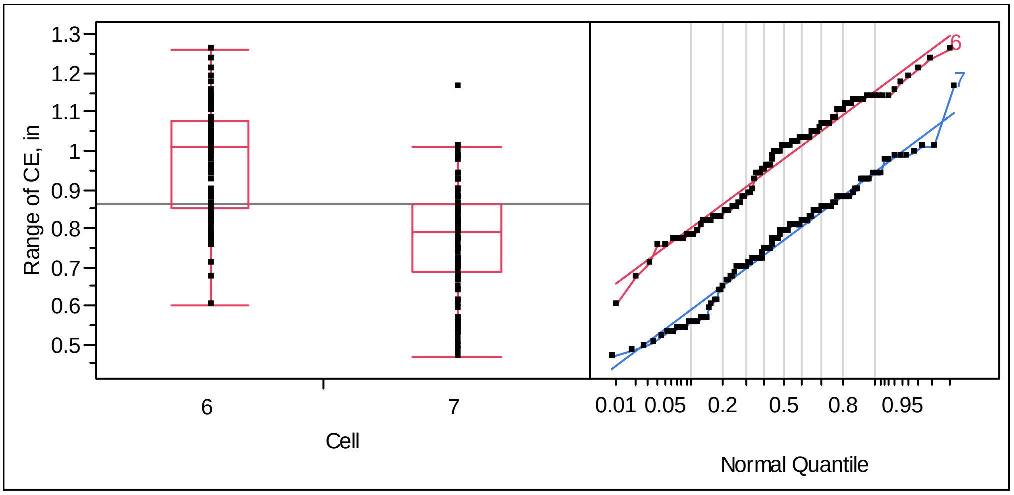
Mean YRCE values



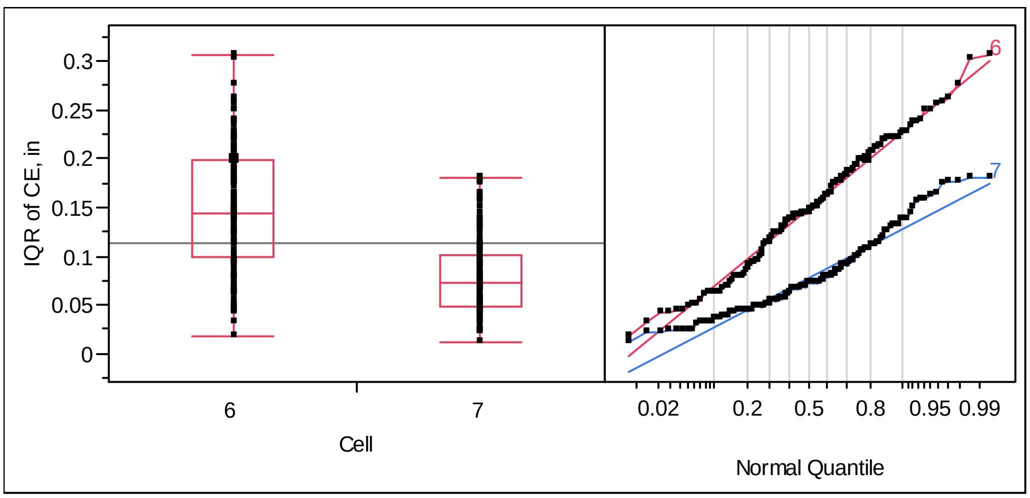
IQR Plots for HMA LVR cells

3) **Drainage**

PCC Aggregate Drainage Layer

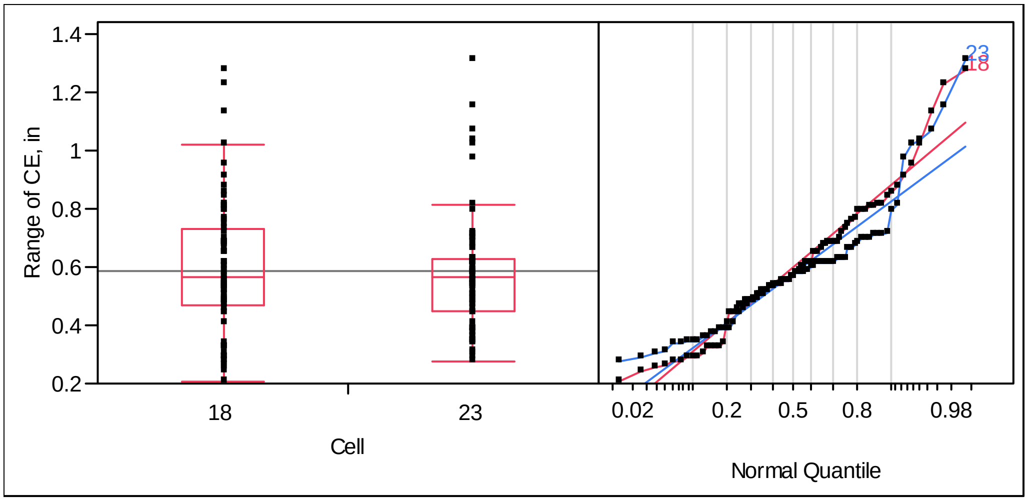


YRCE Plot

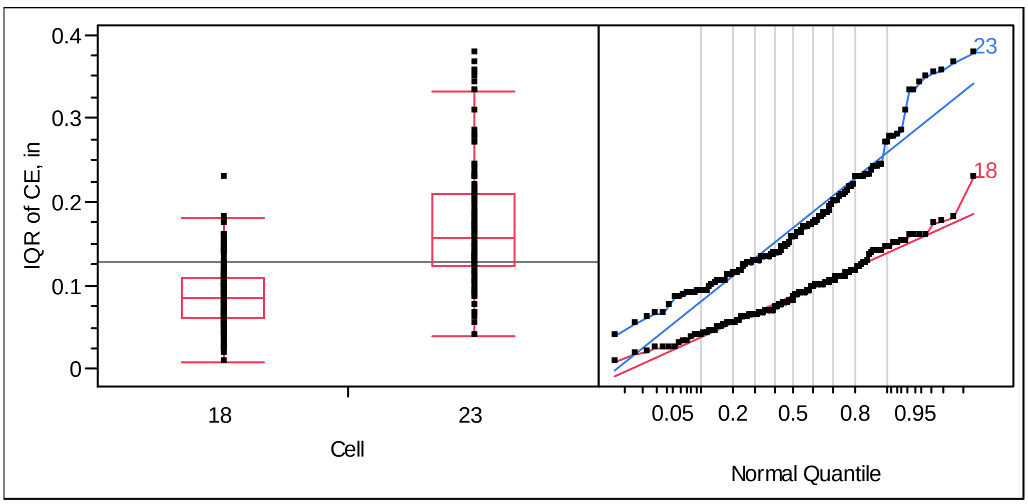


