Highway Sign Support Systems: Condition Assessment Deterioration Models and Asset Management

Final Report

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Sign support systems are important structures in the Connecticut Department of Transportation (CTDOT) bridge management system. Periodic inspections and maintenance activities are needed as long-term cost-effective maintenance strategy. This research provided the deterioration model and asset management plan for sign support systems to be considered for integration with the existing BMS. The investigation included reaching out to every Department of Transportation (DOT) in the US to complete a survey on the topic. The experimental portion of the project focused on field instrumentation and testing of a highway sign support that is cantilever-type structure. The data was collected and analyzed, and it was used to verify the three-dimensional finite element (FE) model developed, which was used to test the structures design capacity.</td></tr>
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Metric Conversion Factors

APPROXIMATE CONVERSIONS TO SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

Table of Contents

List of Figures

List of Tables

Body of the Report

Executive Summary

Sign support systems are important structures in the Connecticut Department of Transportation (CTDOT) bridge management system. Periodic inspections and maintenance activities are needed as long-term cost-effective maintenance strategy. This research provided the deterioration model and asset management plan for sign support systems to be considered for integration with the existing BMS. The investigation included reaching out to every Department of Transportation (DOT) in the US to complete a survey on the topic. The experimental portion of the project focused on field instrumentation and testing of a highway sign support that is cantilever-type structure. The data was collected and analyzed, and it was used to verify the three-dimensional finite element (FE) model developed. The FE model was then tested to design load capacity to investigate the complete strength of the sign support.

Asset risks and replacement/repair priority list were developed using the probability of failure and commuter impacts that are functions of ages, structure types and material, number of traffic, and population. This research showed the complete cycle of infrastructure asset management, starting from asset condition database management, deterioration prediction modeling, risk analysis, and replacement/repair priority decision-making. Upon analyzing the data and conducting the calculations, the results indicate that the structure's age and other factors that determine Mean Time to Failure (MTTF) are the primary contributors to the failure rate. This study identified two main categories of sign support failures: (1) structural damage and (2) readability or accessibility damage. Structural damage results from physical factors, such as anchor bolts, while accessibility damage refers to the clarity and reflectivity of the signs.

CHAPTER 1 Introduction and Background

Definition of the Project

An event occurred on I-190 SB in Worcester, Massachusetts that underscores the importance of this project. On August 9th, 2022, a cantilevered sign support collapsed on the roadway obstructing traffic in both the low-speed and middle lanes (Figure 1.1). Thankfully no motorists were injured and MassDOT had the road clear by 8:43 am [1], but such an incident illustrates the potential risk associated with these structures and what can happen if they are not regularly maintained and replaced.

Figure 1.1. Collapsed Sign Support [1]

To conduct an effective investigation of sign support structures, a survey focusing on asset management, design process, inspection frequency, material usage, and failure types was drafted up and circulated to all DOTs (Appendix A). Data from each response was recorded, organized, and interpreted to assess the common issues affecting sign support structures and effective management practices of these structures. Efforts made during the qualitative portion of the project included distribution of the survey to the DOT divisions, evaluation and analysis of survey responses received from the qualified individuals (at 46% response rate).

The research work then concentrated on the experimental and analytical phases of the project. In September 2022, CTDOT sign support asset no. 21740 located over I-384 in Manchester, CT was chosen for the experimental work (Figure 1.2). Prior to sensor installation, an overview of the Non-Destructive Testing equipment was conducted. A mounting procedure encompassing the obtained equipment was developed and executed once it was understood how the equipment operates, logs data, and mounts to the structure. The project concluded with the analysis of collected experimental data as well developing an associated conclusion.

Figure 1.2. CTDOT Asset No. 21740

Prior to sensor installation, an overview of the Non-Destructive Testing equipment was conducted. A mounting procedure encompassing the obtained equipment was developed and executed once it was understood how the equipment operates, logs data, and mounts to the structure. The experimental work that lasted for six months concluded with the analysis of collected experimental data and the development of the finite element model.

The research work included the development of a simplified deterioration prediction model for the service life of highway sign support structures. The work adopted the probabilistic risk assessment and developed systematic prioritization method of replacement/repair and maintenance work.

List of Tasks

The objectives of this research were accomplished through the following tasks:

1. Task 1: Review State of Practice: The first step in the development process was to assemble and review current practice, technical literature, research findings of recently completed and ongoing projects, and procedures and codes addressing highway sign support on deterioration models, asset management, evaluation, and testing. Unpublished experience from the bridge engineering community were solicited and reviewed. A comprehensive review of literature using various search resources was performed. A complete literature search of all related research work done by FHWA and DOT's was conducted. Use of online databases enabled the research team to conduct a worldwide publication search of documents on the topic. Research focused on recent developments in the areas pertinent to sign support risk assessment and field testing.

The task involved a questionnaire and survey analysis of many Department of Transportation personnel throughout the US. There was also an evaluation of the current inspection data collected by CTDOT.

2. Task 2: Non-destructive condition assessment by coordinating with CTDOT maintenance team. This task evaluated the compiled data base of sign supports in Connecticut and sorted the inventory to identify good candidates for equipment installation. The efforts were closely coordinated with CTDOT representatives and key stakeholders such as transportation enforcement and maintenance, and planning authorities.

   This task involved the use of a data acquisition system, and instrumentation that include (1) Anemometers to obtain wind velocity and direction, (2) Accelerometers to obtain the acceleration response of the structure, and (3) Strain Gauges to measure the strain response of the structure. Four strain gauges were installed at the base of the pole of the overhead sign support structure, four strain gages at the top arm of the lattice structure holding the arm, as well as one accelerometer and one anemometer at the top arm. The equipment supplier company provided training to both CCSU and CTDOT personnel and installed the sensors at the sign support structure selected. The company's field staff required one bucket truck that was provided by CTDOT for use during the installation day. The instruments remained connected to the structure for months to continuously collect data. The data acquisition system and the sensors are officially owned by the CTDOT, so they can readily remove them for future use on other structures

3. Task 3: Analyzed current designs using Finite Element Analysis (FEA) and developed new innovative designs for highway overhead sign support structures to mitigate stresses generated due to corrosion and wind-induced fatigue loads. The main focus of this task was to improve the reliability of methods for determining traffic loading on sign supports. The field data collected was utilized to build the Finite Element Model (FEM) three-dimensional sign support structure using the software SAFI HSE (Highway Sign Structural Engineering). Verifying the FE model with the experimental data provided the opportunity to better understand the behavior of the sign support and the loading influence. Parametric study and design provisions was performed using the analytical model. The sensitive parameters were identified, and criteria were developed to account for these parameters. Based on the findings, modifications to the sign support system were suggested for future use.

4. Task 4: Deterioration Prediction Model: The deterioration model or deterioration prediction model is the forecasting curve of the structures' condition over time. It is the basis for the benefit-cost (B/C) analysis and used to maximize return on investment (ROI) on the network over the lifetime of the infrastructure asset. In this research, the objective was to develop a simple deterioration curve that is easy to be integrated with existing Bridge Management System (BMS). Markovian deterioration or Aldeterioration models may deliver better condition prediction however, it is difficult to be integrated with BMS. PI's are tentatively suggesting the use of Weibull distribution function that is widely used in reliability theory.

5. Task 5: Risk Assessment and Asset Management: PI's adopted the probabilistic risk assessment and developed systematic prioritization method of replacement/repair and maintenance work. Quantitative risk evaluation was obtained by multiplying the probabilistic variables of risk impact and probability of occurrence of the risk. The evaluated risk was represented in terms of normal probability destruction function. High risk assets are the first ones that need attention. However, considering the of replacement/repair, Benefit-to-Cost ratio can be used as the replacement/repair prioritization of the assets.

   In addition to the risk assessment and B/C analysis, PI's investigated the LOS (Level of Service) of the assets based on the customer's perspective. This research described the method to measure the level of services converted into the utility values that assess the level of service of different kinds of facilities.

6. Task 6: The project work tasks were documented in the final report and shared with respective stakeholders and formed the basis for the researcher's recommendations for sign support asset management.

Literature Review

Documents published by state DOTs standardizing elements of their sign support assets is evidence of sound asset management. Several DOTs have published Transportation Asset Management Plans (TAMPs) to secure federal funds and comply with federal legislation, specifically the Moving Ahead for Progress in the 21st Century (MAP-21) Act and the Fixing America's Surface Transportation (FAST) Act [2]. Responsible for approximately 1,654 sign supports, CTDOT has established performance measures (Figure 1.3) and maintenance programs to better manage sign support assets.

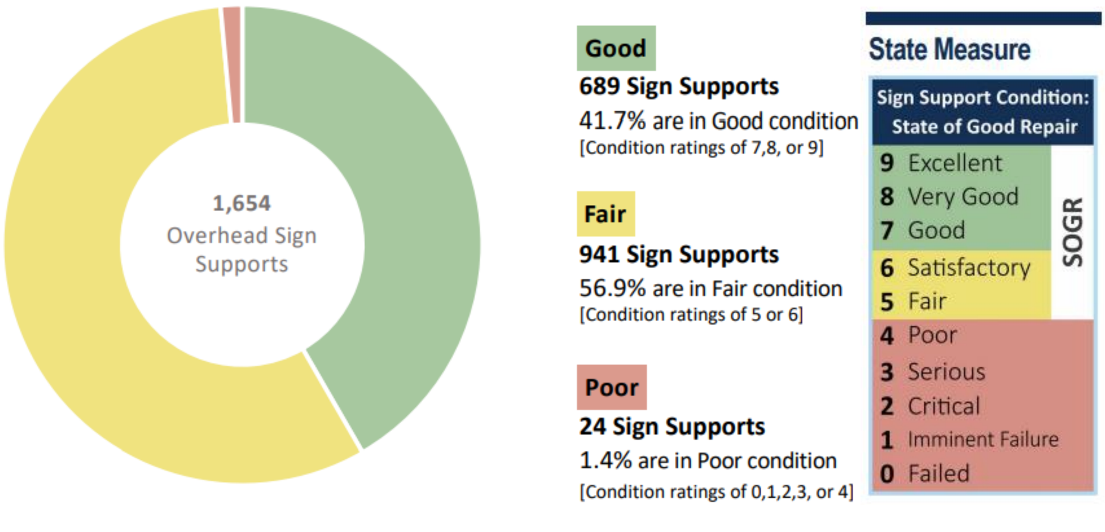

Figure 1.3. CTDOT Sign Support Inventory with Performance Scale [2]

Supports with a score of 0 have failed and a score of 9 indicates the support is in excellent condition. Assets receiving scores between 5 and 9 are said to be in a State of Good Repair (SOGR).

The Federal Highway Association (FHWA) assesses sign supports using a good, fair, poor system. Recent data suggests that 41.7% are in good condition, 56.9% are in fair condition, and 1.4% are in poor condition [3]. CTDOT's TAMP combines each of these rating systems so that sign supports in good condition correspond to scores 9-7, sign supports in fair condition correspond to scores 6 and 5, and sign supports in poor condition correspond to scores 4-0 [2].

All 1,654 sign supports maintained by CTDOT can be categorized by type: cantilevered, full span, and bridge mounted. CTDOT's TAMP breaks down the total number of supports into the following categories: 643 cantilevered supports, 617 full span supports, and 394 bridge mounted supports [2]. An additional support type not used by CTDOT is the butterfly (Figure 1.4), or butterfly truss type support. The type of support may also indicate what the inspection interval will be for each asset. CTDOT maintains that every 6 years, full span supports are inspected. Every 4 years cantilevered and bridge mounted supports are inspected. And if a support is fabricated out of aluminum, it shall be inspected every two years no matter the type of support [4].

