April 5, 2018

NEBRASKA
Good Life. Great Journey.
DEPARTMENT OF TRANSPORTATION

Linking Infrastructure Challenges with Data

Project: 001 Pavement Deterioration

Project Overview

The goal of this project is to identify deterioration rates that are more descriptive than the current blanket assumptions of 1.5% per year for concrete and 2.5% per year for asphalt. These rates are significant determinants in NDOT's funding formulas for maintenance and construction allocation.

To attempt to derive more accurate and descriptive rates, this analysis uses thirteen years' worth of road condition data, amounting to 225,000 individual measurements. This analysis turns these measurements into sequences, calculate the deterioration rate for each sequence, and correlate these rates to roadway characteristics to be able to predict the rates for each road segment based on simple rules.

The project's high-level findings are as follows:

- Roadway surface type (asphalt, concrete, or asphalt-on-concrete composite) correlates strongly with traffic volumes. In the analysis dataset, average daily traffic volumes for asphalt pavements are less than 2000 vehicles per day, compared with an average of greater than 15,000 vehicles per day for concrete pavements. Concrete pavements deteriorate, on average, faster than asphalt pavements but in the presence of seven or more times greater traffic.

- The "average" deterioration rate masks considerable variability in deterioration rates between segments.
- For a given type of pavement, the dataset's explanatory variables—including truck ADTs, surface/base thickness, and maintenance district number—are only able to explain 10 – 20% of the overall variation in deterioration rates between segments. The limited explanatory power in the dataset is attributed to confounding factors not included in the dataset, including roadway design standards and maintenance activities.
- Higher traffic volume (and truck traffic volume) roads do not, on average, see higher rates of deterioration than other roads, suggesting that Nebraska's roadway design and maintenance strategies effectively mitigate pavement distresses.

Based on the findings presented in this report, the following recommendations are offered:

1. Update NDOT's currently used deterioration rates to reflect the empirical findings, presented in this report. Composite pavements (concrete, overlaid with bituminous paving) should be assigned a separate rate from asphalt pavements, as this analysis finds strong evidence that these rates differ.
2. When recording pavement condition, record the actual measured values, separate from any manual overrides. For example, when measuring cracking, current policy prohibits recording a value less than the previous value, even if a maintenance activity has reduced measurable cracking. Although it is valuable to track "underlying" cracking that may be hidden by an armor coat or other pavement treatment, it is also valuable to record the improved pavement condition attributable to the maintenance activity, even if that treatment only temporarily masks underlying distresses.
3. Record pavement condition and maintenance activities using a common asset referencing system. This will allow for future analysis of the effectiveness/value of maintenance activities, as well as controlling for maintenance activities when analyzing or predicting overall road deterioration.

Recommendations for Further Analysis:

- The analysis dataset may yield greater insights if reprocessed to remove the confounding influence of maintenance activities.

Analytical Approach

This section describes the analytical methodology employed for this study. To determine deterioration rates, this analysis first prepared the analysis dataset. Then, the data is analyzed to find associations between deterioration rates and roadway characteristics.

Data Preparation

Assumptions:

- Two-way roads are only profiled once every other year per direction
- Cracking measures don't get reset with maintenance activities
- Maintenance activities are "environmental" variables. Sequences are defined as a series of bienniums with increasing predominant age.

Started with 12 years of condition data (2004 – 2016).

1. Joined the Predominant Age field to this data
2. Removed road segments with condition values outside of the inner 99% range
3. Separated even year measures from odd year measures (to account for the fact that two-way roads are only profiled in a single direction each year).
4. Removed NSI values corresponding to "overrides" (92, 88, 70, 60)
5. Ordered the data into sequences of years based on increasing predominant age, and calculated the average rates of change for each condition measure (IRI, cracking, rutting, faulting).
6. Joined the road inventory data. The inventory data uses a different referencing scheme, requiring a many-to-many join between the segments for which we have condition deterioration rate data and the roadway inventory segments.

The deterioration rates report here are inclusive of maintenance activities, and describe the observed rates between major reconstruction activities.

This analysis attempts to find exploitable relationships between our independent variables and our outcome variables for both concrete and asphalt pavements (where asphalt is defined to include both pure bituminous roads, and composite roads). The variables in this analysis are shown in the table below.

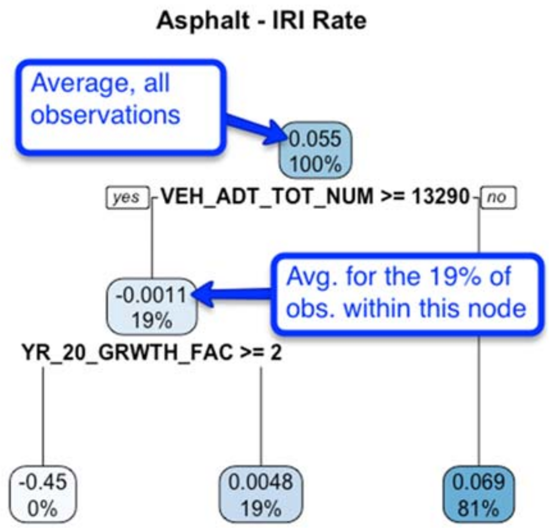
Outcome Variables			Independent Variables	
nsi_rate	Annual Avg. Change in NSI		NAT_FUNCT_CDE	National Functional code

iri_rate	Annual Avg. Change in IRI		LAYER_DPTH_AMT_B	Base Layer Thickness
cracking_rate	Annual Avg. Change in Cracking		LAYER_DPTH_AMT_S	Surface Layer Thickness
faulting_rate	Annual Avg. Change in Faulting		SPD_LMT_Q	Speed Limit
rutting_rate	Annual Avg. Change in Rutting		TRUK_ADT_TOT_NUM	Truck Average Daily Traffic
			CNTY_CDE	County
			VEH_ADT_TOT_NUM	Average Daily Traffic, All Vehicles
			YR_20_GRWTH_FAC	Traffic Growth Rate
			Age	Years Since Pavement Constructed
			DIST_NUM_M	Maintenance District Number
			NHS_CDE	National Highway System code
			POP_GRP_CDE	Population Group Code
			RDWY_MTRL_CDE_B	Base Roadway Material Group
			RDWY_MTRL_CDE_S	Surface Roadway Material Group
			RRL_URB_CDE	Rural / Urban Code
			SCN_BYW_S	Scenic Byway Designation
			SNDHLL_AREA_SW	Sandhill Area Designation
			ST_FUNCT_CDE	State Functional Code

Analysis Methodology

Descriptive statistics were calculated for all outcome variables, including averages, confidence intervals for the averages, and correlations between outcome variables and explanatory variables. To attempt to find generalizable relationships between deterioration rates and roadway characteristics, two methods were used to extract deterioration regularities from the data: decision trees, and regression analysis.

