SUMMARY**REPORT**

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Quantification of the Correlation Between Bridge Skew Angle and Concrete Deck Deterioration Rate in New Jersey

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This study investigates the current body of knowledge about the relationship between bridge skew angle and bridge deterioration rate and applies those findings to New Jersey bridges. Tools used in the study were graphical analysis (histograms and a scatterplot with regression lines) and statistical methodologies, specifically analysis of variance (ANOVA). The source of the skew angles of all New Jersey bridges was the Federal Highway Administration Long-Term Bridge Performance InfoBridge™ Web portal.(1) The study team calculated the number of years that passed before a bridge's condition rating declined by one rate.

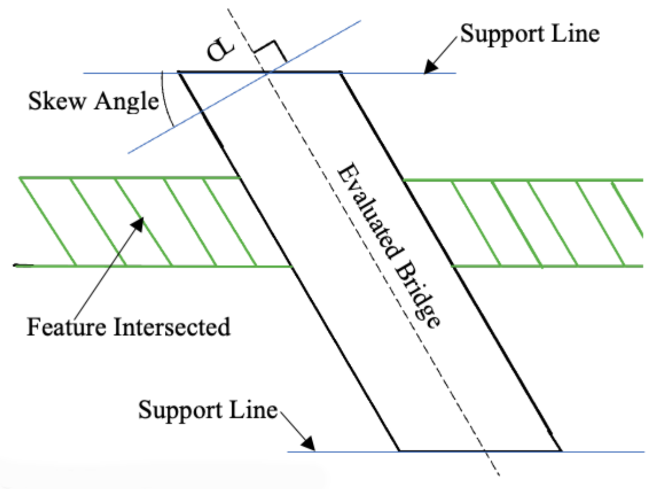
The first step was to classify the bridges by skew angle degree and then plot each group by the number of years that passed before the bridges deteriorated by one rate versus the condition rating. Bridge skew angles were put into groups of five, from 0–5°, 6–10°, and so on. The results demonstrated a clear trend: Bridges with small skew angles took longer to deteriorate than bridges with large skew angles. A scatterplot with a regression line was also plotted with the years that passed before the bridge began to deteriorate on the *y*-axis and the skew angle on the *x*-axis. This result inspired additional research into the probable relationship between skew angle (categorized at this stage for the trend analysis) and deterioration using the statistical method ANOVA.

The study team performed an ANOVA to validate the observed trend. The investigation found a statistically significant ($p<0.05$) link between bridge skew angle and deterioration rate. According to the ANOVA results, the differences in deterioration rates across the two skew angle groups (within groups and between groups) show that bridges with large skew angles deteriorate faster than bridges with small skew degrees; the data revealed that bridges with a skew angle below 30° deteriorate at the slowest rate, bridges with a skew angle 30°–45° deteriorate at the average rate, and bridges with a skew angle greater than 45° deteriorate at the largest rate.

INTRODUCTION

Bridges are nodes of the U.S. transportation infrastructure because they provide vital links for efficient mobility and connectivity.[2] Due to the geographical complexity of transportation systems, not all bridges are constructed perpendicular to their intersected feature. On the contrary, bridges align at a skew angle to their intersected features. A skew angle is the angle at which a bridge crosses an obstacle (e.g., river, road, valley).[3] As figure 1 shows, a skew angle is measured between a line perpendicular to the girder's longitudinal axis (center line) and the line of supports of the abutment. Therefore, the skew angle is a significant geometric feature of a bridge that affects its performance.[3,4] The relationship between skew angle and deterioration is fundamental for bridge design, maintenance, and management techniques.[5,6] The purpose of this study is to look at the relationship between bridge skew angle and bridge deterioration, shedding light on the implications of skewed bridge alignments. This study aims to give bridge engineers, legislators, and researchers significant insights by evaluating comprehensive data and using modern statistical techniques to optimize design standards and increase bridge longevity.

Figure 1. Line drawing. Depiction of bridge skew angle.