Figure 1.4. PennDOT Butterfly Support [2]

CTDOT's TAMP breaks down inspections into four main components of each asset: signs & illumination, structure, foundation, and traffic safety features. CTDOT logs inspections and the location of each asset using GPS in InspectTech [2]. Having a clearly defined maintenance schedule and an organized method for logging inspection data is crucial to asset management. Other DOTs have implemented standardized documents as well defining installation and inspection methods, sign support selection criteria and even repair manuals [5]. The Wisconsin Department of Transportation (WisDOT) has published a table of available sign support types as well as selection criteria for each support (Appendix B) [6]. WisDOT also has a chapter in their Facilities Development Manual dedicated to standardized sign support structure designs and selection processes (Figure 1.5) [7]. These standardized designs help contractors fabricate a reliable sign support structure without redesigning the whole structure every time a job comes out to bid. Also included on WisDOT's website is a list of LRFD Standardized Overhead Sign Structure Plans [8]. The typical drawing for a WisDOT monotube cantilever sign support is attached to Appendix C. Nebraska Department of Roads (NDOR) published a complete inspection and installation manual for sign supports and high mast lighting [9]. NDOR's manual includes pictures of best practices concerning torquing, anchor bolt plumbness, plate connection tolerances, corrosion prevention, as well as other important installation and inspection considerations.

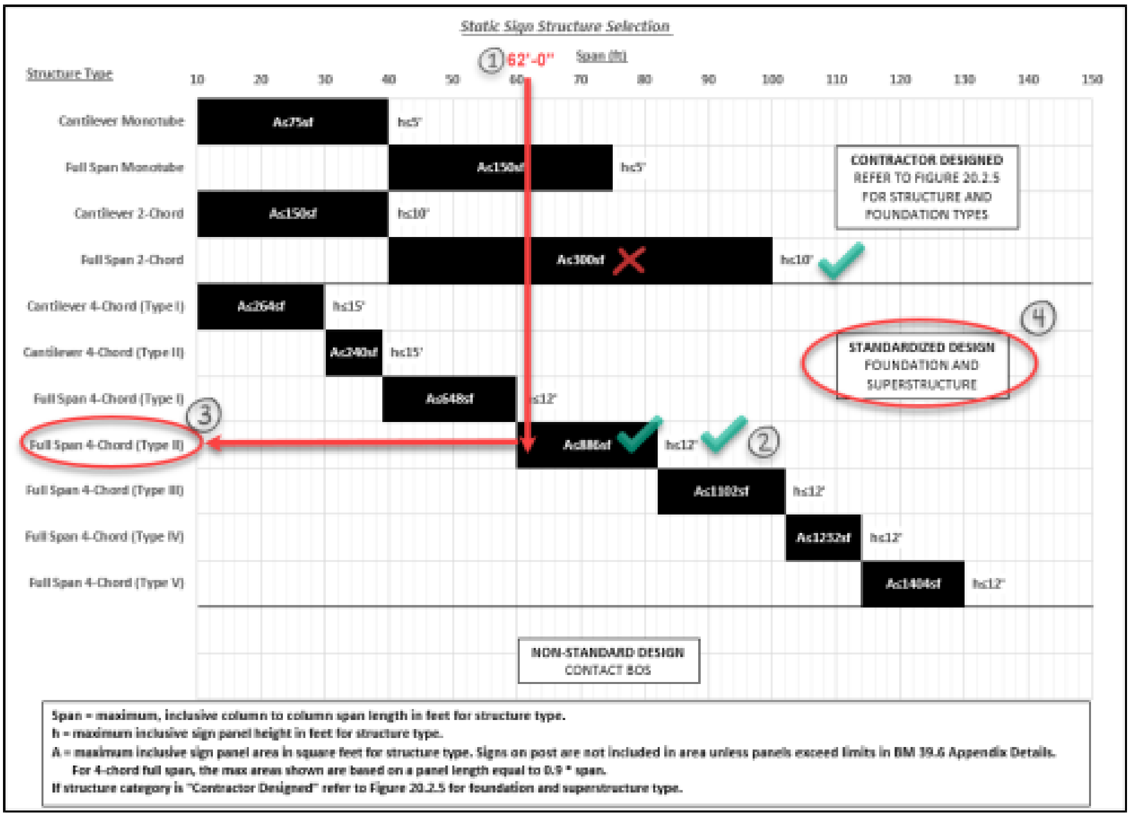

Figure 1.5. WisDOT Sign Support Selection Worksheet [2]

Setting long term performance goals and proper life cycle planning assists scheduling of sign support replacement and repair. CTDOT's TAMP outlines some performance targets for sign supports managed by CTDOT. In 2019, it was projected that 96.6% of sign supports will be in a SOGR by the end of 2020 and 95.2% of sign supports will be in a SOGR by the end of this year. A 10-year goal is also established by CTDOT's TAMP setting out to achieve a SOGR for 90% of sign supports. The decrease in percentage of sign supports in a SOGR around 2026 is due to a large number of supports reaching their life expectancy at the same time (Figure 1.6). CTDOT's TAMP maintains that funding for sign supports will be approximately $4M per year with replacement of 40% of sign supports in poor condition funded by other projects. It is noteworthy that 100% of the funds in the sign support budget go towards replacement. Perhaps allocating a portion of those funds towards repair could be a more economical option.

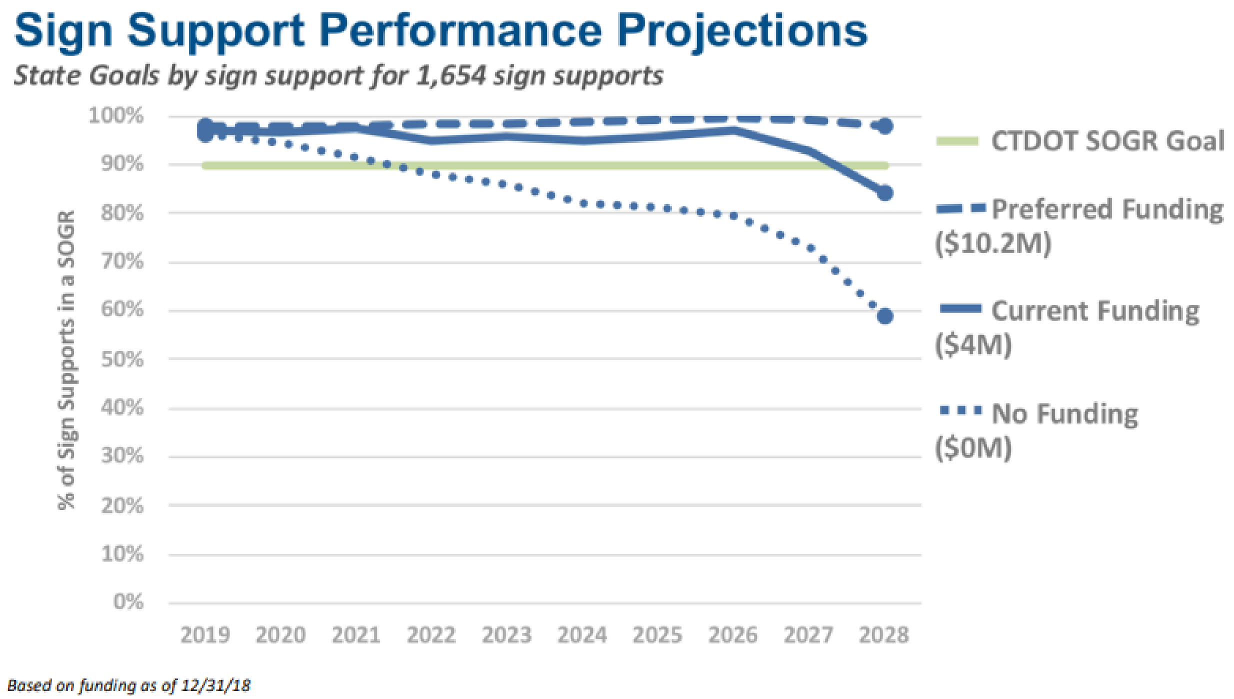

Figure 1.6. CTDOT Sign Support Performance Projections [2]

The NCHRP Report 494 Structural Supports for Highway Signs, Luminaries, and Traffic Signals includes a section discussing inspection, retrofit, repair, and rehabilitation of fatigue damaged support structures. Michigan DOT is the only state DOT who has published a repair manual for sign support structures indicating that most DOTs would rather replace the whole structure entirely instead of making repairs [5]. Supplemental literature review was also contucted on fatigue stresses as these forces are attributed to most sign support structure failures [10].

Life cycle planning is driven by one underlying principle: timely investments in an asset result in improved condition over a longer period of time and lower long-term cost. To execute life cycle planning, CTDOT uses age-based deterioration curves based off of a 34-year service life. The condition-based models need more development to be successfully implemented, so the age-based approach is strictly adhered to. Once a sign support has reached the end of its 34-year service life, they are replaced. If an age-based modeling approach is being used, it is important to have a database documenting how old the assets are. Minnesota DOT (MnDOT) has furnished a bar chart showing a percentage of its total sign support inventory at different age ranges (Figure 1.7) [11]. According to MnDOT's data, 73% of its overhead sign support structures are between 0 to 40 years old, which backs up CTDOT's claim of a 34-year service life expectancy.

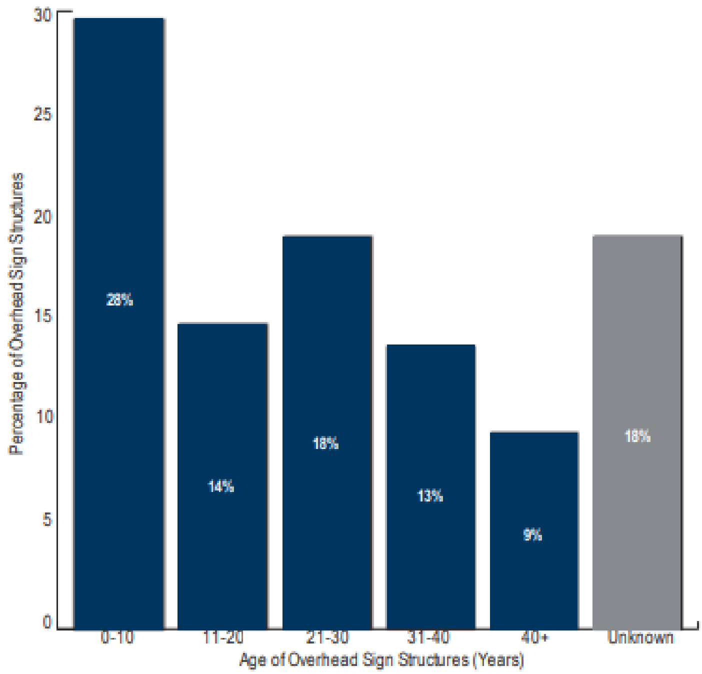

Figure 1.7. MnDOT Sign Supports Organized By Age [11]

CTDOT estimates that it costs $140,000 to replace a cantilever support, $250,000 to replace a full span support, and $50,000 to replace a bridge mounted support [2]. Because these assets are not cheap, it is crucial to select those that are in most need of replacement. While it might be expected that those supports scoring lowest on the SOGR scale will be replaced first, replacement criteria is not entirely condition-based. Many times, sign supports are replaced because the sign panel size increases due to changes in FHWY's Manual on Uniform Traffic Control Devices (MUTCD) for Streets and Highways requirements. A bigger sign panel requires a support stronger than the existing support. Sometimes projects which alter the roadway can lead to the replacement of a perfectly fine support. Other times sign support projects are issued by location, so every sign support along the designated corridor will be replaced regardless of its condition. All of these non-condition-based replacements create potential for waste and excess opportunity cost resulting in economic loss.

To combat the negative effects of non-condition-based replacements, CTDOT's TAMP outlines 5 investment strategies:

1. Program sign support projects based on poor conditions.
2. Reduce the number of sign supports by putting signs next to the road whenever possible.
3. Increase efforts to maintain the sign panel size by decrease the sign legend spacing.
4. Overdesign sign supports with an augmented factor of safety so they can support next-generation sign panels.
5. Reduce the number of bridge mounted sign supports to decrease dead load supported by the bridge and lower inspection costs.