First, a **decision tree** model is fit for each condition measure and type of pavement. A decision tree (or, technically, a regression tree when used to predict a continuous variable) is a machine learning model which separates a population by finding the splits that produce the most differentiated resulting groups (a criteria known as *information gain*). A decision tree can consider an unlimited number of variables, and algorithmically selects the variables and splits that produce the greatest information gain. The resulting rule set can be displayed visually, as in the below:



Second, a **linear (or log-linear) regression** model is fit to attempt to define a line of best fit through the condition measurements by assigning coefficients to the segment attributes. For example, a coefficient is assigned to the segment's average daily traffic which, if positive, would mean that the rate of deterioration increases as traffic increases.

The analytical goal of this project is to define a set of rules that can be applied to road segments that provides a better approximation of reality than the current fixed rates.

A good way of visually evaluating the effectiveness of the rule set is to consider the distribution of the segment rates. Figures 1 – 4, below, show observed rates, currently assigned rates, rates weighted by district, and rates weighted by district, concrete being 25 year or older, and the base layer thickness.

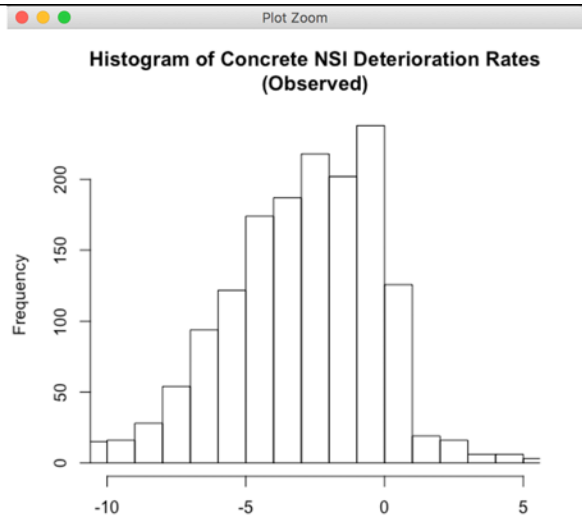


Fig 1: Observed Distribution of Rates

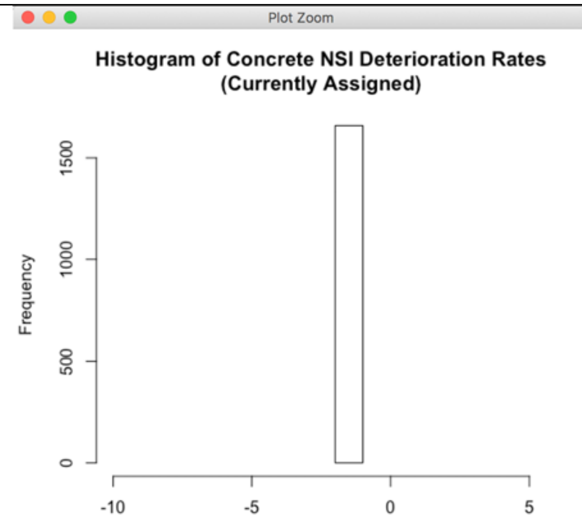


Fig 2: Currently Used Rates

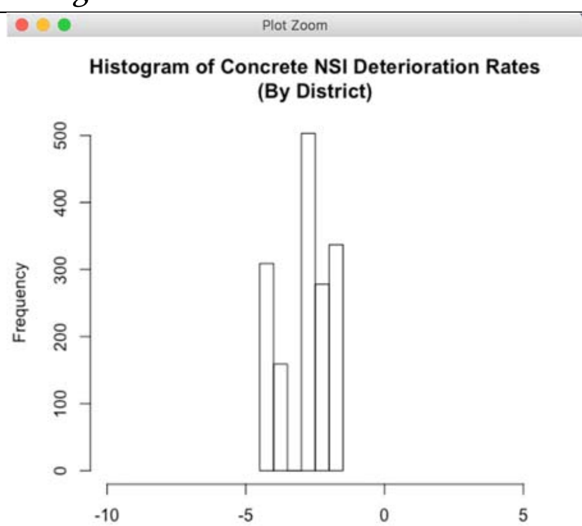


Fig 3: Rates by District

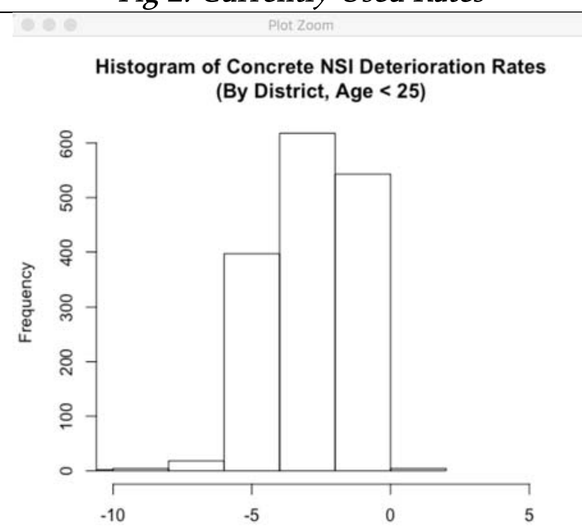


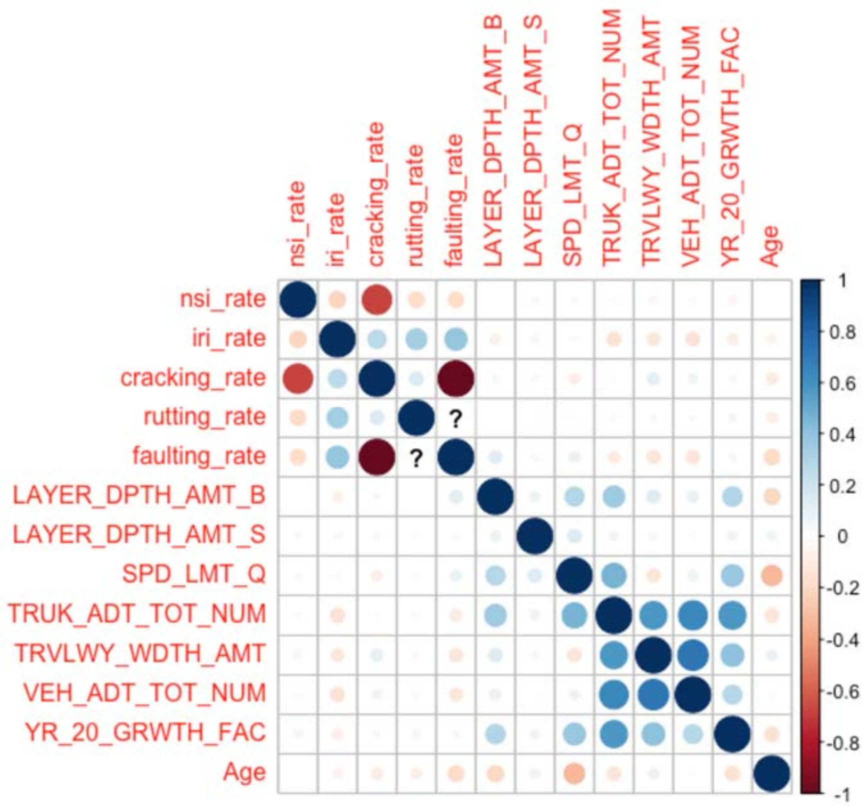
Fig 4: Rates by District, Age, & Thickness