BACKGROUND

Bridges are essential for transportation infrastructure, and engineers and policymakers are concerned about bridges' long-term performance and safety. Currently, as part of the country's more than 4 million mi infrastructure of Interstate Highway System, bridges serve an essential role in transportation by connecting locations divided by rivers, valleys, or gaps in the topography.[7] Bridges are necessary infrastructure for both urban and rural areas, providing for the efficient flow of people, products, and services.[8]

Much research has been conducted to investigate the relationship between bridge skew angle and the rate of bridge deterioration. Researchers who conducted a study on 313 bridges in South Korea discovered that the skew angle was a major factor in the decline of bridge decks. The study also found that bridges with skew angles more than 45° deteriorated faster than those with skew angles less than 45°.[9]

Another study examined data from bridges and discovered that the skew angle was an essential determinant of bridge deterioration. The study found that bridges with skew angles greater than 20° experienced much more bearing damage than bridges with skew angles less than 20°.[10] Various probable reasons exist why bridges that have large skew angles may deteriorate at a faster rate than bridges with small skew angles. For example, the geometry of the bridge may result in uneven loading on the bridge components, a condition that can hasten wear and tear.[11,12] Bridges with large skew angles may also be subject to more environmental variables like wind and water, which may lead to rust and other forms of degradation. Also, gravity load paths are important for how bridge skew angles behave, information that is key for assessing the structural behavior and deterioration because it has an influence on the load distribution and stress concentrations, affecting maintenance and rehabilitation strategies.[5,6,13]

Investigating the relationship between bridge skew angle and deterioration rate is critical in furthering the understanding of bridge performance. More research is needed to investigate this link and find effective solutions to the influence of large skew angles on bridge deterioration. Implementing those solutions ultimately could ensure the safety and efficiency of transportation networks for years to come by gaining a comprehensive understanding of the mechanisms underlying this correlation.

PURPOSE OF RESEARCH

The goal of this research was to focus on the relationship between bridge skew angle and the deterioration rate of bridges and to discover if the bridges in New Jersey follow the same trend of deterioration shown by the bridges studied during the literature review. This project enables researchers to uncover the elements that lead to bridge deterioration and ways skew angles in New Jersey bridge infrastructure are contributing factors. Understanding the relationship between bridge skew angles and structure deterioration will inform future bridge design and maintenance procedures, thereby improving the safety and sustainability of bridge infrastructure.

THESIS STATEMENT

The goal of this study is to investigate the relationship between the skew angles and New Jersey bridge deterioration and to identify the key factors that contribute to the deterioration rate of bridges with large skew angles, information that will be reflected in efficient design and maintenance procedures that can improve the safety and long-term reliability of bridge infrastructure.

SCOPE

Using only bridges in New Jersey, the study examined numerous bridges around the State, specifically those found on the Federal Highway Administration's (FHWA) Long-Term Bridge Program (LTBP) InfoBridge™ Web portal.[1,14] The bridges used in this research are made of various materials, including concrete, steel, and wood, with concrete being the most common. The study team used a combination of data analytic tools, including an automated spreadsheet and mathematical computing platform for analyzing data to estimate the trend of deterioration for each bridge. By methodically collecting and evaluating data on structural integrity and degradation, this study aimed to understand better how these bridges operate in real-world settings. The team established a correlation between these two characteristics—skew angle and degradation—by evaluating the bridges. The study also tried to determine the average number of years that passed before a bridge declined to a lower condition rating. This information is key for evaluating the bridge's long-term performance and maintenance requirements.[15]