IQR Plot

HMA Aggregate Drainage Layer

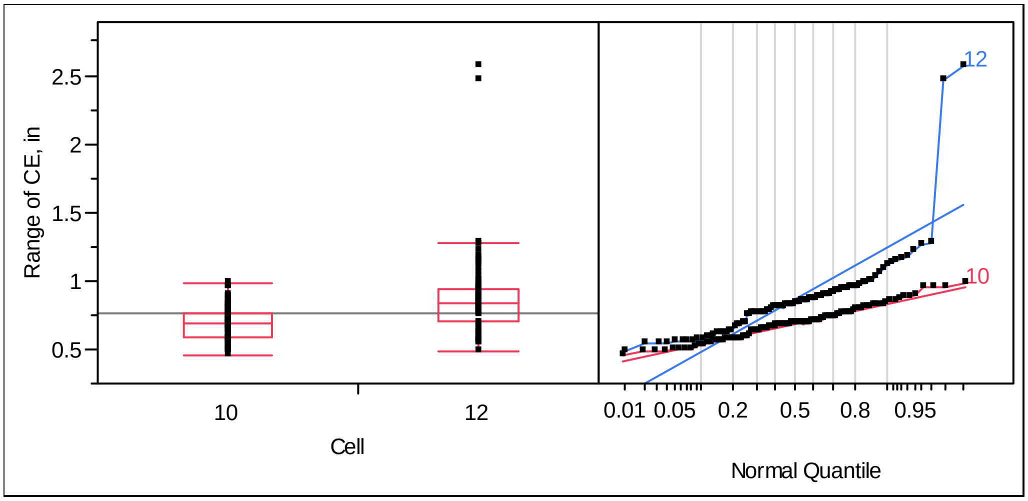


YRCE Plot

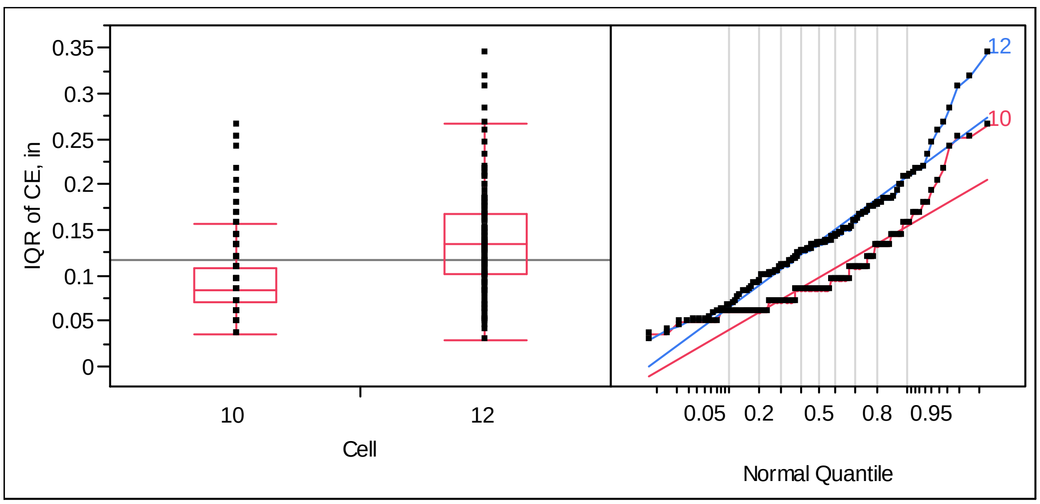


IQR Plot

PCC with Drainage Structure

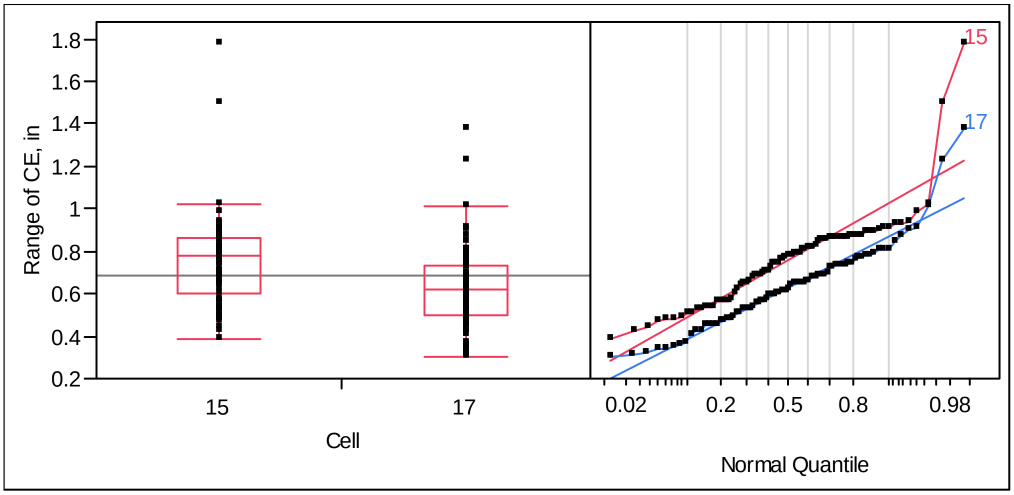


YRCE Plot

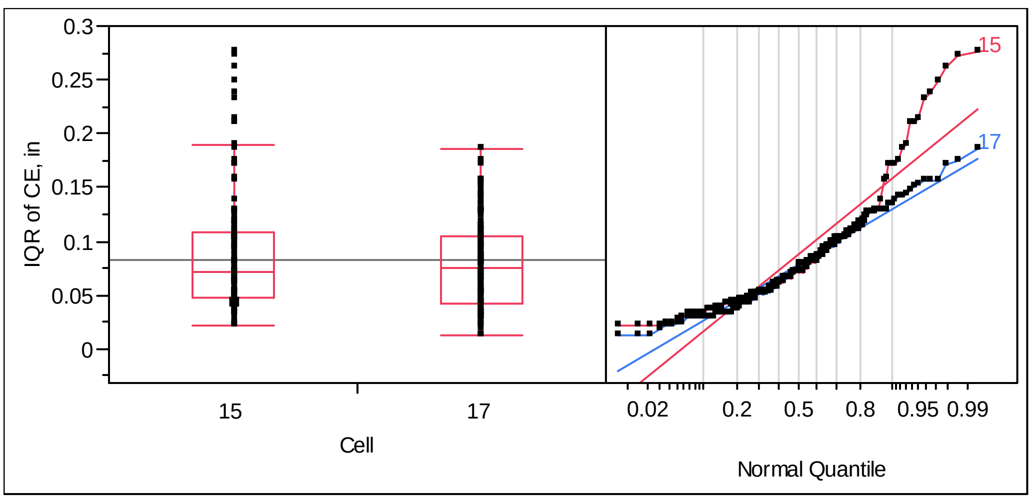