Failure rates of sign support systems are scarce. Each study for the project showed that significant structure collapse occurs infrequently and can be avoided with preventative analysis and a predictive failure model. Sign support asset management is a topic that has not been extensively studied [12]. However, the development of predictive deterioration models for sign support systems is feasible by identifying key factors such as materials, age, location, and wind loading. As cars and trucks pass under signs, the wind that comes off them gradually wears on the sign supports.

Specifically, the welded joints of the supports are the primary point of degradation. Failure analysis of the highway sign structure and design improvement showed that hairline fractures occur due to wind loads. Kipp [13] also showed that it is more practical to analyze the structures under various wind loads instead of a pure static load, as varying wind speeds can cause more damage to structures over time. The study attempted to model wind effects on different sign support systems and identify their weak points for future repair schedules. It was concluded that the two critical points in the structure were the midpoint of the span and the base of the columns. The probability of failure and reliability of the curves should depend on the lanes and the average daily traffic under each structure. This study also validated the use of predictive computer modeling for measuring sign support wind degradation.

Looking more at the types of sign supports specifically, field testing and analysis of aluminum highway signs trusses looked at how existing designs can be modeled to increase their wind load capacity. The study by Barle et al. [14] showed this to be the case by examining cantilever-type, and Type-III overhead sign supports. The conclusion reached was that by increasing the drag coefficient on these structures, the wind load could be reduced. By analyzing these, we can see that minor modifications to sign supports have a significant impact.

Different types of sign supports have varying tolerances for wind capacity and respond differently to stresses. Two studies support this conclusion: one by Yang et al. [15] and the other by Ehsani et al. [16]. These two papers conclude that monotubes rely on stiffness for reliability rather than strength criteria, while the opposite is true for box truss structures. Therefore, the type of sign support affects reliability if all other factors are equal.

The idea of conducting regular inspections of aging models can identify problems before they occur. Shboul et al. [17] analyzed predictive failure models and showed that a comprehensive approach to predictive failure can be achieved by simulating wind speeds. This work supports the findings of Barle et al. [14] who concluded that variable wind speeds cause more wear and tear than static wind speeds. The conclusions drawn by Shboul et al. [17] were used to detect two severe fractures in signs that would have otherwise gone unnoticed. This discovery was due to new inspection practices [18]. While the study is more technical, the hypothesis suggests that wind is one of the highest risk factors for sign support degradation, primarily caused by passing traffic underneath.

The study's validity is reinforced by reviewing related peer literature and their methods. Two key research publications on the topic are "Road Asset Management Systems" by Miller et al. [19] and "Analysis of Traffic Sign Asset Management Scenarios" by Harris et al. [20]. These two publications provided the basis for the approach to asset management and categorization. Kruse et al. [21]

demonstrated how asset management using technology such as GIS information can be effective. Their study supports the subsequent research, highlighting the advantages of using advanced software to monitor assets. When combined with a predictive failure model, this can result in a more efficient maintenance plan.

CHAPTER 2 Research Methods and Findings

Survey

Studying the existing literature on sign support management and structural analysis facilitated sound project design. Each step from writing the survey to sensor installation and data treatment required us to draw upon knowledge acquired from articles discussing fatigue stress, reports covering inspection procedure, and drawings standardizing sign support design. After sufficient literature review, the survey was drafted and distributed (Figure 2.1).

Overhead Highway Sign Support Survey

1) Approximately how many highway sign supports are currently in your state?
   a. Less than 500
   b. 500 - 1000
   c. 1000 - 1500
   d. 1500 - 2000
   e. More than 2000, approximately: _________
2) What is the approximate inspection frequency of highway sign supports, in years?
   a. 5
   b. 10
   c. 15
   d. 20
   e. Other: ________
3) What is the best estimate, in years, for the replacement of a highway sign support?
   a. 10-19
   b. 20-29
   c. 30-39
   d. 40-49
   e. 50+
4) What are the approximate percentages of highway sign supports with the following designs?
   a. Full-span ____ %
   b. Cantilever ____ %
   c. Bridge-mounted ____ %
   d. Other:______________________
5) What are the approximate percentages of material types used to construct sign supports?
   a. Steel: ______ %
   b. Aluminum: ______ %
   c. Concrete: ______ %
   d. Other:______________________
6) Which type of highway sign support requires the most maintenance?
   a. Full-span
   b. Cantilever
   c. Bridge-mounted
   d. Other:______________________________
7) What is the most common reason for replacing a highway sign support structure?
   a. The structure has reached the end of its useful life
   b. The structure needs to be updated according to new or existing specifications
   c. Modifications to the roadway cause the structure to be relocated
   d. Other:______________________________
8) What is the most typical failure of highway sign support structures?
   a. Crumbling or cracked foundations
   b. Loose nuts or bolts
   c. Broken welds
   d. Tilting or leaning
   e. Other:______________________________
9) Are the current designs for highway sign support structures standardized?
   a. Yes
   b. No
10) Are damping or energy absorbing devices being used in current sign support designs?
   a. Yes
   b. No

Figure 2.1. Overhead Highway Sign Support Survey Sent to the Nations DOTs

As the survey results were received, graphical representations were constructed to show certain trends in the data. The scatterplot (Figure 2.2) plots inspection frequency against total number of sign support structures and the pie chart (Figure 2.3) shows DOT estimates for sign support life expectancy.

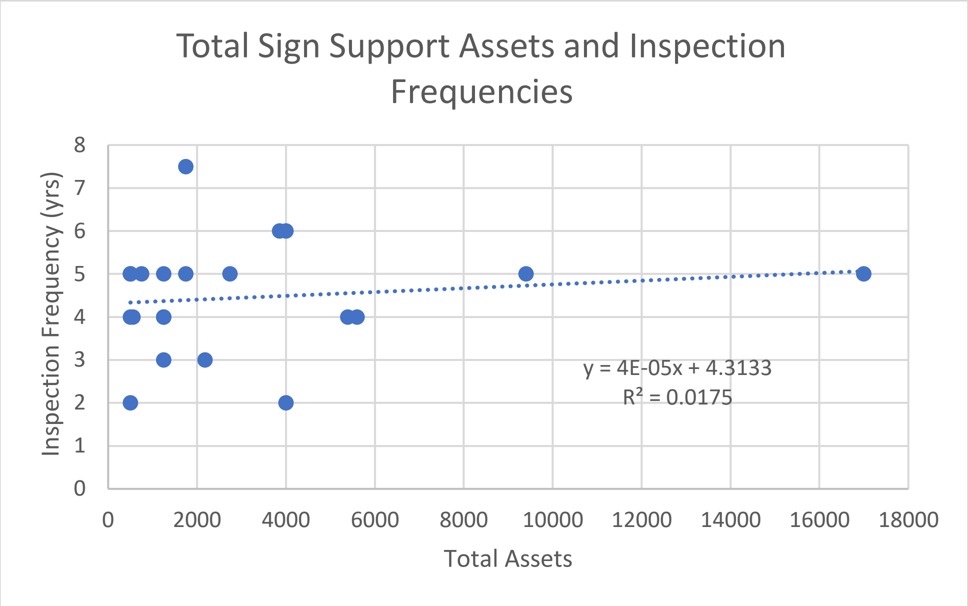

Figure 2.2. DOT Inspection Frequency Scatterplot

Each data point on the scatterplot represents a DOT who participated in the survey. The y-axis represents the years passed in between inspections and the x-axis represents how many sign support structures a given DOT maintains. A linear regression was used to graph a line that best fit the recorded data. Although the linear regression produces a relatively low R^2 value, it's important to note that a DOT with as many as 34 times the sign support structures performs inspections at a similar frequency.

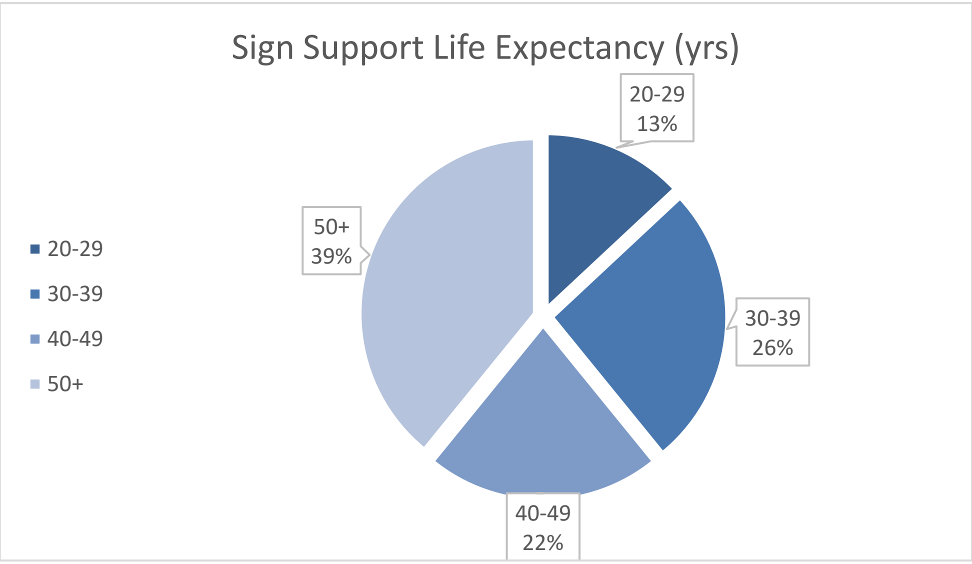

Figure 2.3. Sign Support Life Expectancy Pie Chart

Each section of the pie chart constitutes a percentage of DOT response and corresponds to an approximate life expectancy. 72% of DOTs claim sign support structures can remain in service after 40 years, which potentially renders the service life estimated in CTDOT's TAMP an underestimate. Those DOTs reporting an estimated sign support service life expectancy greater than 50 years also commented on its response that repeated maintenance would be performed on the structures before programming a replacement. Other DOTs however reported that structures would be replaced before major maintenance was required.

Other notable findings reported in survey responses include:

- 29% of DOTs reported that 25% to 48% of their sign supports were constructed of aluminum while the other 71% reported over 93% of sign supports were constructed of steel.
- A revision to an anchor bolt tightening procedure has reduced hardware section loss due to corrosion
- Inspections are being prioritized based on asset condition and location. Those structures in worse condition which require more maintenance and structures located in areas exposed to adverse external factors (i.e. flood plains, snow belts) are being inspected at a higher frequency.
- Other DOTs report annual inspection of bridge-mounted sign supports indicating that these particular assets are high maintenance.

Selection Method of Sign Support to Test

The PI's were given access to the CTDOT Bridge Asset Management website, which revealed that there are 1,651 highway sign support structures in the state of Connecticut within the responsibility of CTDOT. Using the Pivot function in Excel, a number of tables were developed to data mine and select an appropriate structure to test. The sign supports were divided structurally as shown in Table 2.1, including the count of structures older than 34 years. Table 2.2 shows the overall structural rating of the all the sign support. It is noteworthy that 98.7% of all sign supports are fair condition or better.

Table 2.1 helped establish that the cantilever type sign support is the most predominant. Further, since the study is looking into deterioration of sign supports, which is directly related to age of structure, and since the DOT has an established policy of replacing sign support structures after 34 years, a quarter of the structures that are older than 34 years are still in service. Among the cantilever type, there are 155 sign supports that meet this criteria. Table 2.2 shows that the vast majority of the sign supports, 98.7%, are still in fair and better structural condition. Only 20 in poor condition and 2 in serious condition.

Table 2.1. Types of Highway Sign Supports in Connecticut

Type	Amount per Type	Percentage	Older Than 34 Years	Percentage
Cantilever	681	41.2%	155	9.4%
Full-Span	618	37.4%	163	9.9%
Bridge Mounted	352	21.3%	101	6.1%
Total	1651		419	25.4%

Table 2.2. Structural Rating of the CT Highway Sign Supports

Rating	Serious (3)	Poor (4)	Fair (5)	Satisfactory (6)	Good (7)	Very Good (8)	Total
Count	2	20	166	715	672	76	1651
Percentage	0.1%	1.2%	10.1%	43.3%	40.7%	4.6%	100.0%

Therefore, it was determined that the sign support to be tested needed to be of the cantilever type, older than 34 years, in fair and better condition. Practical considerations were also applied, namely to be on a significant highway and to have ease of access to instrument. This produced the sign support number 21740, in Manchester, CT, at Exit 4 of Highway 384. It is type Truss Arm Cantilever RC, steel strength is A-595. A picture of the sign support selected is shown in Figure 2.4, and its dimensions schematic is shown in Figure 2.5.