Limitations

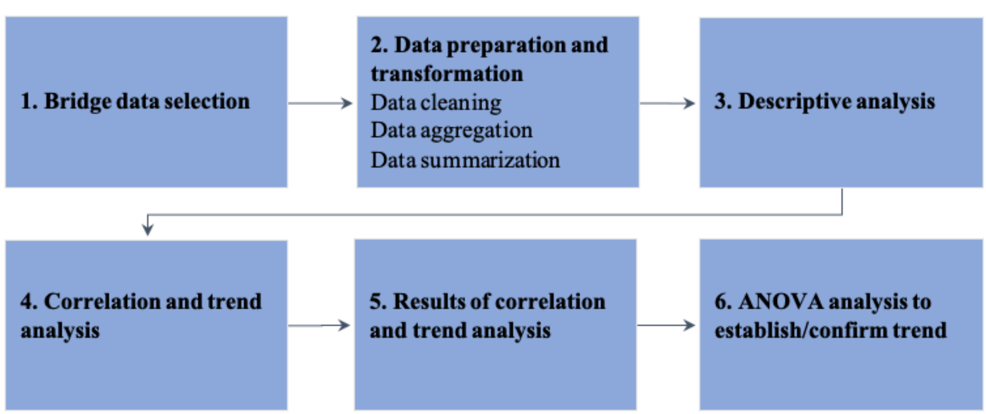
The study's methodology and results are based solely on bridges in New Jersey. Different locales may have different environmental conditions, traffic patterns, and maintenance procedures, any one of which may alter this study's findings' ability to be generalized to other sites. The study did not consider certain elements recognized as contributors to bridge deterioration. For example, the study did not consider characteristics like material quality and design elements, which are known to influence the rate of deterioration.

Also, the study team did not consider the effects of seismic activity on bridge deterioration. Earthquakes and other seismic occurrences can hasten deterioration, especially for older bridges or those in seismically active areas. As a result, the findings of this study should be reinforced with more research that focuses on the effects of seismic activity on bridge deterioration in seismic areas. Furthermore, recognizing that other elements, such as the bridge's age, might contribute to its degradation is critical. When examining the cumulative impact of numerous factors, isolating the effect of the skew angle alone becomes difficult. Aging and different environmental circumstances interact with the skew angle and influence the rate of deterioration.[16] Consequently, a comprehensive analysis that considers many elements would be required to provide a more nuanced knowledge of bridge degradation. Finally, while this study found a link between bridge skew angle and deterioration, the researchers know that correlation does not always imply causation. Causation can be determined only by performing a carefully controlled data analysis and having a thorough grasp of the underlying damage mechanisms caused by the operability of the bridge that may result in a causal relationship.[17,18,19]

DATA PROCESSING

The study team collected the data used in this study from FHWA's LTBP InfoBridge Web portal.[1] Figure 2 shows each step completed to collect and process the data.

Figure 2. Process flowchart. Data collection and processing flowchart.



ANOVA = analysis of variance.

The following information provides details about actions completed in the flowchart's activity box with the corresponding number:

1. **Bridge data selection:** All the bridges selected for this study were in New Jersey. Aside from the fact that New Jersey has more than 6,000 bridges, which is a representative sample size for an accurate analysis, the climatic conditions, age, materials used, and maintenance culture of the different counties and bridge owners differ across the State, providing a varied dataset. Not all bridges in New Jersey are skewed. Skewed configurations are occasionally required when safety and alignment difficulties (congested locations, natural or man-made impediments, complicated intersections, etc.) mandate critical highway and highway bridge design considerations.[17,4,19] For this study, all the bridges, including ones with skew angles of 0°, were considered to establish the correlation between skew angle and bridge deterioration.
2. **Data preparation and transformation:** Data collected from field assessments, performance monitoring, nondestructive evaluation testing, laboratory analysis, and other sources are combined and structured in a defined format. This process is part of cleaning the data to correct errors, inconsistencies, or missing information and ensure data quality and integrity. The data for this analysis were cleaned using the structure number to identify the bridges. The year built, deck condition rating, years it takes to deteriorate one rate down, and skew angle were then selected for the various structure numbers. This cleaning process eliminated data entries with missing information and, therefore, could not be attributed to a specific bridge. The data were transformed by converting raw data into a more structured and usable form, using various operations and calculations. Data cleaning, aggregation, summarization, and the creation of derived variables are examples of the data preparation process:
    a. **Data cleaning:** Data cleaning is the process of discovering and repairing or deleting errors, inconsistencies, and inaccuracies in a dataset. The process is also known as data cleansing or data scrubbing. This vital data preparation stage assures the data's quality and dependability for analysis, modeling, or other data-driven tasks. The study team cleaned the data by remedying missing values, e.g., removing rows and columns with excessive missing data, depending on the data's effect on the analysis. In the case of duplicate data, the team removed the duplicate. Also identified for special attention by the team were outliers with extreme values either to remove or transform to fit the data needed for analysis. Finally, the team removed redundant data, which did not contribute to the data analysis.