If we increase the complexity of our model, allowing district to interact with a dummy variable for if the concrete is older than 25 years, interacted with the surface material thickness, we're now explaining ~14% of the total variation in NSI deterioration rates, and have a distribution of values that's starting more closely resemble what's observed empirically (Fig. 4).

Results

The figure below shows the degrees of correlation between the numeric attributes in our final dataset.

It's particularly worth noting the Truck ADT (TRUK_ADT_TOT_NUM) correlations. One of this project's pre-test hypotheses was that truck ADTs would be a significant determinant of deterioration rates. In fact, we find no correlation or the opposite: truck ADTs are negatively correlated with the IRI rate, and very weakly negatively correlated with cracking, rutting, and faulting. It's worth noting, however, that truck ADTs are also correlated to base layer depth amount, total vehicle ADT, road width, and the 20 year growth factor—all of which invoke higher design standards. It's not that additional ESALs lead to smoother pavement, but rather it seems that NDOT's pavement engineers have been very effective at choosing appropriate pavements for routes with heavy truck traffic.



Comparing all pavements together can be misleading, however, to the extent that asphalt pavements typically see far less traffic than concrete or composite pavements.
Some 98% of asphalt pavements in the deterioration dataset see average daily traffic of less than 7500 vehicles per day. Concrete pavements, by contrast, average over 15,000 vehicles per day.

It terms of materials, composite pavements are more like asphalt than concrete, but in terms of pavement distresses, composite pavements are more like concrete. The table below presents average daily traffic counts by surface material type:

Pavement Type	*Observation Count*	*Average Daily Traffic (All Vehicles)*	*Average Daily Truck Traffic*
Asphalt	1858	1955	257
Composite	1372	13,814	2401
Concrete	1587	15,787	1586

The deterioration rates presented below show lower rates of deterioration for asphalt than for concrete. These results must be interpreted as "asphalt pavements with average traffic of 1955 vehicles per day deteriorate more slowly than concrete pavements with average traffic of 15,878 vehicles per day." These results do not suggest that, all else being equal, asphalt deteriorates more slowly than concrete!

This analysis provides several useful pieces of information:

1) Empirically based estimates of the "average" deterioration rates for each condition measure and surface material type.
2) Statistical evidence that the average deterioration rates for asphalt pavements differs from that of composite pavements.
3) Rule sets which can further improve the accuracy of the updated average deterioration rates for asphalt NSI, concrete NSI, and asphalt IRI. Given the limited descriptive power of these models, similar rules have not yet been prepared for rutting, cracking or faulting, but are available as an extension of this study.

In addition, this analysis offers these notable findings:

1) There's a lot of variation in the deterioration rates that's not readily explained using the independent variables in this study. None of the analytical approaches employed were able to explain more than 30% of the variance between segments of roadway when accounting for surface and base materials, and frequently the models employed explained 10% or less of total variation.
2) Roadway attributes (e.g. ADT, growth factor) influence design standards, which in turn influence pavement longevity in ways our explanatory variables do not readily

control for, resulting in counterintuitive relationships in the data, such as the association of higher Truck ADTs with slower deterioration.

3) Some roadway segments are improving over time with maintenance activities, especially for rutting measurements.

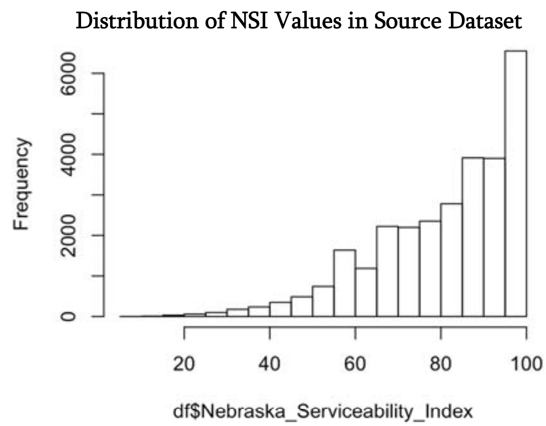
The limited explanatory power of the explanatory variables may be attributable to:

- Error in explanatory variables (e.g. inaccurate estimates of Truck ADTs)
- Road Condition Measurement error
- Variation due to maintenance activities, which are not accounted for in the dataset
- Lack of an appropriate "geographic" variable (the only "geography" variables in the dataset were county, maintenance district, and a dummy variable indicating the Sand Hills area)
- Lack of appropriate variables representing design standards
- Data processing error when conflating road attributes to deterioration sequences