Figure 2.4. Picture of Sign Support 21742

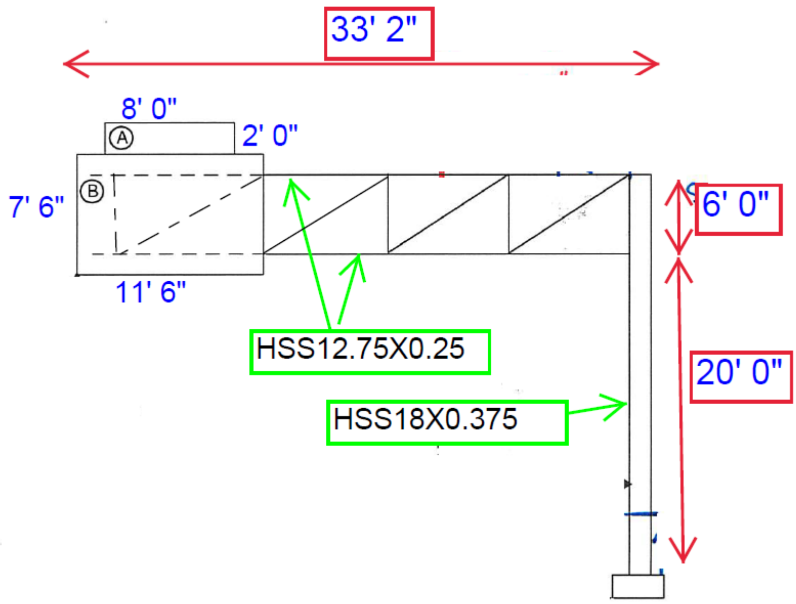

Figure 2.5. Dimensions Schematic of Sign Support 21740

Field Instrumentation and Test of Sign Support

The quantitative portion of the project began with constructing a concrete slab on grade complete with a precast pole foundation. A pole needed to be erected to accommodate three solar panels and the concrete slab-on-grade was placed to secure the instrumentation cabinet.

To secure the cabinet, a 3' 4" x 6' 8" concrete slab-on-grade was placed adjacent to the foundation of the sign support. The construction effort was organized by CTDOT who provided all the labor, materials, and equipment. After the traffic control crew established a safe work zone in the low-speed lane on I-384 EB, excavation for the slab and pole foundation commenced (Figure 2.6). The footing for the existing sign support is pictured to the left of the excavation. Approximately 6” of stone was placed in the hole and spread to match bottom of footing elevation. Figure 2.6 shows the first bucket of material being removed for the precast pole foundation. The foundation was set so that top of footing and top of precast were at the same elevation (Figure 2.7).

Figure 2.6. Excavation Backfilled with Stone

Figure 2.7. Precast Pole Foundation Set to Grade

After the precast foundation was set to grade, the formwork and bulkhead for the concrete slab was installed. 3/4" plywood and 2" x 4" lumber was used to construct the form and bulkhead. The form and excavation created space for a 10" thick slab to properly anchor the utility pole and instrumentation cabinet. Some reinforcing steel was used to counteract any tensile forces within the slab. Ten 1' lengths of #4 rebar were driven into the stone vertically and one piece of wire mesh was laid horizontally inside the form prior to concrete placement.

Additionally, a 1" piece of foam was used as an expansion joint between the slab and the existing footing (Figure 2.8) to prevent cracking in the slab during the curing process. The mix design used by CTDOT included two bags of Rapid Set DOT Cement, four 5-gallon buckets full of sand, four 5-gallon buckets full of 3/8" stone, and approximately 5 quarts of water. A portable cement mixer was used to mix the materials and the concrete was placed and finished using a wheelbarrow, mag floats, and brushes (Figure 2.9). Once the concrete went through a 24-hour curing process, the form was stripped and the utility pole was bolted down to the precast foundation.

Figure 2.8. Expansion Joint and Reinforcing Steel

Figure 2.9. Concrete Slab Brush Finish

With the slab and pole construction complete, sign support instrumentation began. The following list overviews the equipment provided by Bridge Diagnostics, Inc. (BDI):

- One BDI 2369 5g accelerometer
- One Young USA Model 03002 anemometer
- One weather-resistant instrumentation cabinet
- Eight Ememe® Micro-Measurements strain gauges, item code: MMF404523
- Three SunWize® SW-S130P solar panels complete with brackets and mounting hardware.

The cabinet contains four 12v batteries, a cellular modem capable of remote data transmission, and all the necessary components allowing the sensors to function as system. A wiring diagram illustrating all components and connections in the instrumentation cabinet is included in Appendix D. Fastening the instrumentation cabinet to the concrete slab are four 3/8" concrete wedge anchors, one in each foot. The wiring to the cabinet runs through water tight grommets to protect the sensitive components inside.

The first sensors installed on the sign support were four strain gauges located 3' up the sign support column. The strain gauges were installed equidistant around the circumference of the column. Proper installation called for surface preparation. To prepare the surface, the paint was removed using a right-angle grinder with an abrasive wheel. With the steel exposed, any remaining residue was wiped away with isopropyl alcohol and Ememe® CSM-3 degreaser.

Each strain gauge was adhered along the major axis of the column using M-Bond 200 two-part epoxy (Figure 2.10). After the sensors were epoxied to the structure, they were insulated from the weather using absorbent pads and UV/water resistant foil. To enhance the data collected from the four strain gauges mounted around the circumference of the column, two bridges were installed. A bridge links two strain gauges on opposite sides of the column together to function as a unit. The two bridges make it possible for the strain gauges to detect forces acting on axes supplemental to the major axis, like torsion. A similar four strain gauge system was installed on the top chord of the cantilever arm.

Figure 2.10. Typical Strain Gauge Installation

Following strain gauge installation was accelerometer unboxing and preparation (Figure 2.11). The accelerometer's primary function is to "wake up" the instrumentation system and record data one second before and after activation. The accelerometer is activated once vibrations in the structure exceed a certain threshold. Mounted using a band clamp around the top chord of the cantilever arm, the accelerometer is located at the midpoint of the cantilever arm.

Figure 2.11. Accelerometer Attached to Band Clamp

The last piece of equipment fastened to the sign support was the anemometer which detects wind speed and direction. The anemometer was designed to receive a piece of 1" IPS pipe and was mounted to the top of the sign support column with two band clamps running around both the column and the 1" IPS pipe. Figure 2.12 portrays an approximate location of the sensory equipment fastened to the sign support.

The final piece of field work to be completed was to setup the solar array. The array consists of three panels mounted to the top of the 12' utility pole. Each panel was rotated about the pole incrementally to create a fan-like shape maximizing UV exposure (Figure 2.13). The mounting brackets feature a lightweight CNC aluminum design providing a lightweight yet sturdy fastening solution.

Figure 2.12. Sensor Types and Locations

Figure 2.13. Solar Array

Deterioration Prediction Model

In this research, it is suggested that the simplified deterioration model using the Weibull function is used instead of developing a new deterioration prediction model as there are many technical publications already available. In addition, many asset management efforts failed due to the overly complicated deterioration prediction modeling. Parameters for Weibull reliability function, beta and gamma were reviewed as follows.

Typically, during the initial stage of operation, newly built machines or structures have a high probability of breakdown or failure due to defective parts or incorrect installation. Once the initial stage is stabilized, it enters a period of stable service until it reaches the end of its service life (Figure 2.14). The Weibull distribution function is a widely used failure prediction model in reliability theory. Reliability refers to reducing the frequency of failures over time and is a measure of the probability of successful, failure-free operation during a given interval. This can be quantified as the *Mean Time Between Failures* (*MTBF*) for repairable products or the *Mean Time to Failure* (*MTTF*) for non-repairable products. The Weibull function is commonly used in reliability theory for its simplicity and accuracy. Figure 2.15 shows a typical failure rate over time using the Weibull function, with the usage time as *x*, β as scale parameter, and γ as shape parameter. In this example, γ is assumed to be 3, and β is 30, which directly relates to the spread of the distribution curve. In reliability theory, β represents either *MTBF* or *MTTF*. The cumulative distribution curve shows the cumulative probability of occurrence over time for a specific action, in this case, the probability of failure over time.

$$f(x) = 1 - e^{-(\frac{x}{\beta})^{\gamma}} \qquad \text{Eq. 1}$$

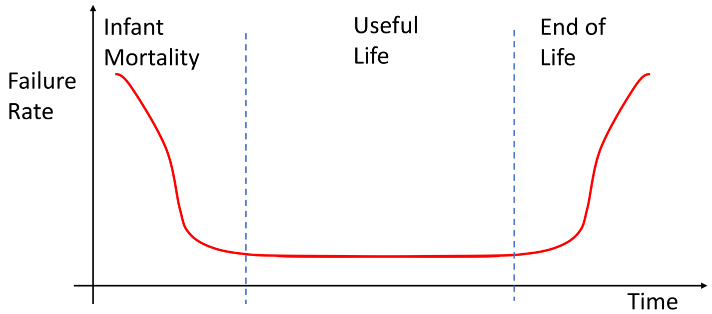

Figure 2.14. Bathtub curve showing the reliability of newly installed assets

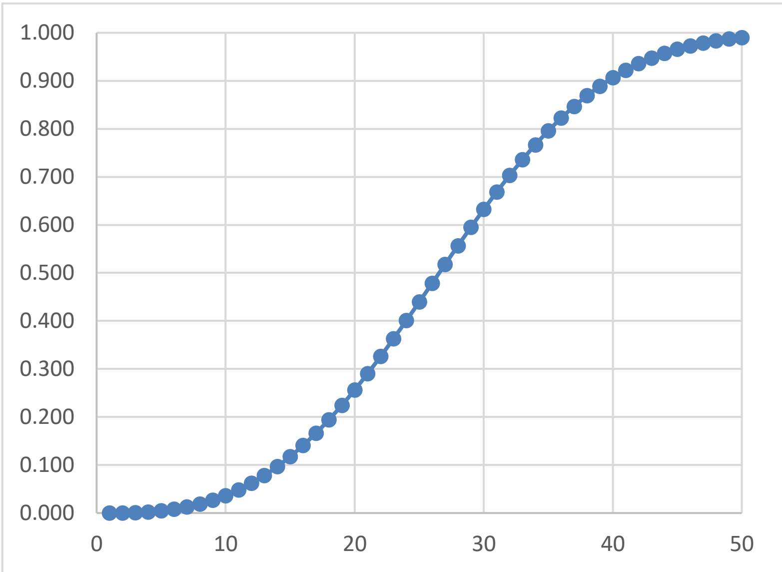

Figure 2.15. Weibull function when MTTF β = 30, shape factor, γ = 3

Infrastructure Asset Management using Quantitative Risk Analysis

Infrastructure Asset Management aims to efficiently maintain and prioritize the maintenance of assets while predicting budget requirements. A quantitative risk analysis is performed to determine the likelihood of asset deterioration and failure. The risk management plan involves four steps: (1) risk identification, (2) quantifying failure impact, (3) estimating the probability of failure, and (4) risk quantification calculated as *Probability of Occurrence (P)* x *impact (I), or Risk = P* x *I*. The estimated risk can be used to determine maintenance and replacement/repair priority. The probability of occurrence (*P*) is calculated using the mean-time-to-failure and the age of the infrastructure using either the Weibull function or Normal distribution function.