    b. **Data aggregation:** A mathematical process that summarizes or combines several values within a dataset to produce a single representative value is known as an aggregation function, also known as an aggregate function or summary function. The study team used the average, or mean, to find one representative value for the years that pass before the condition rating drops by one rate. The research team counted the number of occurrences, or data points, inside a specific category to determine the total number of bridges. The research team used variance—a measure of the spread of data points around the mean that measures the dispersion, or variability, of values within a dataset—and used standard deviation—a measure of the average distance between data points and the mean that quantifies the dispersion, or variability, of values within a collection—for the hypothesis testing.

    c. **Data summarization:** Data summarization is the process of condensing and displaying a dataset or a subset of data simply and informally. Data summarization is also known as data aggregation or summarizing statistics. The data subset provides a high-level overview of the dataset's properties, patterns, and insights. To display the distribution of numerical data by dividing the data range into intervals and representing the frequency, or count values, in each interval, the team created a graph (figure 3).
3. **Descriptive analysis:** Descriptive analysis techniques are used to understand the fundamental properties and trends in data. These techniques include summarizing data using statistical measurements, creating visualizations (e.g., charts and graphs), and detecting noteworthy patterns or outliers. Researchers used a spreadsheet program to create a descriptive analysis of this study's data. For each bridge in the dataset, researchers plotted the deck condition rating against the bridge's skew angle to determine the rate at which the bridges deteriorated. A trend was then established for the number of years that passed before the condition rating dropped by one point for all the bridges, and finally, a graph of how long the condition ratio takes to drop by one point was plotted against the skew angle.
4. **Correlation and trend analysis:** The correlation and trend analysis established a relationship between the two variables (deck condition rating and skew angle).

The degree and direction of the association between two variables were assessed using correlation analysis. This scenario investigates the relationship between bridge deck condition rating and skew angle. A positive connection suggests that as the skew angle grows, so does the bridge deck condition rating. A negative connection, on the other hand, indicates that a large skew angle relates to a poorer bridge deck condition grade. The process of assessing the pattern or direction of change in the bridge deck condition rating regarding the skew angle over time or across a sample of bridges is known as trend analysis.[17] This analysis aids in the identification of any systematic trends or tendencies in the data. One method is to categorize bridges based on their skew angle ranges (e.g., 0–5°, 6–10°) and then compute the time it takes for the bridge deck condition rating to drop by one point for each group. Researchers can examine the data and identify any regular trends by charting these average years over the skew angle range.

Figure 3. Graph of each skew angle group to show the years it takes for a bridge to drop its condition rate. The *x*-axis represents years and the *y*-axis the condition rate.