IQR Plot

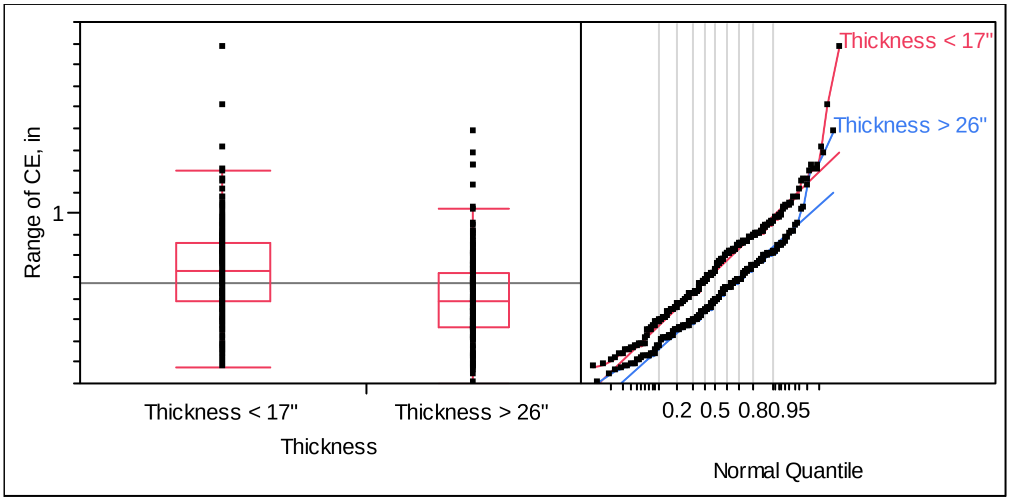
4) Total Pavement Thickness



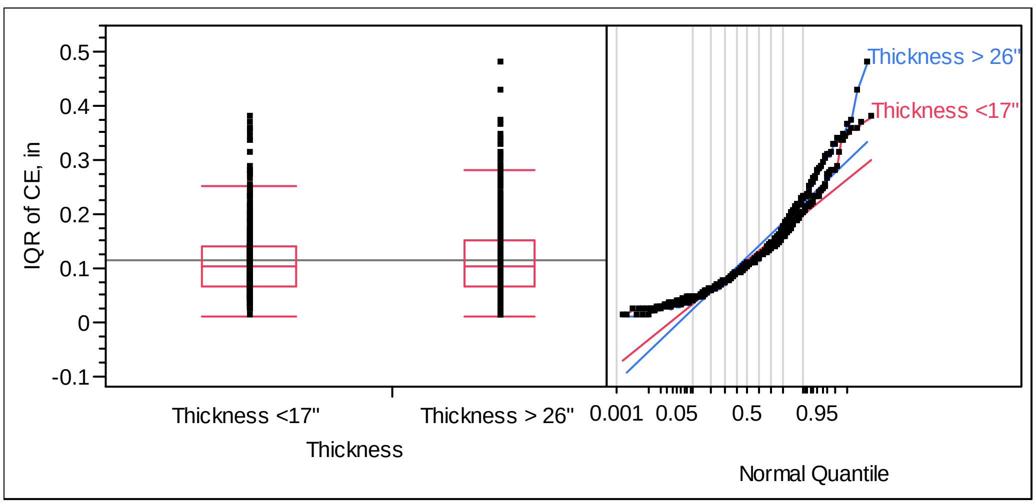
YRCE Plot for First Analysis



IQR Plot for First Analysis

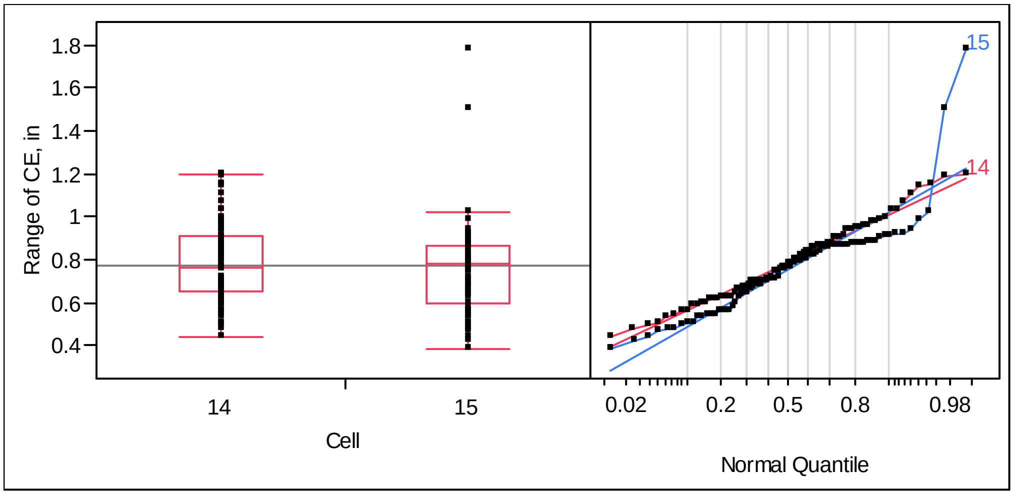


YRCE Plot for Second Analysis