Methodology and Process

The data used in the predictive modeling was collected with the purpose of estimating the reliability and probability of failure of each structure. The Connecticut DOT (CTDOT) collected the data through the Bentley Asset Performance Management Solution® and used the built-in query system to access the data. However, due to the recent implementation of the system, the data was incomplete and filters were applied to limit the data to those entries with complete information. The sample size after filtering was *1,838*. The data filtering was necessary to avoid the impact of missing data points on the overall calculations. The method and objectives of the study are illustrated in Figure 2.16.

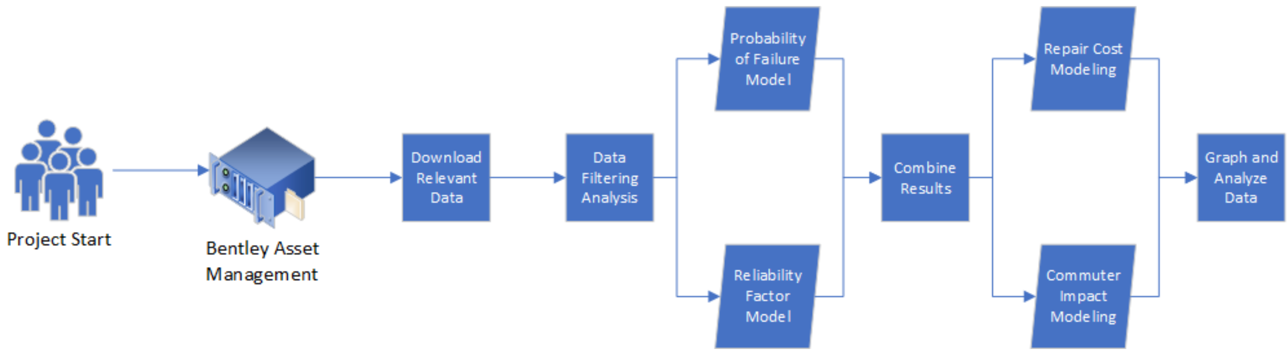

Figure 2.16. Research Methodology

The *Mean-Time-to-Failure* (*MTTF*) was calculated by taking an average of various adjustment factors relevant to each sign. The four adjustment factors used were: (1) average daily traffic, (2) number of lanes under the structure, (3) material type, and (4) structure type. These factors were selected as they best represent the average wear and tear of the structures, as determined through extensive literature reviews of existing sign support systems.

The variables that begin with "*s*" in each factor represent the estimated number of years a structure would fail without considering other influences. For instance, an adjustment value of 36 for a support made of A36 steel (according to ASTM) represents the material of the structure. The shape, location, and average daily traffic are not taken into account when assigning these scores, but are considered when averaging the scores to obtain the final *MTTF* estimate.

The methodology of estimating *MTTF* involves finding the average of the scores of each factor and calculating the average number of years before a structural failure. Since each structure is unique, determining the *MTTF* for each individual structure would require an enormous amount of time and is beyond the scope of this study. By assigning scores based on the relative durability of each factor, a normalized *MTTF* score can be assigned to each structure based on an average.

The yield strength of the material (sMAT) accurately reflects the role that the material of a sign support structure plays in its general deterioration over time. According to the ASTM [22] standards reference documents, the yield strengths of various materials are shown in Table 2.3, assuming all other factors remain constant.

Table 2.3. Support material adjustment value (ASTM 2019)

Description	Adjustment Value	Material Type
Other	42	N/A
A-36 Steel	36	Carbon Alloy
A-242 Steel	50	High-strength low-alloy
A-595 Steel	50	High-strength low-alloy
A-53 Steel	35	Carbon Alloy
A-588 Steel	55	High-strength low-alloy
Extruded Aluminum	25	High-strength low-alloy

High-strength low-alloy steel has the highest yield strength and thus the most tolerance for wind loading. On the other hand, materials like extruded aluminum have a low yield strength and the least wind resistance. Carbon alloy steel falls in between these two categories.

Average daily traffic (*sADT*) is a transportation metric that calculates the number of vehicles that pass under a given structure. This measurement is important because, according to Kipp et al. (1987), wind is a major contributor to sign support degradation, and the primary source of wind is from vehicles passing under the structure. Thus, the number of vehicles passing under the structure contributes to the degradation of the signs (Table 2.4).

Similarly, lanes under the structure (*sLNE*) relates directly to the length and coverage area of the sign support (Table 2.5). It is assumed that each lane is 12 ft. (3.66 m) in width, which is the standard width of a highway lane across the country. While the number of lanes doesn't necessarily correspond to an increase in average daily traffic, a longer structure with more failure points will have a lower *MTTF*, as discussed by Yang et al. [15]. For example, a more extended structure spanning more lanes in a highly trafficked area, such as the City of Hartford, will have a lower *MTTF* than a rural structure.

Table 2.4. Average daily traffic adjustment value

Average Daily Traffic (ADT)	Adjustment Value
0 — 10,000	35
10,001 — 25,000	27
25,001 — 45,000	25
45,001 — 75,000	23
75,001 — 100,000	21
100,001 — 140,000	18
140,000 +	16

Table 2.5: Lanes under structure adjustment value

No. Lanes Under Structure	Adjustment Value
1	35
2	33
3	31
4	30
5	28
6	26
7	24
8	22
10	20
12	18

The different types of sign supports (*sTYP*) contribute to the *MTTF* (Table 2.6) as some are more secure than others. According to Kipp et al. (1987), the failure points of sign support structures tend to be in the welded and joined areas. Hence, box trusses have a lower *MTTF* due to the presence of more welded and joined areas. On the other hand, support structures mounted on pre-existing structures, such as an overpass or bridge, have a higher *MTTF*, as they are secured to something sturdier.

Table 2.6: Sign support type descriptions and adjustment values

Description	Adjustment Value
Monotube Span Bridge Sign Support	22
Non-Standard Single Tube Span Bridge	22
Single Arm Monotube Cantilever Sign Support	24
Single Arm Non-Standard Cantilever Sign Support	24
Single Arm Tubular Cantilever Sign Support	24
Double Arm Cantilever Sign Support	26
Box Truss Span Bridge Sign Support Type I	27
Box Truss Span Bridge Sign Support Type II	27
Box Truss Span Bridge Sign Support Type III	27
Box Truss Span Bridge Sign Support Type OTS	27
Non-Standard Box Truss Span Bridge Sign Support	27
Tubular Span Bridge Sign Support	28
Truss Arm Cantilever Sign Support (Type 1—3)	29
Truss Arm Cantilever Sign Support (Type 1—7)	29
Double Arm Butterfly Sign Support	30
Structure-Mounted Sign Support	35

In conclusion, the methodology of estimating the *mean-time-to-failure* (*MTTF*) of sign support systems in this study involves averaging scores based on four relevant factors - average daily traffic, lanes under the structure, material type, and structure type. Each of these factors has been shown to contribute to the overall reliability of the structures, and their consideration in the *MTTF* calculation helps to provide a more accurate estimate of the probability of failure for each structure. The scores assigned to each factor are based on prior research, and the resulting *MTTF* score can be used to prioritize maintenance and replacement/repair for the structures.

The formula to calculate the *MTTF* for any given structure is as follows:

$$MTTF = (sADT + sMAT + sTYP + sLNE)/4 \qquad \text{Eq. 2}$$

The *MTTF* score can be inserted into a probability distribution function to model the probability of failure. The Weibull function (Eq. 3) used to model this is as follows:

$$p(f) = 1 - e^{\left(-\left(\frac{Age\ of\ Structure}{MTTF}\right)^{\gamma}\right)} \qquad \text{Eq. 3}$$

Where γ is the shape factor of the Weibull function. A shape factor of 3 was used to calculate *p(f)* because this shape factor relates to the failure rate behavior (increasing over time). This is known as a "wear-out failure," or a failure rate that increases over time. Figure 2.17 shows the result of the probability of failure (*p(f)*) over ages of structures. It is apparent that the *p(f)* and ages are related.

The reliability factor (*r(f)*) can be found simultaneously alongside the *p(f)*. The *r(f)* is a measurement to identify the measure of failures over a time interval. It measures the probability of failure-free operation during a given interval. Calculating *r(f)* is done by the following equation:

$$r(f) = e^{\left(-\left(\frac{Age\ of\ Structure}{MTTF}\right)^{\gamma}\right)} \qquad \text{Eq. 4}$$

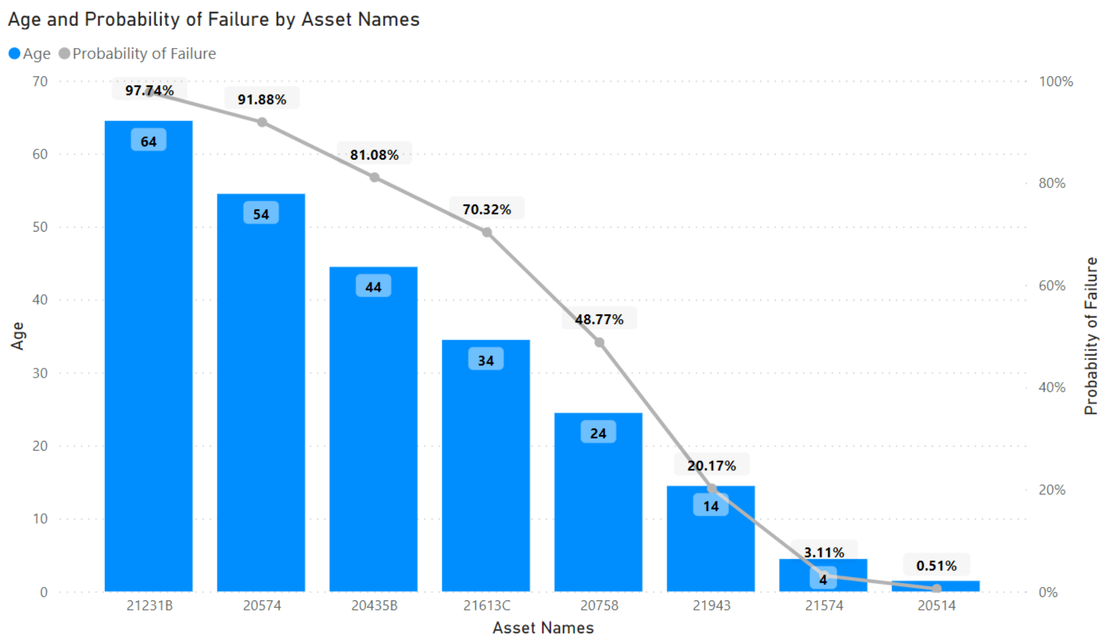

Figure 2.17. Probability of failure over ages of structures

CHAPTER 3 Findings and Applications

Results of the Field Test of the Sign Support

The instrumentation system installed on CTDOT Asset No. 21740 was active for a six-months period that started in November, 2022 and ended in May 2023. Up to this point, the research effort evaluated sign support management strategies, like repair manuals, Transportation Asset Managements Plans, standardized drawings, and structure selection criteria; gathered feedback from DOTs participating in the survey; and reached the experimental phase to measure the forces sustained by sign support structures.

The data acquisition system (DAS) collected the data from the various sensors and saved on the system's hard drive. The drive was accessible remotely through a modem that transmitted the data online and made it available at a software application called TeamViewer. The data files were collected weekly to the PI's laptop for analysis. The analysis software was performed by the spreadsheet software, Excel and Scout.

The eight strain gauges distribution was: 4 sensors placed the bottom of the main post at three feet from the concrete base, and 4 sensors placed on the top horizontal cantilever arm at three feet from the connection to the post. The placement configuration was:

- The two top sensors at the top arm in the Up-Down (U/D) direction measured strain due to swaying of the top arm upwards and downwards, had the title ACb 1596 Maximum-Minimum. They were connected to Channel 1 transducer and the data collected is presented at Figure 3.1.
- The two top sensors at the top arm in the East-West (E/W) direction measured strain due to horizontal sideways movement of the arm, had the title ACb 1604 Maximum-Minimum. They were connected to Channel 2 transducer and the data collected is presented at Figure 3.2
- The two bottom sensors at the post in the North-South (N/S) direction measured strain the post swaying parallel to the road, had the title ACb 1601 Maximum-Minimum. They were connected to Channel 3 transducer and the data collected is presented at Figure 3.3
- The two bottom sensors at the post in the East-West direction measured strain in the post swaying perpendicular to the road, had the title ACb 1537 Maximum-Minimum. They were connected to Channel 5 transducer and the data collected is presented at Figure 3.4

The x-axis for the four graphs represents time. An Accelerometer, that was placed at midpoint of the top arm (having the title UAb 2369 of Channel 5), had the ability to activate the system to capture the information from the sensors due to high vibration caused by wind gust loads. The system was programed to capture the highest strain levels experienced by the structure every one-hour period. There was also a wind speed sensor attached at the top of the vertical pole to provide wind loading data to assist with the experimental and finite element analysis (Figure 3.5).