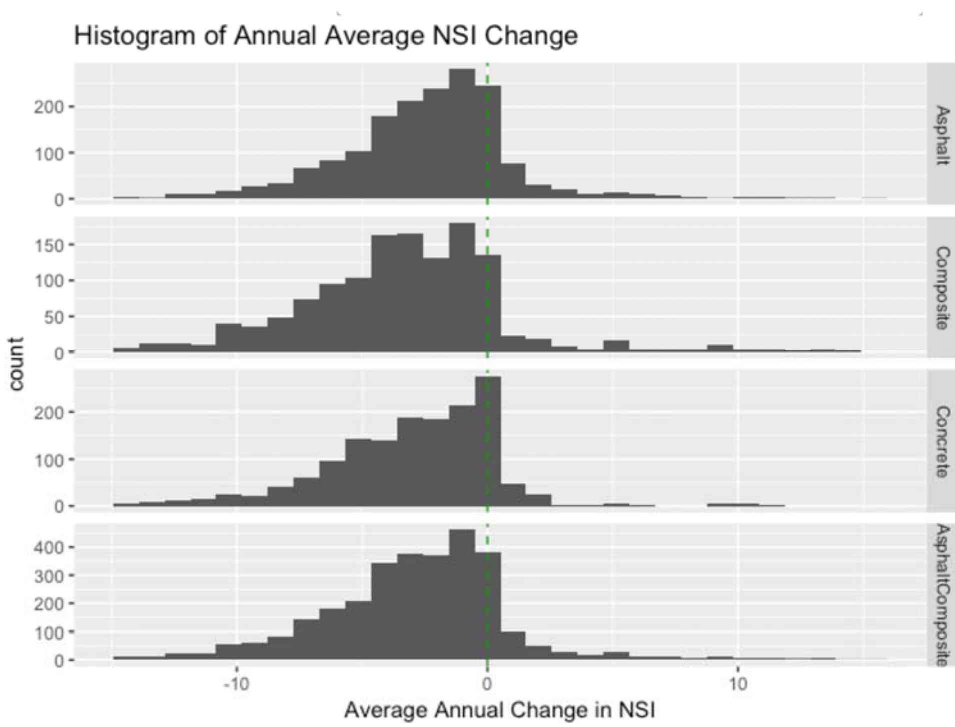
Below, each deterioration measure is presented with a histogram showing the overall distribution of scores for that measure across Nebraska's pavements, a histogram showing the observed deterioration rates (by surface type), and a table showing the statewide averages by surface type.

Values for AsphaltComposite represent a weighted average or combined datasets for asphalt and for composite road segments.

Nebraska Serviceability Index



Shows the distribution of values across all observations in the raw source data

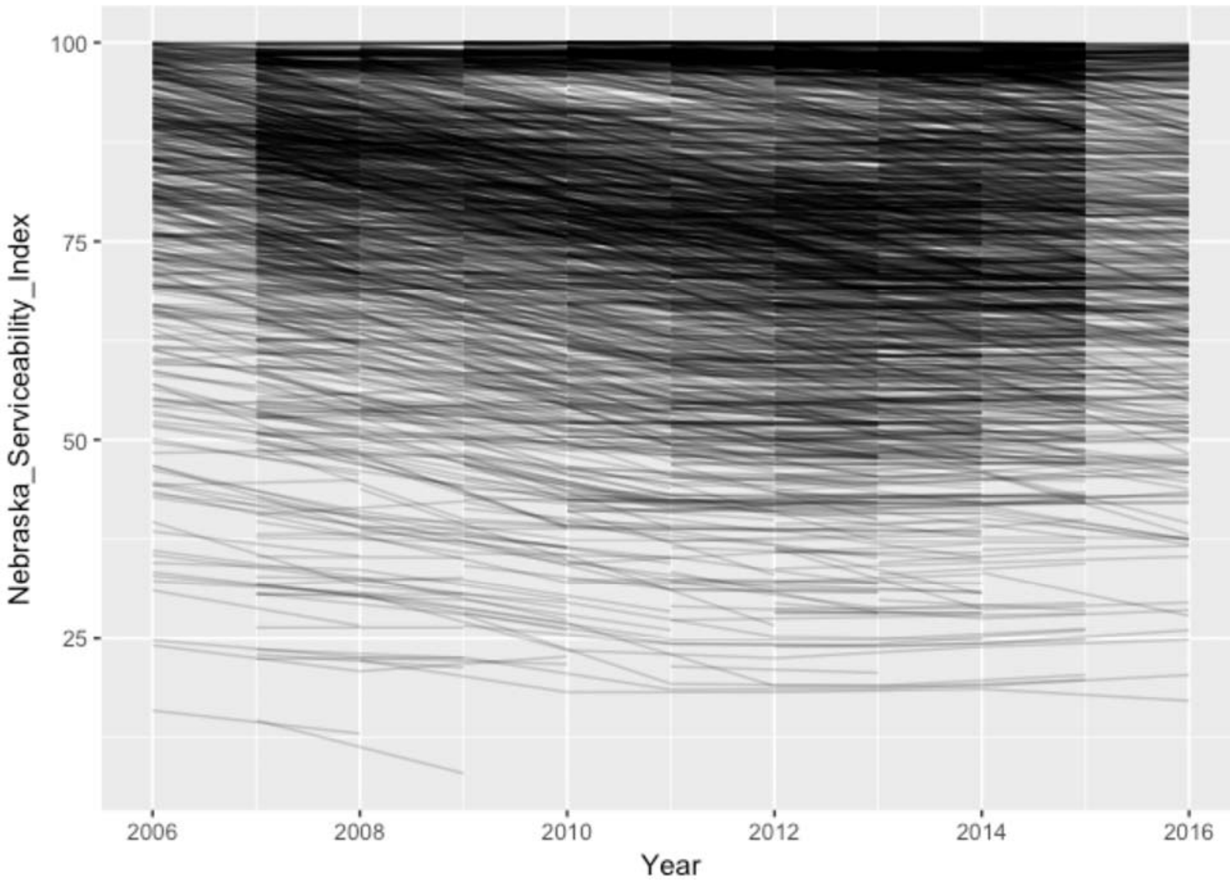


Shows the distribution of calculated deterioration rates.

Surface Type	Statewide Average	Median	95% CI Lower Bound	95% CI Upper Bound
Asphalt	-2.41	-2.16	-2.63	-2.20
Composite	-3.30	-3.27	-3.55	-3.05
Concrete	-3.01	-2.54	-3.20	-2.82
Asphalt + Composite	-2.80	-2.63	-2.96	-2.64

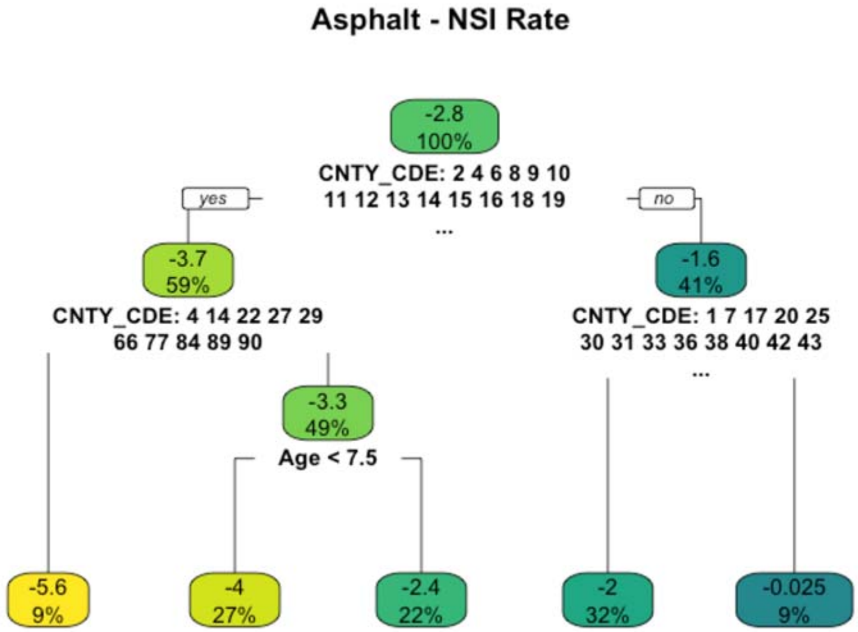
In the table above, note that asphalt, composite, and concrete each have distinct NSI deterioration averages.