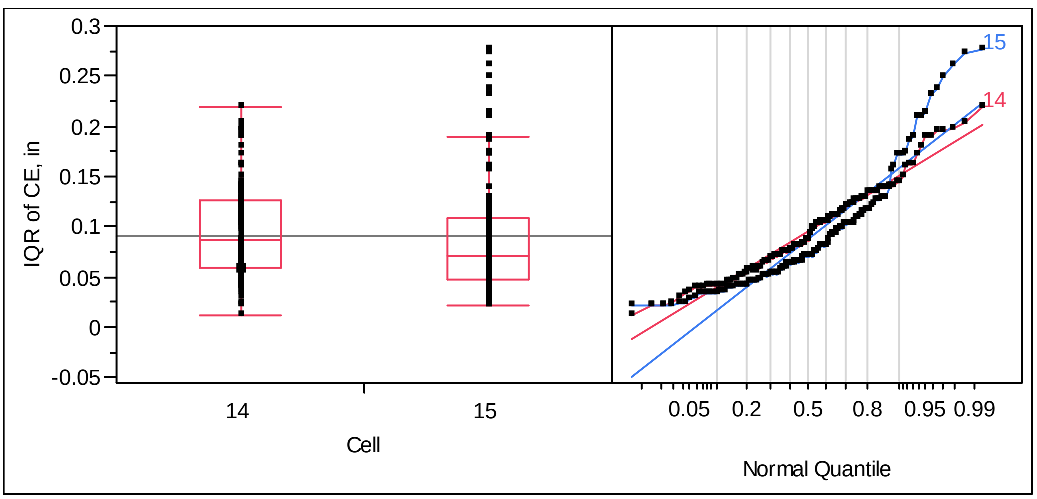


IQR Plot for Second Analysis

5) Asphalt Binder Type

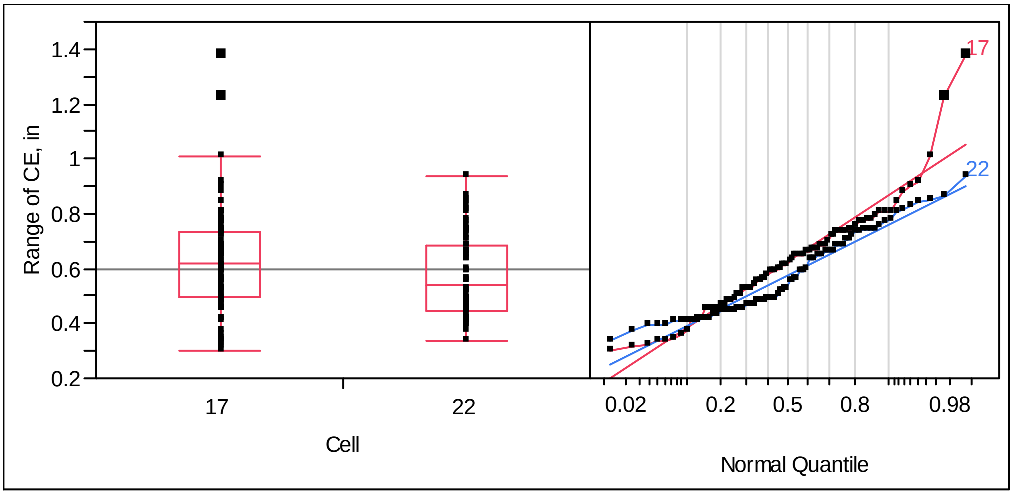


YRCE Plot

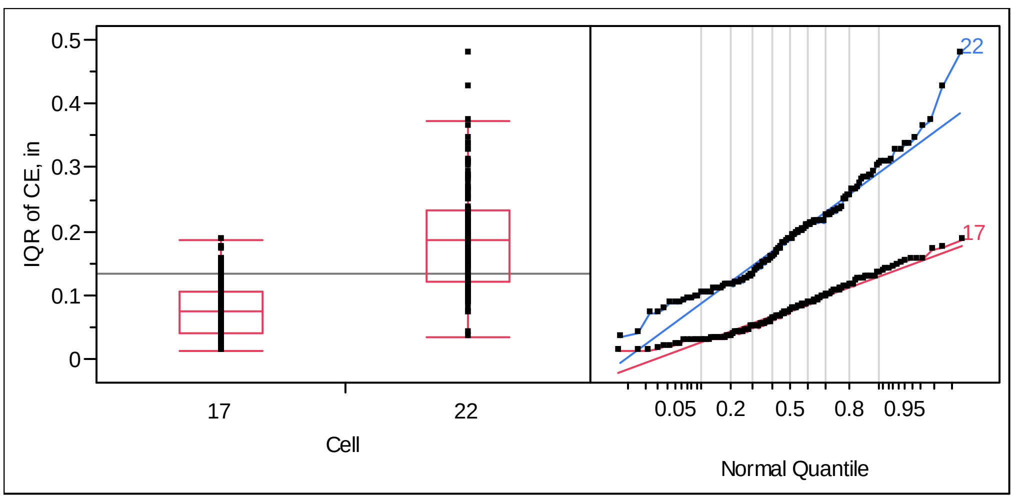


IQR Pot

6) Base Material

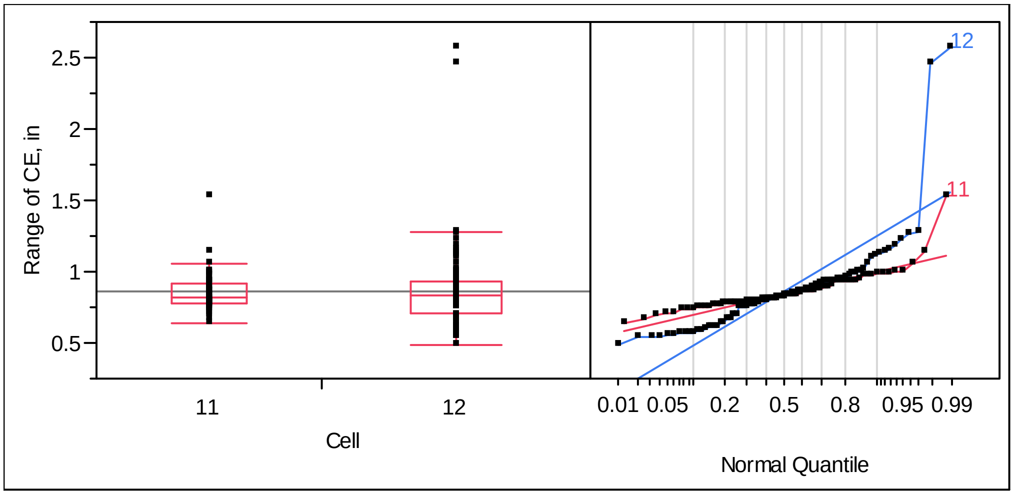


YRCE Plot