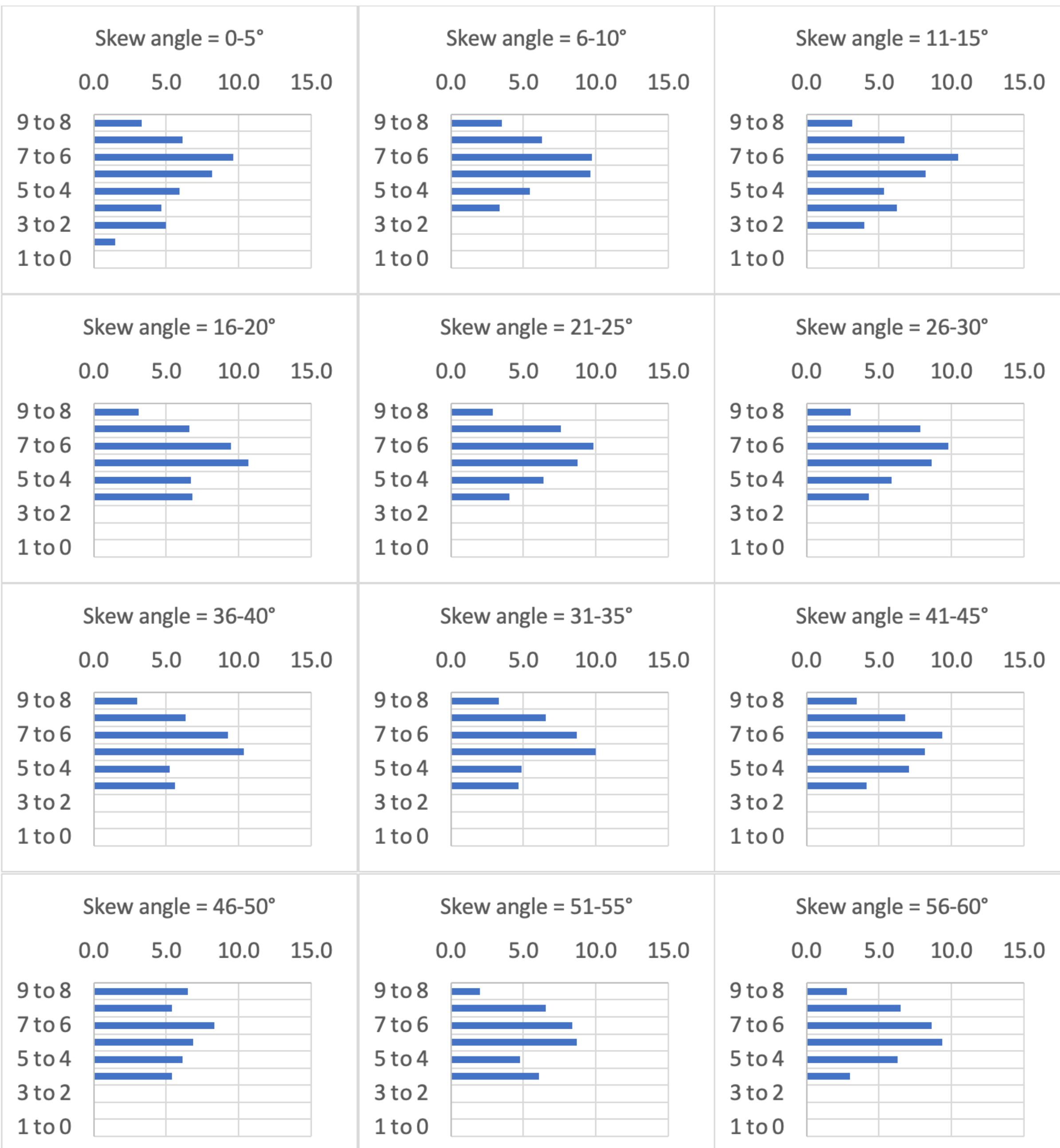
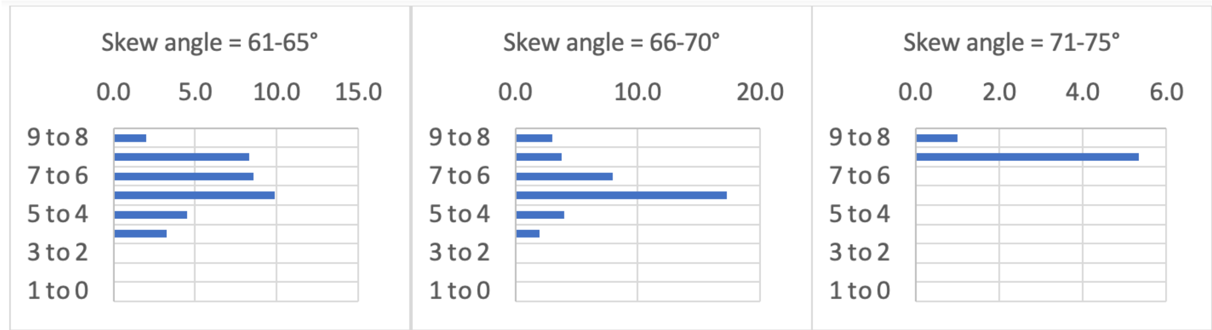


Figure 3. Graph of each skew angle group to show the years it takes for a bridge to drop its condition rate. The *x*-axis represents years and the *y*-axis the condition rate. (Continued)



Source: FHWA.