The figure below shows trend lines for all 3791 NSI deterioration sequences in the dataset. Overlapping trend lines show up as darker black portions on the chart.

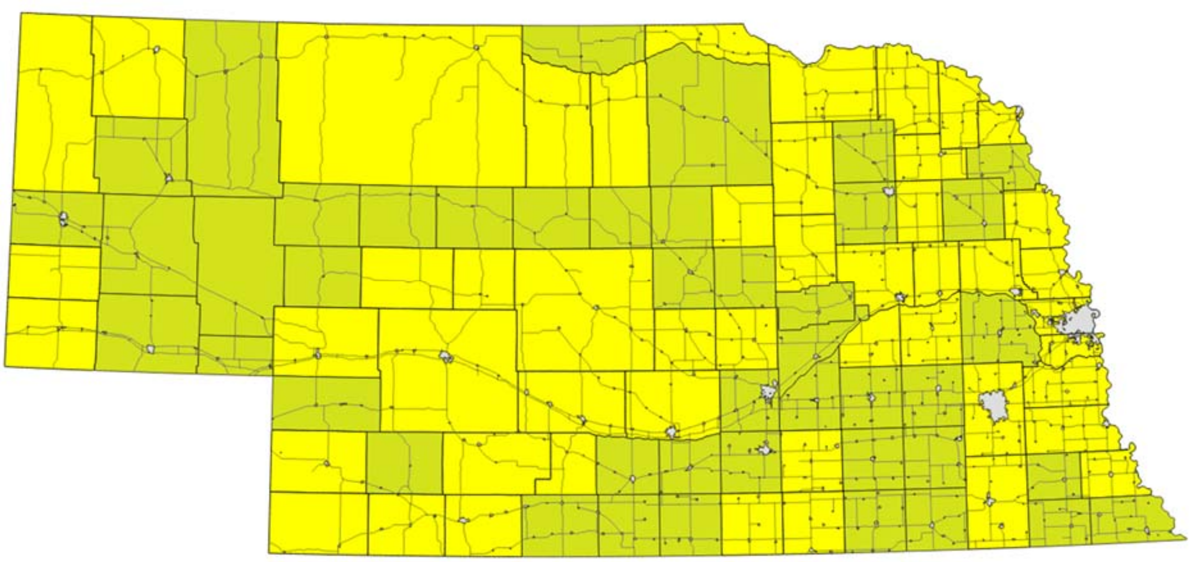


NSI – Asphalt + Composite

This simple decision tree can explain 10% of variance in asphalt NSI deterioration:



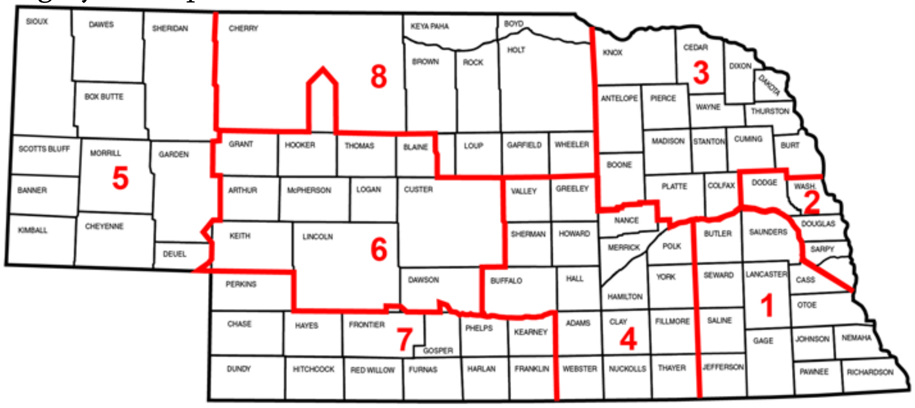
The first split explains ~5% of the variation in deterioration based on county. The map below illustrates this split.



County Group 1 (-1.6%)	County Group 2 (-3.7%)
1, 3, 5, 7, 17, 20, 25, 30, 31, 33, 35, 36, 38, 39, 40, 41, 42, 43, 45, 46, 48, 49, 50, 52, 58, 60, 61, 62, 63, 67, 68, 69, 70, 74,	2, 4, 6, 8, 9, 10, 11, 12, 13, 14, 15, 16, 18, 19, 21, 22, 23, 24, 26, 27, 28, 29, 32, 34, 37, 44, 47, 51, 53, 54, 55, 56, 57, 59,

76, 78, 79, 80, 81, 85, 86, 87, 88, 93	64, 65, 66, 71, 72, 73, 75, 77, 82, 83, 84, 89, 90, 91, 92

This layout roughly corresponds to maintenance division boundaries:



Where District 1 is mostly lower deterioration (excepting Lincoln), District 2 is mostly higher deterioration, District 3 is mostly higher deterioration, District 4 is mostly lower deterioration, District 5 deteriorates toward the state boundaries, District 6 is mostly higher deterioration, District 7 is mixed, and District 8 is mostly higher deterioration.

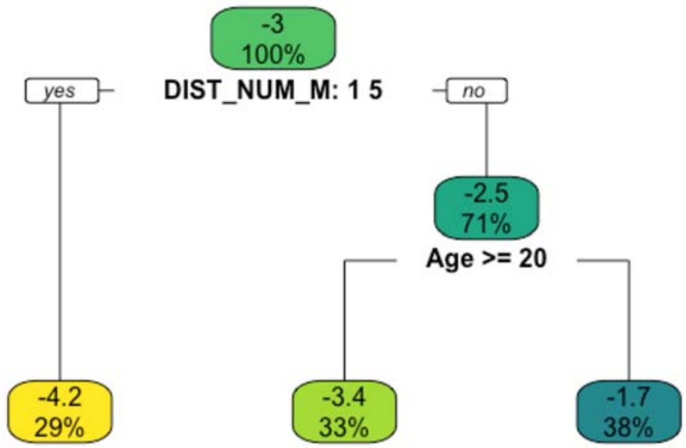
Suggested Asphalt NSI Deterioration Rate Rules:

County	County Group 1	County Group 2
Rate	-2.75	-3.25

Compared to a statewide rate of 2.5% deterioration per year, these rates more accurately reflect what is observed in practice, and account for some of the variation in asphalt deterioration rates between counties.