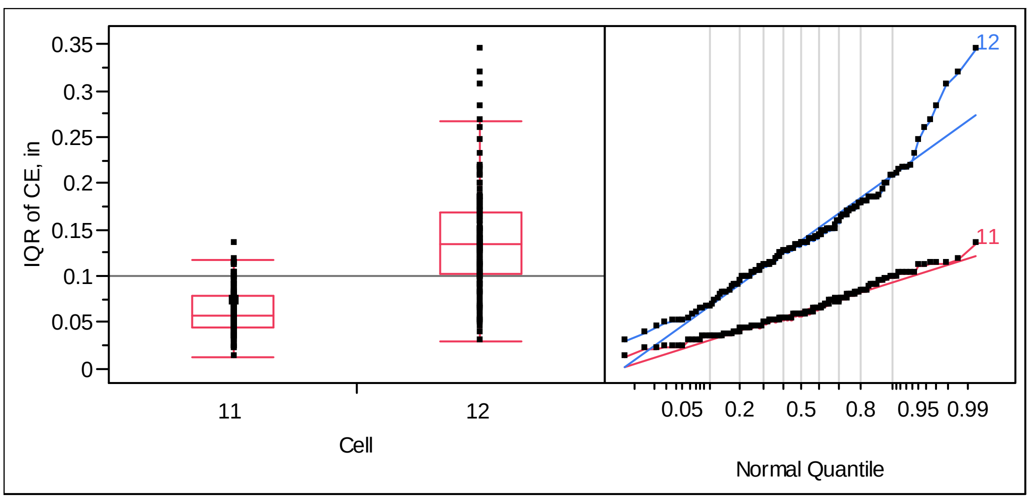


IQR Plot

7) Joint Spacing



YRCE Plot



IQR Plot

Appendix G

Regression Analysis Results

Mainline HMA Cells

For model: $YRCE_{HMA-ML} = \beta_0 + \beta_1 h_{total} + \beta_2 t_{design} + \beta_3 D_1 + \beta_4 D_2$