5. **Results of correlation and trend analysis:** After examining the dataset, the study team determined the correlation coefficient between the skew angle and the number of years that passed before the bridge deck condition rating dropped by one condition rate. This study showed a correlation coefficient of −0.116 for a condition rating of 9–8, −0.210 for a condition rating of 8–7, −0.841 for a condition rating of 7–6, 0.0069 for a condition rating of 6–5, −0.398 for a condition rating of 5–4, and −0.4191 for a condition rating of 4–3.

The correlation coefficient always has a value between 1 and −1, and that value is used as a general indicator of the strength of the association between variables. A positive number indicates a positive correlation (as one variable grows, so does the other), and a negative value shows a negative correlation (as one variable increases, so does the other). A value close to zero indicates a weak or no association. Table 1 shows that a correlation coefficient's absolute value indicates the size of the correlation: the bigger the absolute value, the stronger the correlation.[20]

The negative correlation coefficient indicates that the skew angle and the bridge deck condition rating have an inverse association. An inverse association demonstrates that the bridge deck condition rating drops faster as the skew angle increases. However, the correlation coefficients suggest a varying association, implying that other factors may significantly affect the bridge deck condition rating.[21,22] Generally, bridges have a fast deterioration rate between condition rates 9 and 7 that slows somewhat upon reaching condition rates between conditions 7 and 5. Upon reaching condition rate 5, the deterioration again speeds up. Table 2 presents that trend, where the red-to-green scale represents the progression from fast-to-slow rate of deterioration; as the color shades become closer to a solid red, the faster the deck is deteriorating.

Table 1. Correlation coefficient table.

Correlation Coefficient	Correlation Type	Correlation Strength
−0.7 to −1	Negative	Very Strong
−0.5 to −0.7	Negative	Strong
−0.3 to 0	Negative	Moderate
0 to −0.3	Negative	Weak
−0	Zero	None
0 to 0.3	Positive	Weak
0.3 to 0.5	Positive	Moderate
0.5 to 0.7	Positive	Strong
0.7 to 1	Positive	Very Strong

Conversely, the closer the color shade comes to a solid green, the slower the deck deterioration.

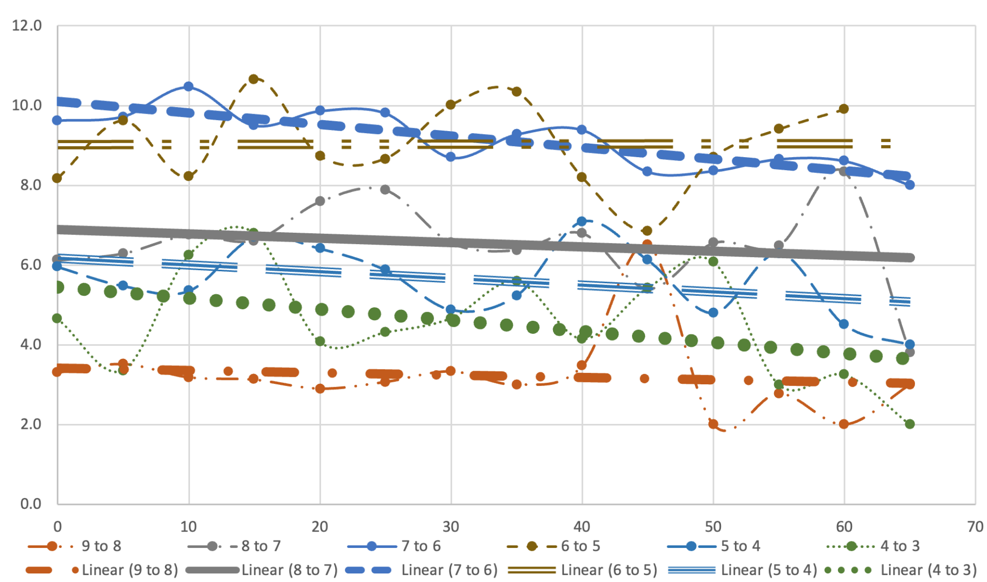
The graph in figure 3 depicts the relationship between the years that passed before a bridge deteriorated by one rate point on the *y*-axis and the bridge's skew angle on the *x*-axis. The condition rating represents the entire status or quality of the bridge, with higher numbers signifying better conditions. Figure 4 shows a trend line has a downward slope from left to right, showing a clear pattern in the data. This slope implies that when the skew angle increases (going to the right on the *x*-axis), it takes fewer years for the bridge to deteriorate. The fastest deterioration trends were