NSI – Concrete

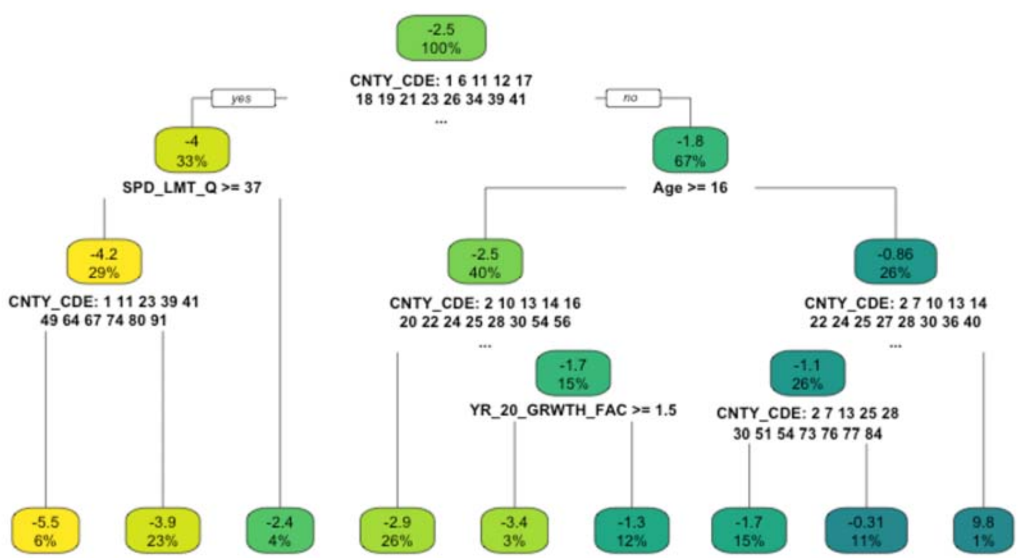
The following decision tree explains 8% of the variation in concrete NSI:



The statewide average concrete NSI deterioration rate is -3% per year.

In Districts 1 and 5, the average deterioration rate is 4.2% per year. In other districts, among concrete pavements older than 20 years the average rate is 3.4%, and otherwise 1.7%.

A more complex decision tree, shown below, explains some 25% of the variance in NSI deterioration rate between concrete segments, but is too complex for practical implementation:

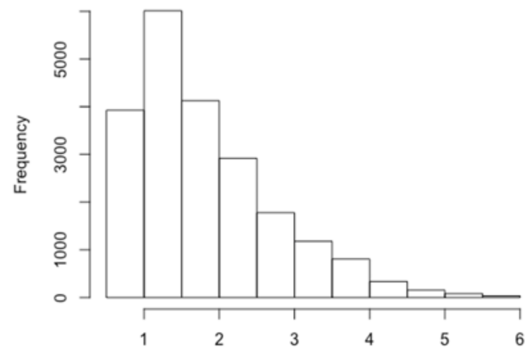


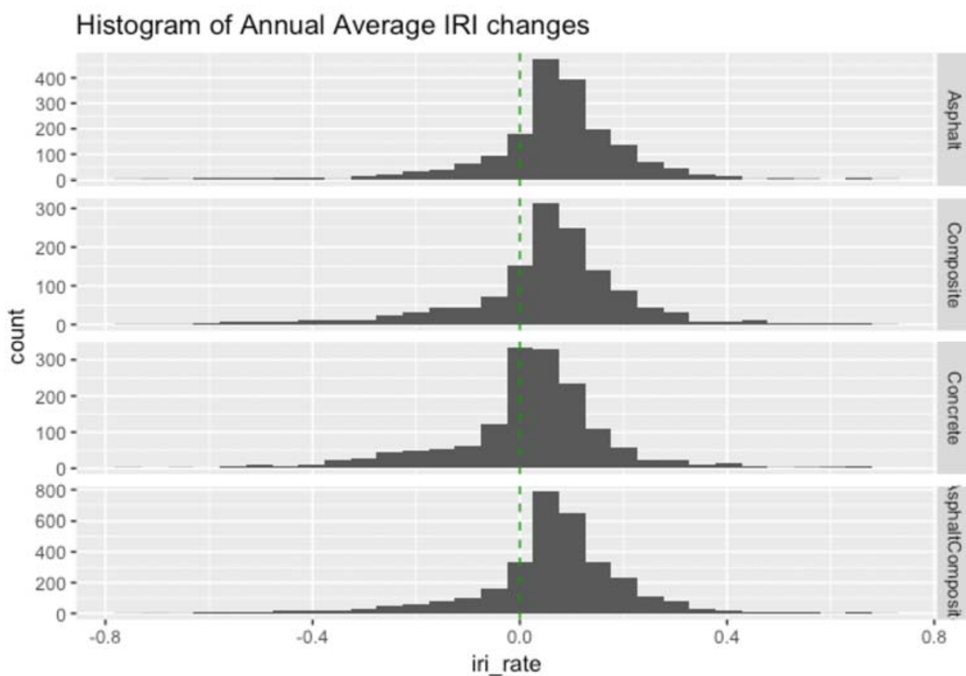
Suggested Rules for Concrete NSI deterioration Rates:

1) In Districts 1 and 5: 3.5%
2) In other districts, 2.5%, unless Age > 20, then 3%