Coefficient Estimates

Label	Estimate	Std. Error	t-value	P-value
B_0	0.876843	0.0228305	38.407	0.0000
h_{total}	-0.007016	0.000993925	-7.059	0.0000
t_{design}	-0.044820	0.0262502	-1.707	0.0883
D_1	-0.036019	0.0247301	-1.456	0.1458
D_2	-0.144469	0.0239208	-6.039	0.0000
Model Results	R^2	0.193005	σ^	0.187494
	N	559	d_f	554

Summary Analysis of Variance Table

Source	d_f	Sum of Squares	Mean Square Error	F-value	P-value
Model	4	4.65781	1.16445	33.12	0.0000
Residual Error	554	19.4753	0.0351541		
Lack of Fit	2	0.69957	0.349785	10.28	0.0000
Pure Error	552	18.7758	0.0340141		

For model: $YRCE_{HMA-ML} = \beta_0 + \beta_1 h_{total} + \beta_2 D_1$

Coefficient Estimates

Label	Estimate	Std. Error	t-value	P-value
B_0	0.859029	0.0188741	45.514	0.0000
h_{total}	-0.0082724	0.00082707	-10.002	0.0000
D_1	-0.151115	0.0229641	-6.581	0.0000
Model Results	R^2	0.18547	σ^	0.188028
	N	559	d_f	556

Summary Analysis of Variance Table

Source	d_f	Sum of Squares	Mean Square Error	F-value	P-value
Model	2	4.47598	2.23799	63.30	0.0000
Residual Error	556	19.6572	0.0353546		
Lack of Fit	4	0.881401	0.22035	6.48	0.0000
Pure Error	552	18.7758	0.0340141		

For model: $IQR_{HMA-ML} = \beta_0 + \beta_1 h_{total} + \beta_2 t_{design} + \beta_3 D_1 + \beta_4 D_2$

Coefficient Estimates

Label	Estimate	Std. Error	t-value	P-value
B_0	0.0957309	0.005986	15.990	0.000
h_{total}	0.0006462	0.000260	2.481	0.013
t_{design}	0.0030907	0.006877	0.449	0.653
D_1	-0.0296215	0.006523	-4.541	0.000
D_2	0.0604395	0.006306	9.584	0.000
Model Results	R^2	0.1228	σ^	0.06482
	N	967	d_f	962

Summary Analysis of Variance Table

Source	d_f	Sum of Squares	Mean Square Error	F-value	P-value
Model	4	0.565628	0.141407	33.66	0.000
Residual Error	962	4.04163	0.004201		
Lack of Fit	2	1.10704	0.553521	181.07	0.000
Pure Error	960	2.93459	0.003057		

For model: $IQR_{HMA-ML} = \beta_0 + \beta_1 h_{total} + \beta_2 D_1 + \beta_3 D_2$

Coefficient Estimates

Label	Estimate	Std. Error	t-value	P-value
B_0	0.0972287	0.004971	19.559	0.000
h_{total}	0.0006986	0.000233	3.002	0.028
D_1	-0.0295437	0.006518	-4.531	0.000
D_2	0.0611831	0.006083	10.058	0.000
Model Results	R^2	0.1225	σ^	0.06479
	N	967	d_f	963

Summary Analysis of Variance Table

Source	d_f	Sum of Squares	Mean Square Error	F-value	P-value
Model	4	0.564779	0.18826	44.85	0.000
Residual Error	962	4.04248	0.004198		
Lack of Fit	2	1.10789	0.369297	120.81	0.000
Pure Error	960	2.93459	0.003057		

LVR HMA Cells

For model: $YRCE_{HMA-LVR} = \beta_0 + \beta_1 h_{total} + \beta_2 S_{type}$

Coefficient Estimates

Label	Estimate	Std. Error	t-value	P-value
B_0	0.213321	0.0375280	5.684	0.0000
h_{total}	0.000058	0.0040806	0.014	09888
S_{type}	0.590121	0.0460152	12.824	0.0000
Model Results	R^2	0.403675	σ^	0.352943
	N	400	d_f	397

Summary Analysis of Variance Table

Source	d_f	Sum of Squares	Mean Square Error	F-value	P-value
Model	2	33.4771	16.7386	134.37	0.0000
Residual Error	397	49.4537	0.124569		
Lack of Fit	2	0.11114	0.0555673	0.44	0.6413
Pure Error	395	49.3426	0.124918		

For model: $YRCE_{HMA-LVR} = \beta_0 + \beta_1 S_{type}$

Coefficient Estimates

Label	Estimate	Std. Error	t-value	P-value
B_0	0.213675	0.027868	7.668	0.000
S_{type}	0.590525	0.035977	16.414	0.000
Model Results	R^2	0.404	σ^	0.352
	N	400	d_f	398

Summary Analysis of Variance Table

Source	d_f	Sum of Squares	Mean Square Error	F-value	P-value
Model	1	33.4771	33.4771	269.42	0.000
Residual Error	398	49.4538	0.1243		
Lack of Fit					
Pure Error	398	49.4538	0.1243		