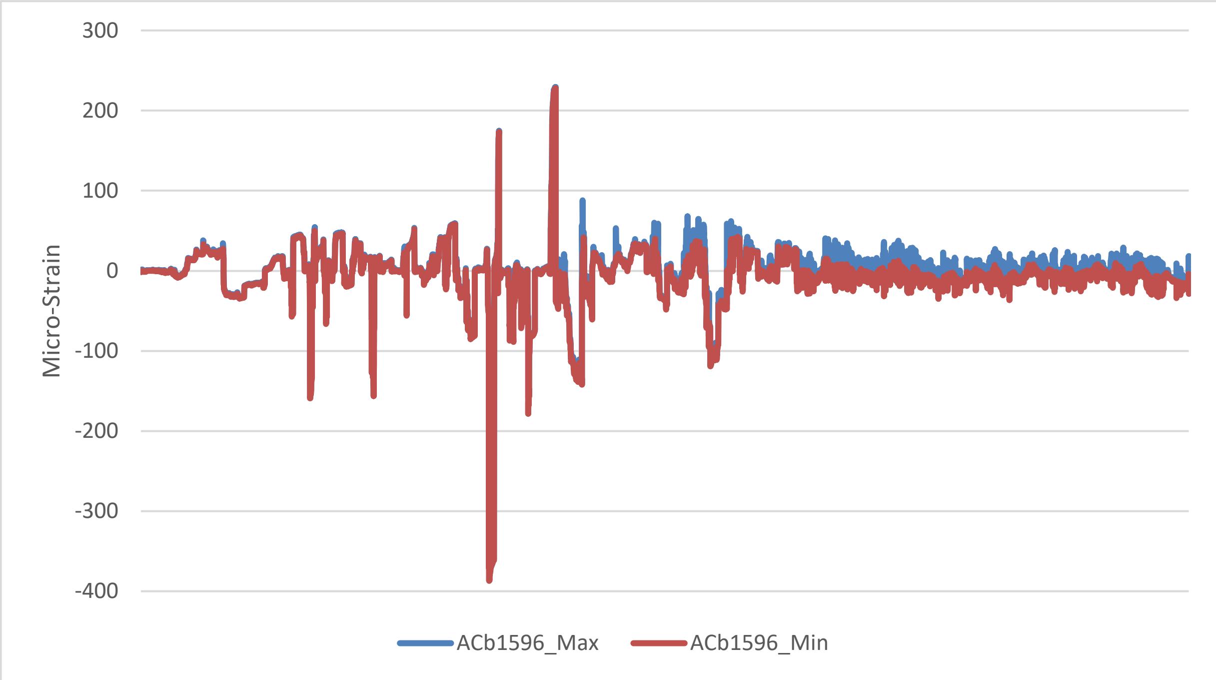

Figure 3.1. Graph of the Top Strain Gauges Data for Channel 1 - Up and Down Positions

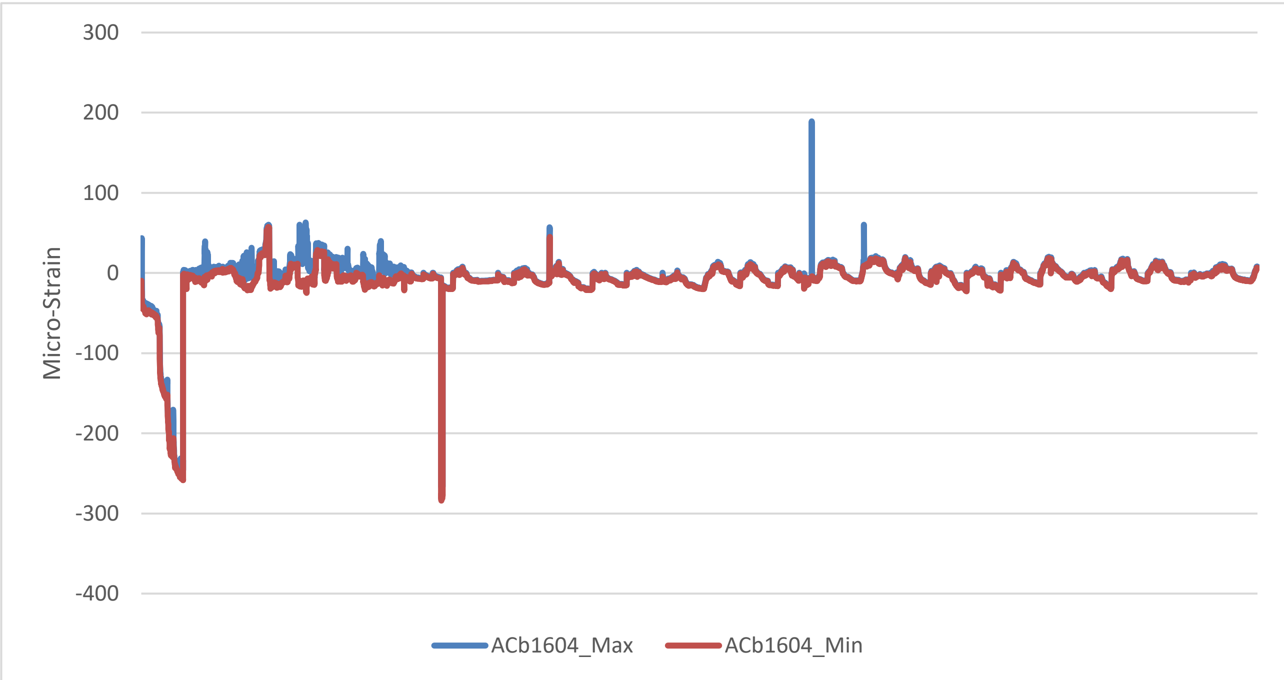

Figure 3.2. Graph of the Top Strain Gauges Data for Channel 2 – East and West Positions

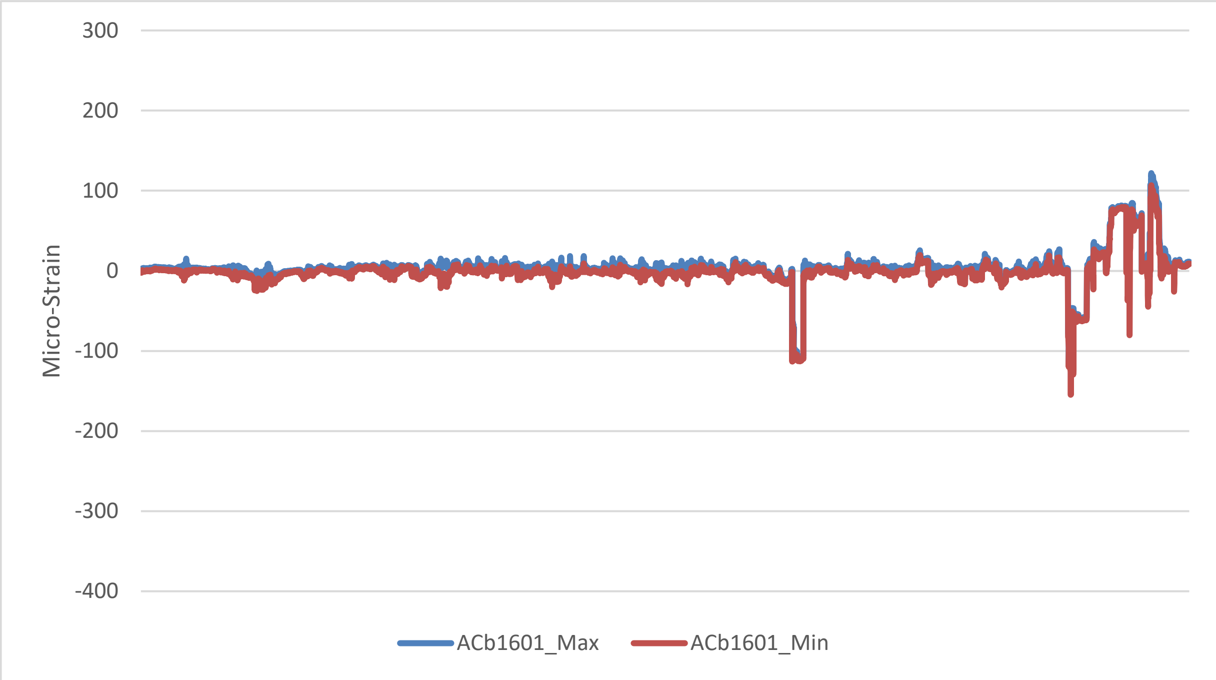

Figure 3.3. Graph of the Bottom Strain Gauges Data for Channel 3 – North and South Positions

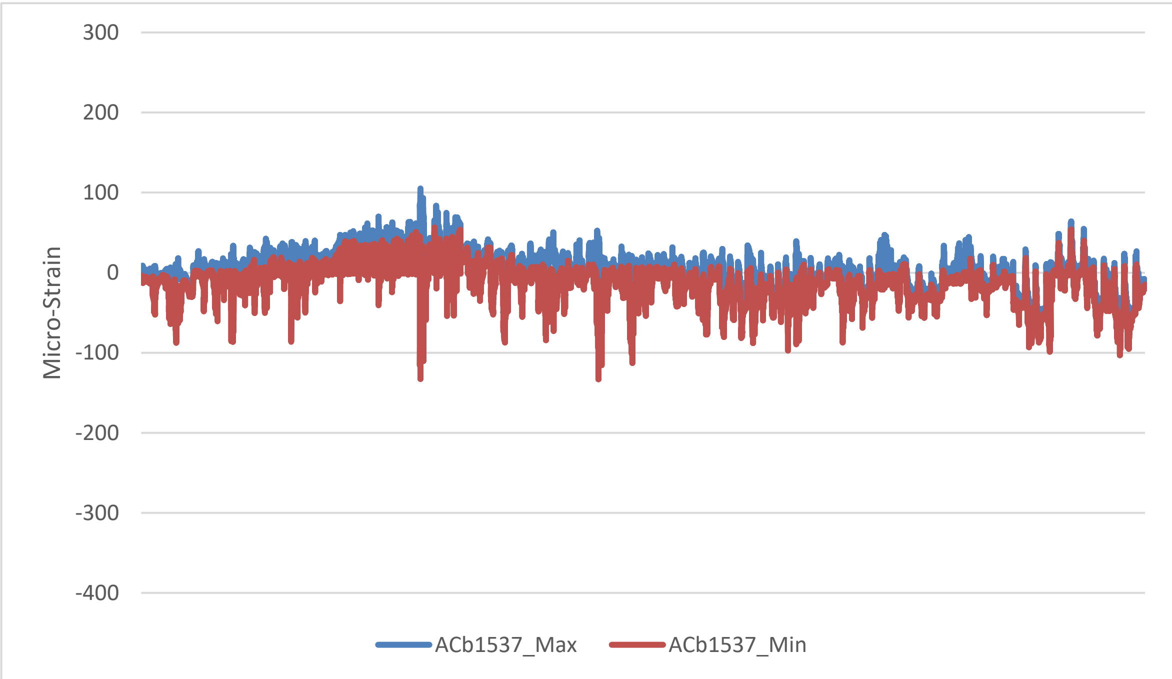

Figure 3.4. Graph of the Bottom Strain Gauges Data for Channel 4 – East and West Positions