International Roughness Index

Distribution of IRI Values in Source Dataset



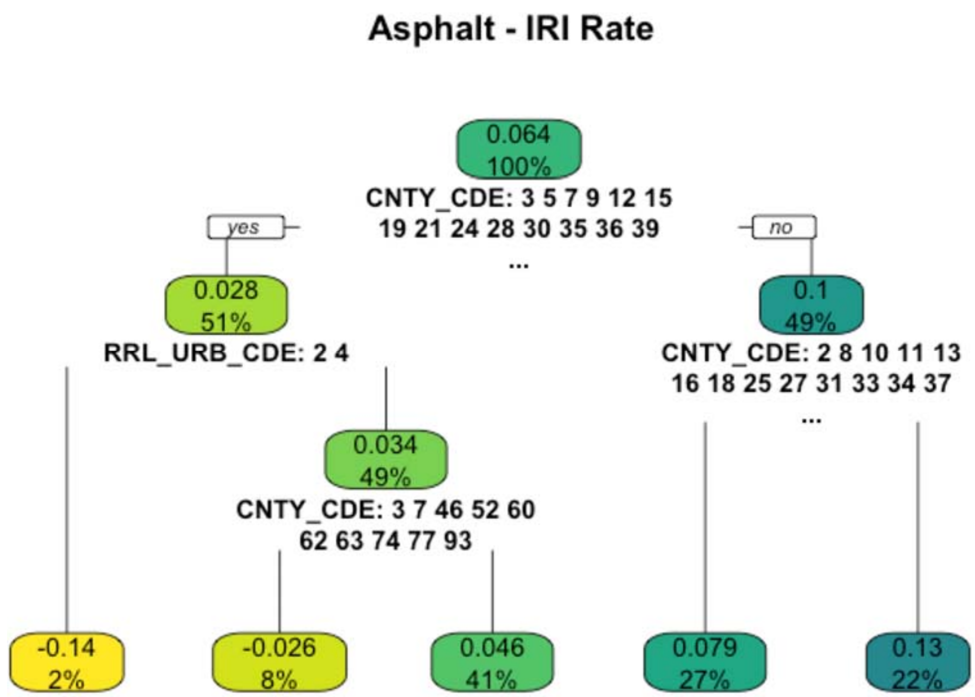


Surface Type	Statewide Average	Median	95% CI Lower Bound	95% CI Upper Bound
Asphalt	0.06	0.07	0.06	0.07
Composite	0.05	0.06	0.04	0.06
Concrete	0.02	0.03	0.01	0.03
Asphalt + Composite	0.06	0.07	0.05	0.06

The averages above indicate that composite pavement and asphalt pavement deteriorate similarly. A rate of 0.05 will conservatively estimate the deterioration of pavements with a bituminous surface, and a rate of 0.025 will estimate the deterioration of concrete pavements.

Asphalt IRI

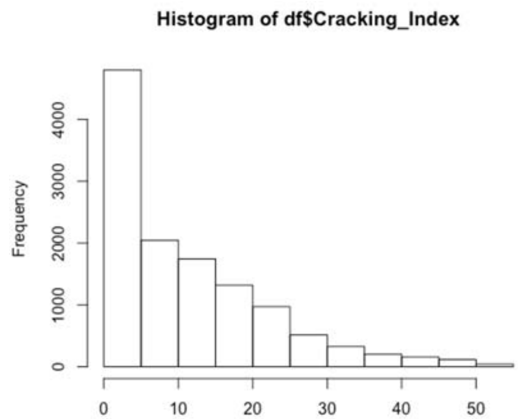
This decision tree explains 10% of the variance in asphalt IRI:

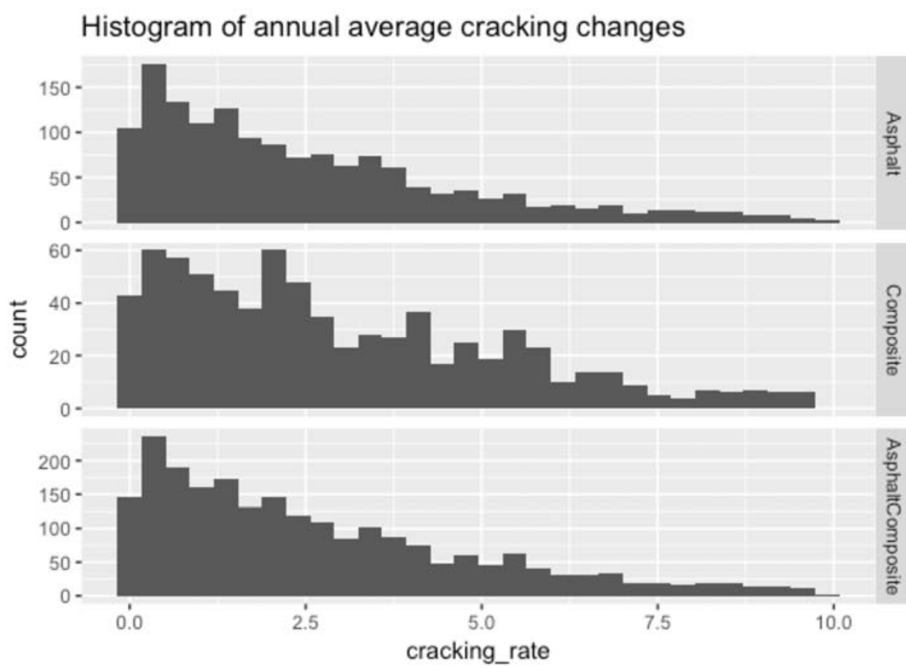


With only 10% of total variation explained, this model may not warrant application as a rule set. County group membership groupings can be provided upon request.

Cracking

The source dataset contains measures only for asphalt cracking.