For model: $IQR_{HMA-LVR} = \beta_0 + \beta_1 h_{total} + \beta_2 S_{type}$

Coefficient Estimates

Label	Estimate	Std. Error	t-value	P-value
B_0	0.0537145	0.00854943	6.283	0.0000
h_{total}	0.00432897	0.00092963	4.657	0.0000
S_{type}	0.102229	0.0104829	9.752	0.0000
Model Results	R^2	0.269376	σ^	0.111558
	N	770	d_f	767

Summary Analysis of Variance Table

Source	d_f	Sum of Squares	Mean Square Error	F-value	P-value
Model	2	3.51936	1.75968	141.39	0.0000
Residual Error	767	9.54547	0.0124452		
Lack of Fit	2	2.27071	1.13536	119.39	0.0000
Pure Error	765	7.27476	0.00950949		

Mainline PCC Cells

For model: $YRCE_{PCC-ML} = \beta_0 + \beta_1 h_{total} + \beta_2 J_{space} + \beta_3 D_1 + \beta_4 D_2$

Coefficient Estimates

Label	Estimate	Std. Error	t-value	P-value
B_0	1.31141	0.185488	7.070	0.0000
h_{total}	-0.01057	0.015802	-0.669	0.5038
J_{space}	-0.00915	0.004406	-2.078	0.0382
D_1	-0.15654	0.034959	-4.478	0.0000
D_2	-0.23774	0.024600	-9.665	0.0000
Model Results	R^2	0.2515	σ^	0.2060
	N	592	d_f	587

Summary Analysis of Variance Table

Source	d_f	Sum of Squares	Mean Square Error	F-value	P-value
Model	4	8.3701	2.0925	49.33	0.000
Residual Error	587	24.8979	0.0424		
Lack of Fit	1	2.5401	2.5401	66.58	0.000
Pure Error	586	22.3578	0.0382		

For model: $YRCE_{PCC-ML} = \beta_0 + \beta_1 J_{space} + \beta_2 D_1 + \beta_3 D_3$

Coefficient Estimates

Label	Estimate	Std. Error	t-value	P-value
B_0	1.1960	0.06789	17.617	0.0000
J_{space}	-0.0109	0.00343	-3.200	0.0014
D_1	-0.1699	0.02871	-5.916	0.0000
D_2	-0.2483	0.01875	-13.251	0.0000
Model Results	R^2	0.2510	σ^	0.2058
	N	592	d_f	587

Summary Analysis of Variance Table

Source	d_f	Sum of Squares	Mean Square Error	F-value	P-value
Model	3	8.3511	2.7837	65.69	0.000
Residual Error	588	24.9169	0.0434		
Lack of Fit	1	2.21111	2.2111	57.16	0.000
Pure Error	587	22.7057	0.0387		

For model: $IQR_{PCC-ML} = \beta_0 + \beta_1 h_{total} + \beta_2 J_{space} + \beta_3 D_1 + \beta_4 D_2$

Coefficient Estimates

Label	Estimate	Std. Error	t-value	P-value
B_0	0.0612	0.04091	1.497	0.1347
h_{total}	0.0221	0.00351	6.312	0.0000
J_{space}	-0.0129	0.00092	-14.135	0.0000
D_1	-0.0567	0.00729	-7.577	0.0000
D_2	-0.0563	0.00549	-10.264	0.0000
Model Results	R^2	0.2836	σ^	0.0521
	N	834	d_f	829

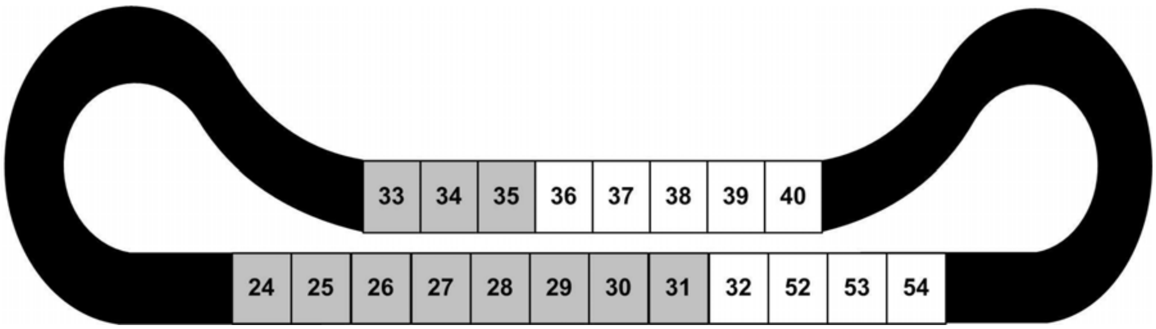
Summary Analysis of Variance Table

Source	d_f	Sum of Squares	Mean Square Error	F-value	P-value
Model	4	0.8912	0.2228	82.06	0.0000
Residual Error	829	2.2507	0.0027		
Lack of Fit	1	0.2594	0.2594	107.85	0.0000
Pure Error	828	1.9913	0.0024		