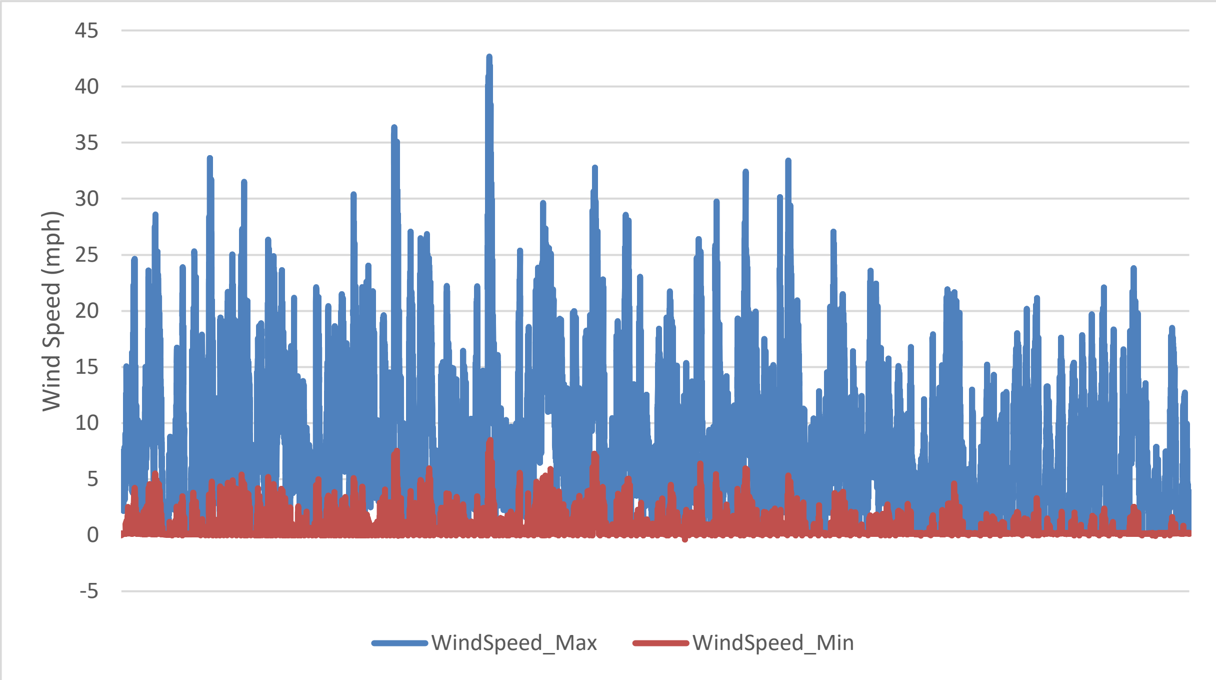

Figure 3.5. Graph of Wind Speed Sensor in mph

From the experimental results, it is observed that the top horizontal pole experienced higher strains as compared to the bottom of the vertical pole. Further, the maximum strain was experienced only once and reached a value of 380 micro-strain. Otherwise, the strains range between 50 micro-strain and 130 micro-strain.

As indicated earlier, the sign support structure is steel type A-595, having a yield strength of 50,000 psi. Since the modulus of elasticity of steel, E, is 29,000,000 psi, and using Hooke's Law, the maximum yield strain that the structure could reach is 1,724 micro-strain. Table 3.1 presents a comparison the experimental data and the yield limit, showing that the maximum strain reached after months of testing and exposure to wind load, was only 22.4% of the elastic yield capacity of the structure. This clearly indicates the strength and resilience of this sign support structure, and that there is significant potential strength still remaining in the structure as a whole.

Table 3.1. Experimental Absolute Maximum Strain and Stress Values Compared to Yield Limit

		Micro-Strain	**Ratio**	**Percentage**	**Stress (ksi)**
Strain Limit		1,724			50.00
Top Strain	Up-Down	386	0.224	22.4%	11.19
Top Strain	East-West	281	0.163	16.3%	8.15
Bottom Strain	North-South	155	0.090	9.0%	4.50
Bottom Strain	East-West	133	0.077	7.7%	3.86

Finite Element Modeling, Verification and Fatigue Analysis

A finite element model (FEM) was developed to analyze the sign support that was field tested under various design loads as specified by the AASHTO – LRFD Structural Supports for Highway Signs, Luminaires, and Traffic Signals (AASHTO LRFD-LTS), 2015 edition [23].

The focus of this task was to improve the reliability of methods for determining traffic loading on sign supports. The field data collected was utilized to build the FEM three-dimensional sign support structure using the software SAFI HSE (Highway Sign Structural Engineering).

The software is a comprehensive structural engineering software solution for the design of overhead highway sign structures and lighting solutions. The software includes a wide range of features and capabilities, including a 3D modeling engine. It can apply automatically load calculations for wind, ice, gravity, seismic and dynamic analysis. It can also model a variety of sign panels and lighting fixtures. The user-friendly interface can assist to develop designs with improved safety and quality.

The HSE software includes the fatigue limit state. The HSE software allows for Fatigue verification according to chapter 11 of AASHTO LTS-13 (ASD) and AASHTO LTS-15 (LRFD) and Stress verification according to the Constant Amplitude Fatigue Threshold (CAFT). The CAFT for infinite life for the different fatigue detail categories are found in AASHTO LTS-13 (ASD) Table 11.9.3.1-1 and AASHTO LTS-15 (LRFD) Table 11.9.3.1-1. The software was to all required fatigue parameters for a structure allowing to consider all applicable fatigue loads such as Galloping, Natural Wind Gust, or Truck-Induced Gust.

Verifying the FE model with the experimental data provided the opportunity to better understand the behavior of the sign support and the loading influence. The model was developed as shown in Figure 3.6, using the dimensions provided in Figure 2.5, and the load applied was the average value of 45 mph obtained from the wind speed graph, Figure 3.5. The limit state values shows that the vertical pole has a value of 0.18 (18%) of actual capacity of the pole, which is with 10% difference as compared to the experimental data, as shown in Table 3.1. Similarly, the top horizontal cantilever pole has a limit state value of 0.10 (10%) of the capacity, which is on average about 8% less than the experimental data.

These results show the accuracy of the model, and that it can indeed be used to predict the behavior of the sign support at complete design load capacity. The software automatically applied the various design loads in accordance with AASHTO LRFD-LTS code (Figure 3.7), while also accounting for the region where the sign support is in, namely Hartford, Connecticut (Figure 3.8). The results of the analysis is dependent on the inclusion or exclusion of fatigue stress calculations in the limit state load combinations (Figure 3.9). It is apparent that fatigue has a significant impact on the results. The results of Figure 3.10 are due to all the loads, excluding fatigue, while Figure 3.11 includes the effects of fatigue. Figure 3.10 shows that the sign support has significantly more reserve capacity than Figure 3.11, actually fatigue is so significant that some of the sections exceed their limit state. The FE analysis (Figure 3.11) indicates that the top portion of the tubular post is the critical component of the sign support due to the fatigue loading. This is probably due to the two cantilever arms at its ends exerting additional stresses to it.

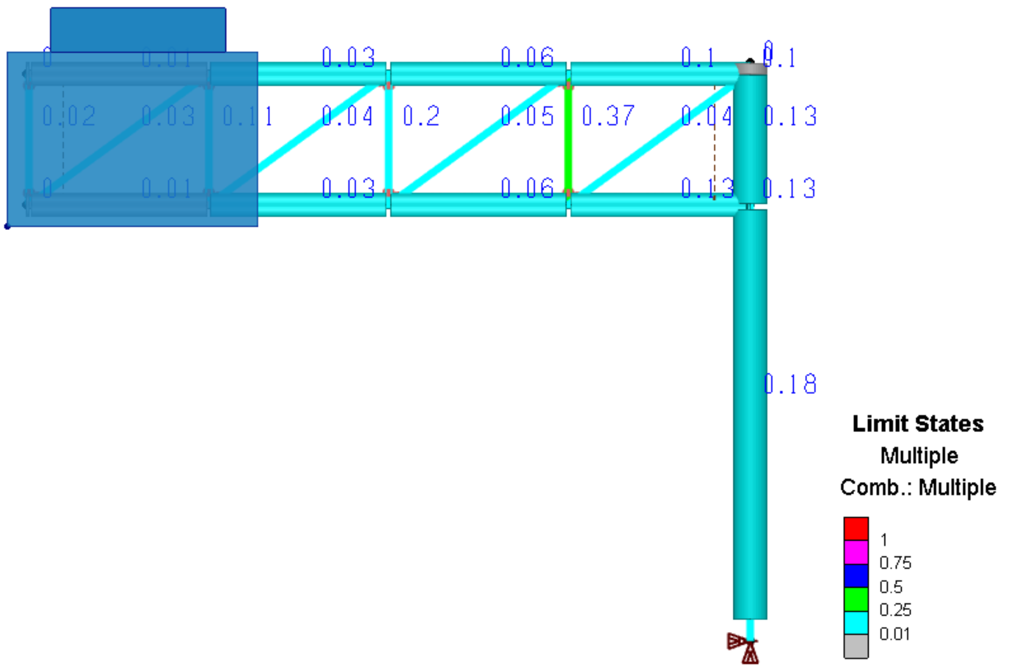

Figure 3.6. FE Model Analysis Due to Wind Load of 45 mph to Simulate Experimental Data

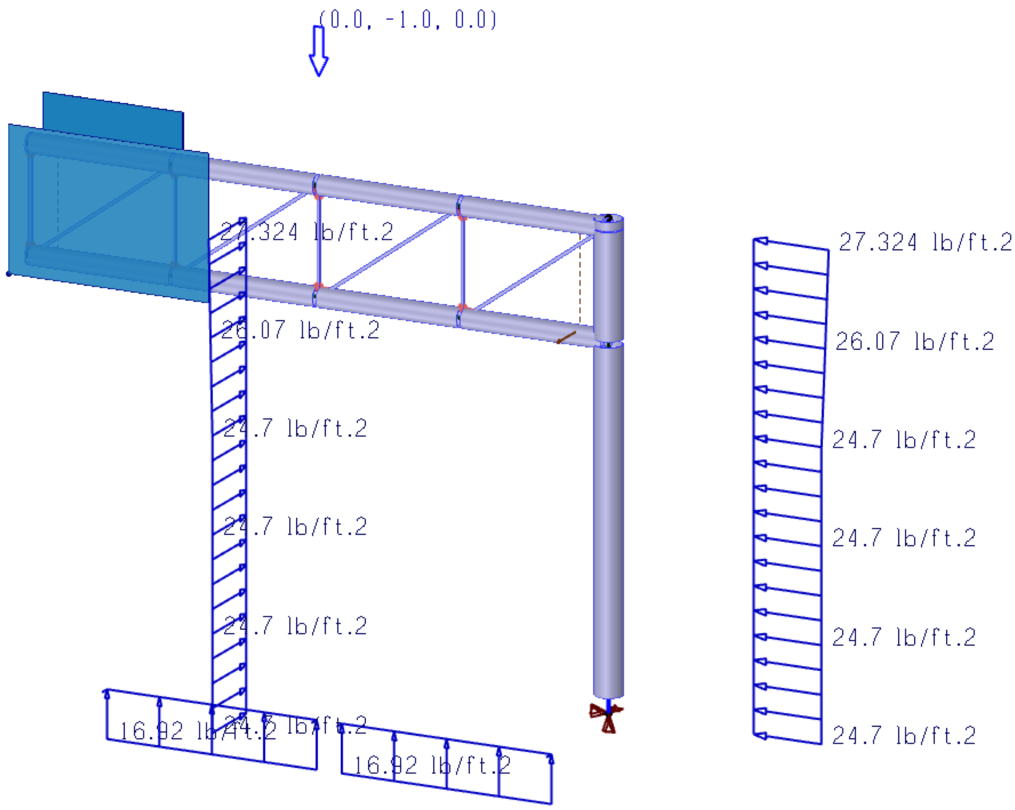

Figure 3.7. Isometric 3D View of the Finite Element Model of the Tested Sign Support