Table 2. Number of years to drop the condition rating by one for various skew angles.

Skew Angles	Condition Rating Drop From 9 to 8	From 8 to 7	From 7 to 6	From 6 to 5	From 5 to 4	From 4 to 3
0	3.3	6.1	9.6	8.2	6.0	4.7
5	3.5	6.3	9.7	9.6	5.5	3.4
10	3.2	6.7	10.5	8.2	5.4	6.3
15	3.1	6.6	9.5	10.7	6.7	6.8
20	2.9	7.6	9.9	8.7	6.4	4.1
25	3.1	7.9	9.8	8.7	5.9	4.3
30	3.3	6.6	8.7	10.0	4.9	4.7
-35	3.0	6.4	9.3	10.3	5.2	5.6
40	3.5	6.8	9.4	8.2	7.1	4.2
45	6.5	5.4	8.3	6.9	6.1	5.4
50	2.0	6.6	8.4	8.7	4.8	6.1
55	2.8	6.5	8.7	9.4	6.3	3.0
60	2.0	8.3	8.6	9.9	4.5	3.3
65	3.0	3.8	8.0	N/A	4.0	2.0

Number of years to drop condition rating by one: More than 7 = Fast deterioration; Between 4 and 7 = Moderate deterioration; Less than 4 = Slow deterioration; N/A = no data.

Figure 4. Graph. Years versus condition rating.



observed for bridges falling from 9 to 8 and 4 to 3 condition ratings, followed by bridges falling from 5 to 4. While bridges with condition ratings between 7 and 5 presented slower rates of deterioration.

Based on these data, the study team performed a statistical study, using analysis of variance (ANOVA) to investigate the potential influence of skew angles on bridge deterioration. Because the bridges represented on the graph belong to different skew groups (the skew angles were grouped in fives, i.e., 0–5, 6–10, and so on), they behaved differently. The ANOVA study sought to evaluate whether a statistically significant difference existed in the rate of deterioration among bridges with various skew angles. The investigation discovered a statistically significant influence of skew angle on bridge deterioration, showing that bridges with large skew angles deteriorate faster than bridges with small skew angles.

6. **ANOVA data analysis to establish and confirm trend:** The study team performed a hypothesis test to establish and study the association between bridge condition rating and skew angles of New Jersey bridges. The following are the hypotheses the team developed and tested:
   a. Null hypothesis (HO)—No significant relationship exists between bridge skew angle and condition rating.
   b. Alternate hypothesis (HA)—A significant relationship exists between bridge skew angle and condition rating. The significant level of this test was $a = 0.05$ (confidence interval = 0.95).[21]

The value of the negative correlation coefficient indicates an inverse association between the bridge condition rating and the skew angle. This means deterioration occurs faster for bridges with large skew angles. Table 3 shows the magnitude and direction of the correlation revealed information about the link between two variables.

The skew angles are categorical, meaning they have been grouped from 0–5°, 6–10°, and so forth, providing between 13 and 14 counts for each deterioration rating group. Because the condition rating is continuous, the ANOVA is the most suitable nonparametric test to be used. A spreadsheet program was used for the ANOVA test, and this test provided the test statistics and *p*-value.

The term "count" refers to the number of observations or data points within each group or category being evaluated. So, for this analysis, count means there are 14 groups of different categories of bridges with different skew angles in the various condition rating groups (bridges have been categorized according to skew angle: 0–5°, 6–10°, and so forth). The "number of bridges" shows the result of individual bridges, if they are dissolved from the groupings, that fall into the various groups shown.