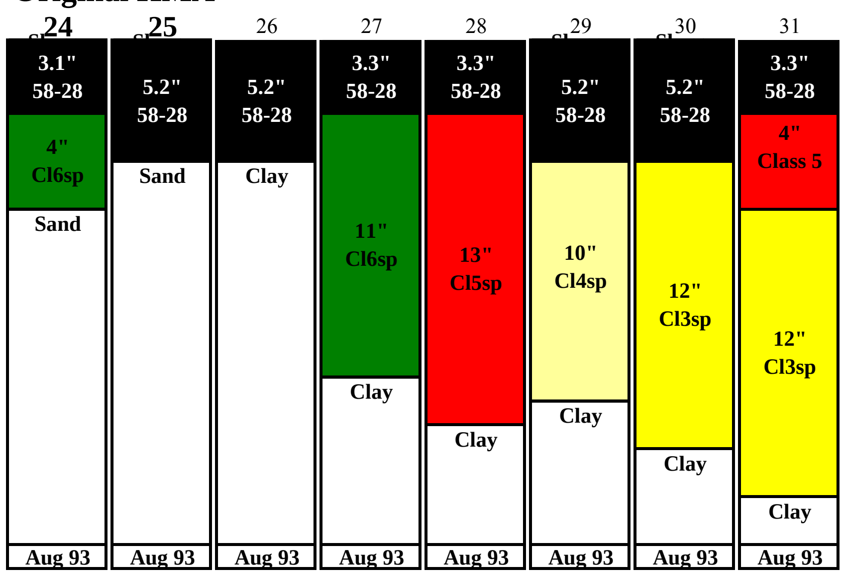
Appendix H

Additional Information

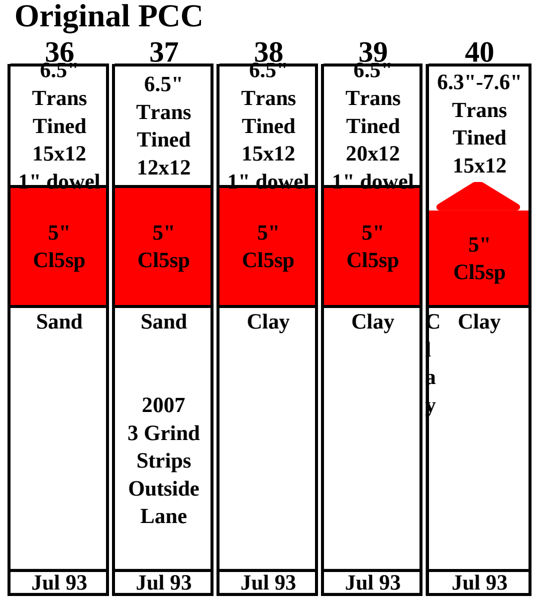
Cross-sections of Low Volume Road Cells at MnROAD



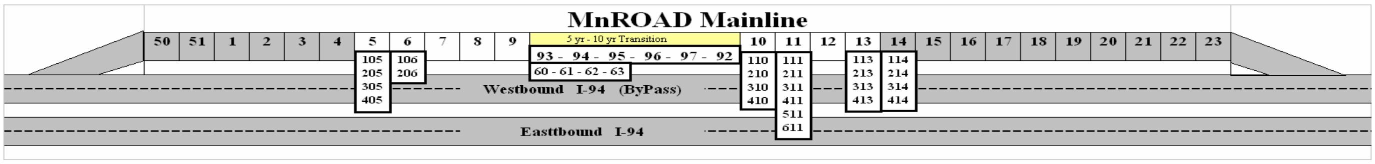
Original HMA



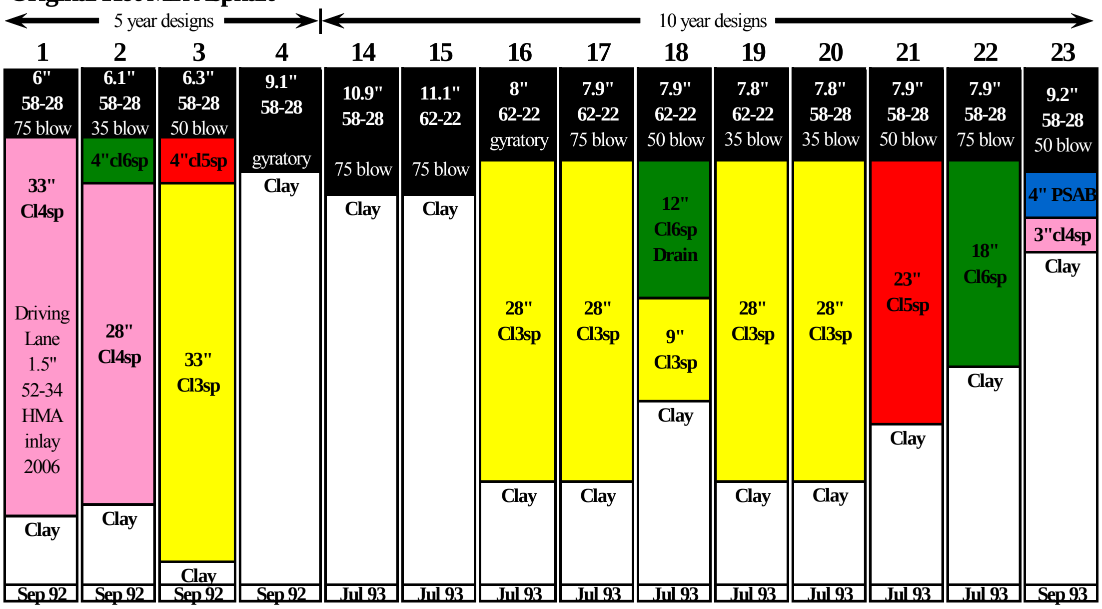
Original PCC



Cross-sections of Mainline Cells at MnROAD



Original Hot Mix Asphalt



Original Concrete