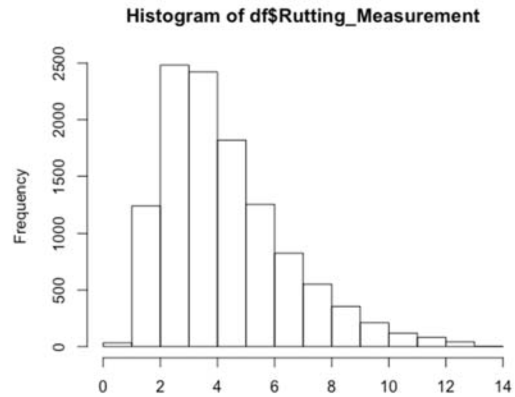


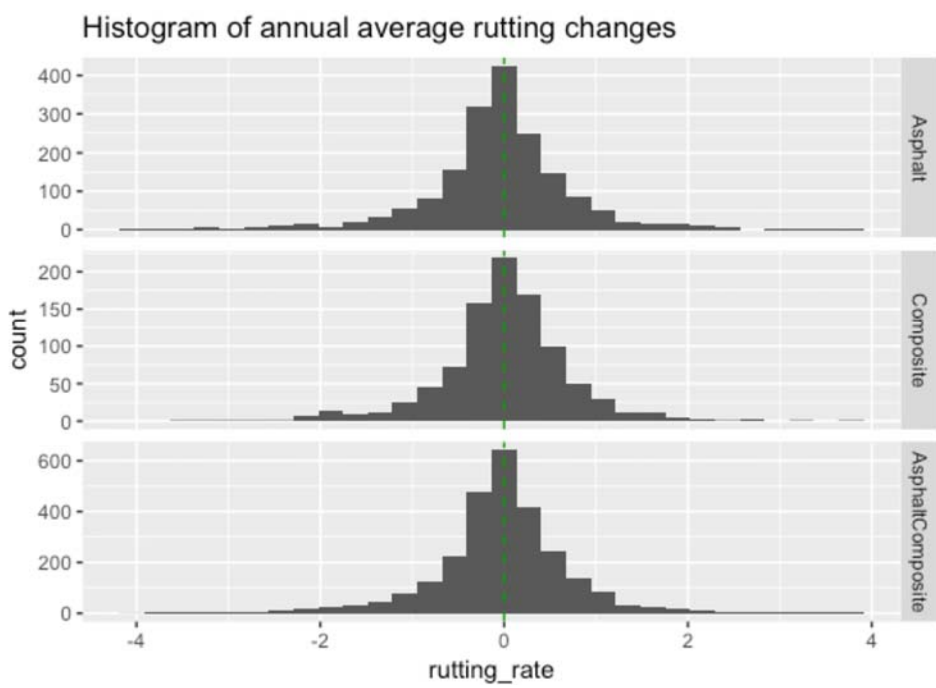
Surface Type	Statewide Average	Median	95% CI Lower Bound	95% CI Upper Bound
Asphalt	2.37	1.68	2.23	2.52
Composite	2.87	2.28	2.61	3.14
Asphalt + Composite	2.55	1.93	2.41	2.68

The table above shows that the cracking rate for composite pavements exceeds that of plain asphalt by 0.5 per year. This is likely attributable to the significantly higher traffic volumes typically seen on composite road segments.

Rutting

Rutting only occurs on bituminous surfaces, and especially those constructed to the switch to Super Pave asphalt mix in 2000.



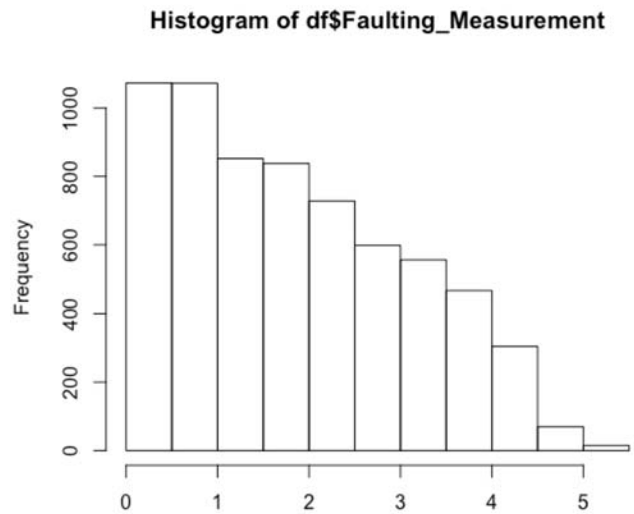


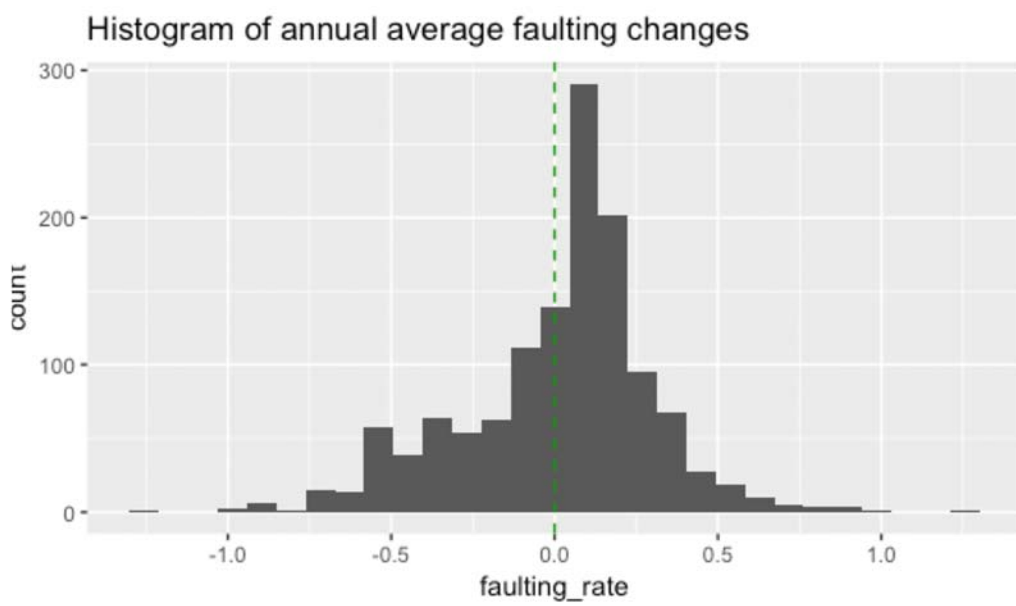
Surface Type	Statewide Average	Median	95% CI Lower Bound	95% CI Upper Bound
Asphalt	-0.07	-0.04	-0.11	-0.02
Composite	-0.03	0.02	-0.08	0.03
Asphalt + Composite	-0.05	-0.02	-0.08	-0.02

With maintenance activities, average rutting rates are very close to zero. Roughly as many asphalt pavement segments show decreasing rutting over time as increasing.g

Faulting

Faulting only occurs in concrete pavement, and generally only in older concrete pavements constructed without dowel reinforcement bars between sections.





Surface Type	Statewide Average	Median	95% CI Lower	95% CI Upper
Concrete	0.01	0.07	-0.01	0.03

Faulting changes, accounting for maintenance activities, are also very close to zero. In this case, the median rate (0.07 increase per year) may be more descriptive than the mean, as the distribution of deterioration rates is slightly left skewed.

Conclusion

The tables and charts above show the deterioration rates by condition measure observed in practice based on twelve years of continuous measurements. These values should provide a more accurate basis for predicting future deterioration, but are presented with the caveat that each mean masks considerable underlying variation between individual pavement segments.

Attempts to derive rule sets to further refine these rates were largely unsuccessful. The lack of explanatory power shown by the regression tree and linear regression models investigated suggest that there are significant exogenous variables missing from our dataset, including attributes to control for maintenance activities.

Nevertheless, several of the modeling findings are noteworthy:

- Truck ADTs are generally uncorrelated with deterioration rates
- Composite pavements follow deterioration trends that are distinct from asphalt pavements and concrete pavements
- Of the attributes available in the dataset, which county a given segment of pavement is located in is the most deterministic of its deterioration rate

Additional value may be available from the source dataset if reprocessed to attempt to exclude condition improvements from maintenance activities and to include more design standard attributes, such as surface and base material codes.