The hypothesis test findings showed a statistically significant association between bridge condition rating and skew angle ($p<0.05$). Table 4 suggests that evidence exists that the two variables are associated and that the observed correlation is unlikely to have happened by chance alone. As a result, HO was rejected, and the study team concluded that there is evidence of a substantial link between bridge condition ratings and skew angles.

Table 3. ANOVA test.

Condition Rating Drop	Count	Number of Bridges	Sum (rating degrees)	Average (years)	Variance (years)
From 9 to 8	14	1,007	45.173	3.226	1.102
From 8 to 7	14	4,874	91.530	6.537	1.176
From 7 to 6	14	8,945	128.310	9.165	0.519
From 6 to 5	13	4,766	117.491	9.037	1.145
From 5 to 4	14	1,320	78.694	5.621	0.784
From 4 to 3	14	594	63.641	4.545	1.900

Table 4. ANOVA results.[18]

Source of Variation	SS	Df	MS	*F*	*P*-value	*F* Crit
Between groups	394.879	5	78.975	71.525	1.637 E-27	2.333
Within groups	85.020	77	1.104	—	—	—
Total	479.900	82	—	—	—	—

The ANOVA table's count values assisted in understanding the distribution and balance of bridge data across multiple groups or categories of skew angles being compared. That understanding enabled comparisons between skew angle groups with varied sample sizes and provided insights into the statistical findings' reliability. Summing the squared differences between each skew angle data point and the mean of the skew angle yields the sum of squares. The sum of squares equals the total variation within the different skew angle groups. The total variation is also used to calculate the significance of differences between groups or factors, with the mean squares and *F*-statistics, derived from it.

The terms "between groups" and "within groups" in the ANOVA refer to two independent sources of variance being investigated. In this study, these sources of variation helped assess the differences or effects of skew angles on the bridges. The *F*-statistic, or the ratio of between-group variation to within-group variation was used to determine the significance of variations across groups. An *F*-statistic that exceeds a critical value indicates that the differences between groups are unlikely to arise by chance. In this case, the *F*-statistic is 2.333, which is much higher than the significance level of α=0.05. Therefore, the difference in deterioration among the different skew angle categories did not occur by chance and, on the contrary, are correlated.

Connecting the graph's condition rating information with the statistical data from ANOVA enabled the study team to conclude that the skew angle significantly influences the bridge deterioration rate.

CONCLUSIONS

Correlation is a statistical measure of the relationship between two variables in bivariate data, meaning a linear connection exists between two independent variables. The correlation coefficient is a numerical measure that reflects the strength of a statistical association.

The results of this study indicate that the skew angle significantly influences the bridge deterioration rate. Even though additional research and analysis are required to investigate the underlying mechanisms and potential confounding factors that may influence the association between bridge condition rate and skew angle, this research provides substantial evidence of their interrelation. The research team acknowledges that it should consider other pertinent variables, such as traffic volume, bridge age, or maintenance history to understand the factors influencing bridge condition because many sources of uncertainty exist in structural design, which could also impact deterioration. (See references 1, 23, 24, and 25) This study effectively established a relationship between bridge skew angle and deterioration rate and stresses the need to consider bridge skew angle in project planning and infrastructure design to maintain bridge longevity and structural integrity.

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Also, I am grateful to FHWA for granting the study team the use of the InfoBridge Web portal and access to data and tools that served as the foundation of this study.[13] The large database of infrastructure information was critical to conducting a thorough study and drawing significant results.

Thank you to everyone who helped with data collection, analysis, and reviews performed by the InfoBridge project team. Their dedication to precision ensured the accuracy of this study's findings. Furthermore, many thanks to colleagues and fellow researchers who participated in this study, offering their knowledge and experiences that contributed to the depth of this study's findings.

Finally, thanks to the family and friends of the study team for their constant support, understanding, and encouragement during this research endeavor. Individuals' input was crucial to the completion of this LTIP Student Data Analysis Contest research paper. Sincerest thanks to everyone involved in this study for their dedication to the growth of bridge performance evaluation and the improvement of infrastructure engineering methods.

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