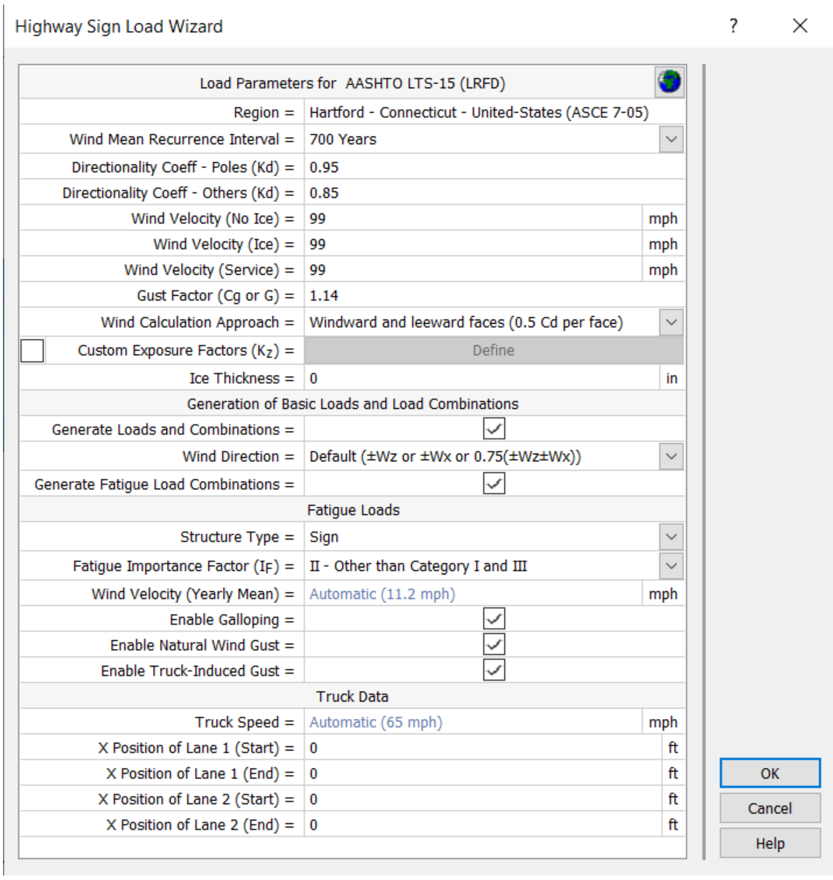

Figure 3.8. Sign Support Load Parameters for AASHTO LTS-15 (LRFD) at Hartford, CT

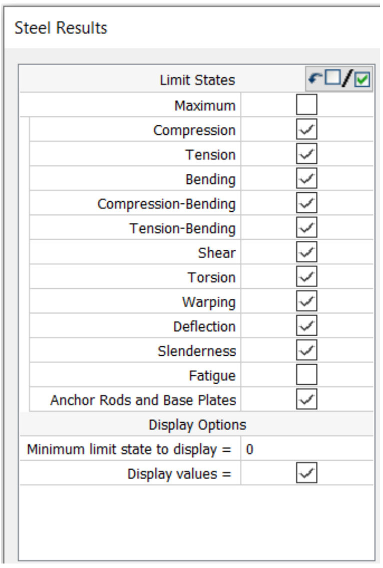

Figure 3.9. Limit States Results for All Load Types Excluding Fatigue

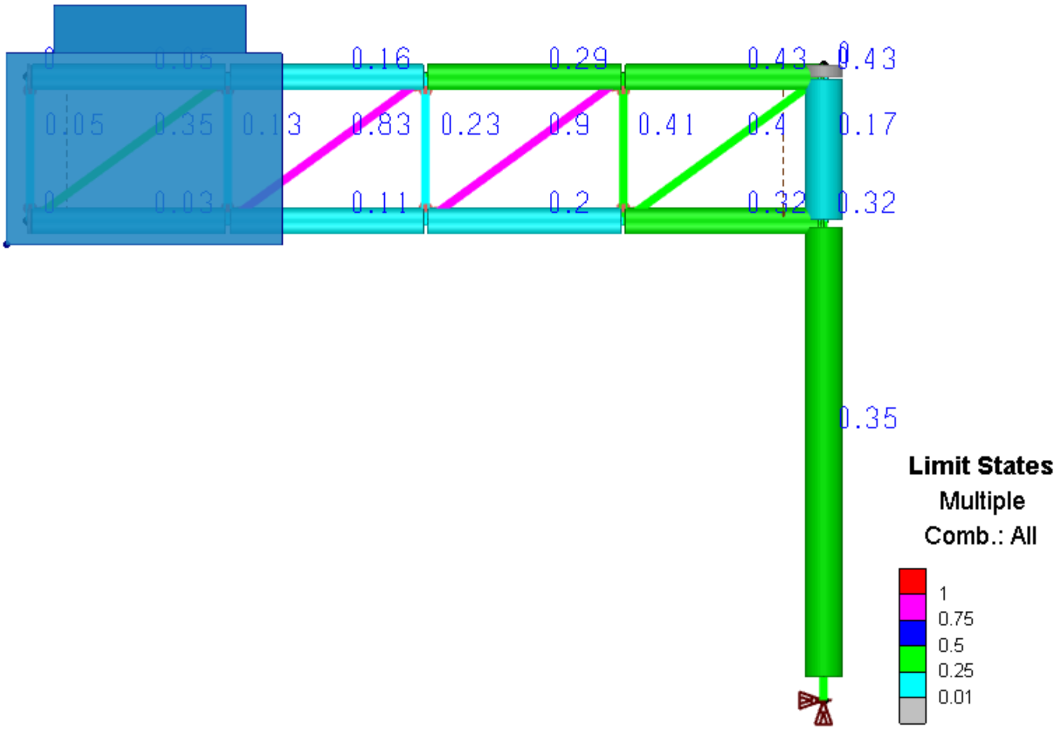

Figure 3.10. Limit States for All Load Combinations where Results Exclude Fatigue

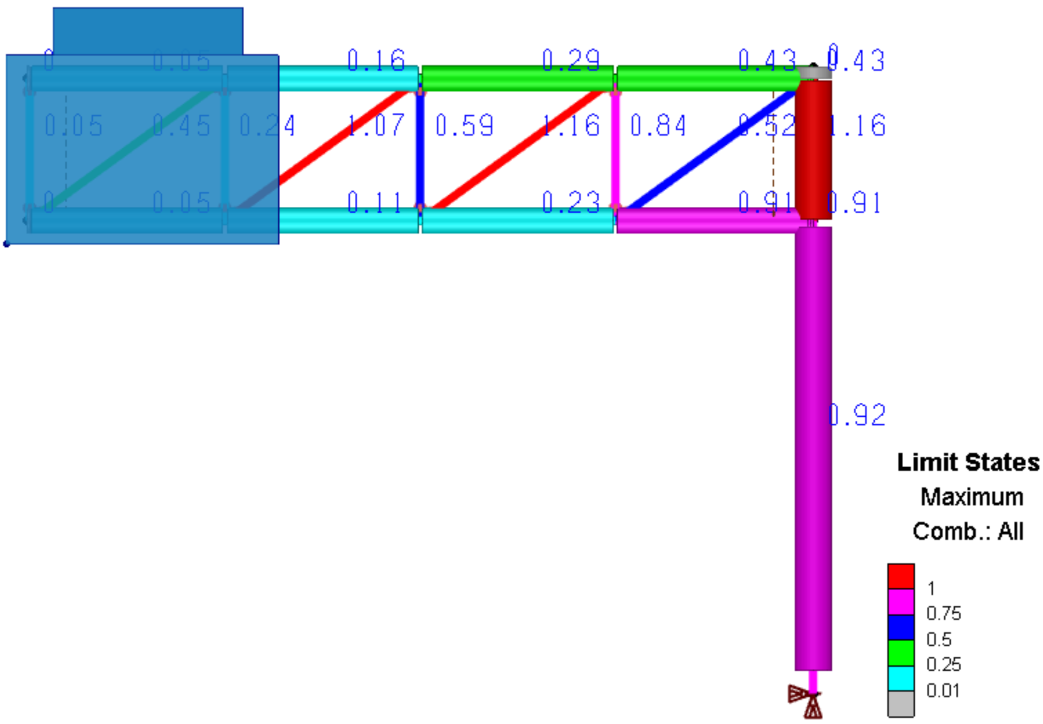

Figure 3.11. Limit States for All Load Combinations where Results Include Fatigue

It can therefore be concluded that the sign support has significant reserve capacity during short-term wind-gust loading where the sections reached only 20% of their capacity. However, in long-term design analysis, fatigue becomes a critical factor that could cause the structure to reach its limit state. Therefore, mitigating this risk could be achieved by monitoring for fatigue cracks during the periodic inspection would ensure that the structure continuous to be safe until replacement.

Replacement Cost of Sign Supports

To estimate the cost of replacing a sign support structure, it is broken down into different components and their impacts on the structure are assigned. The replacement cost for each component can then be calculated by multiplying the replacement cost of the entire structure (*Rpl*) by its impact percentage (*Imp%*). The final estimate for replacing the entire sign support structure is obtained by adding up the replacement costs for all components. The impact factors by structure components are shown in Table 3.2.

Table 3.2. Sign support repair factors

Structure Components	% of repair cost
Horizontal Members	7%
Structure Overall	6%
Sign and Illumination	5%
Foundation Overall	5%
Traffic Safety	5%
Structure Overall	5%
Support Frame	5%
Connections	5%
Vertical Posts/Bracings	4.5%
Parapet	4%
Settlement	4%
Embankment/Erosion	4%
Face Panels	3%
Member Alignment	3%
Grout Pad	3%
Bulbs/Electrical	3%
Collision Damage	3%
Concrete	3%
Guide Railing	3%
Coating	2.5%
Welds	2.5%
Rust	2.5%
Anchor Bolt	2%
Attachments	2%
Base Plates	2%
Bolts & Fasteners	2%

Structure Components	% of repair cost
Reflectivity	2%
Legibility	2%
Sum	100%

For example, if *Rpl = $10,000* and the impact percentage for component A is 7% (*Imp% A = 7%*), then the estimated cost to replace component A is *$10,000 x 7% = $700*. This is represented as the financial impact (*iFIN*) and equation for *iFIN* is shown as Eq. 5.

$$iFIN = Imp\% * (Rpl) \qquad \text{Eq. 5}$$

The *iFIN* value, which is expressed as a dollar value, is used in combination with a Weibull distribution function to create a reliability model. The model identifies the primary factors that contribute to reliability and assesses the likelihood of failure.

$$\text{Risk} = \text{I X } (1 - e^{\left(-\left(\frac{Age}{MTTF}\right)^{\gamma}\right)}) \qquad \text{Eq. 6}$$

This information allows for informed planning based on the financial impact of each component (data is truncated due to size limitations). This calculation produces Table 3.3 that displays the financial cost associated with repairing each structure.

Table 3.3. Component repair cost breakdown (showing only selected data)

Asset Name	Sign and Illumination	Structure Overall	Foundation Overall	Traffic Safety	Structure Overall	Member Alignment	Anchor Bolt	Attachments	Base Plates	Bolts & Fasteners	Bulbs/Electrical	Coating	Collision Damage	Concrete
21311	$ 12,934.68	$15,521.68	$12,934.68	$ 12,934.68	$12,934.68	$7,760.68	$ 5,173.68	$ 5,173.68	$ 5,173.68	$5,173.68	$ 7,760.68	$6,467.18	$7,760.68	$7,760.68
21671	$ 12,934.80	$15,521.80	$12,934.80	$ 12,934.80	$12,934.80	$7,760.80	$ 5,173.80	$ 5,173.80	$ 5,173.80	$5,173.80	$ 7,760.80	$6,467.30	$7,760.80	$7,760.80
20292	$ 2,249.82	$ 2,699.82	$ 2,249.82	$ 2,249.82	$ 2,249.82	$1,349.82	$ 899.82	$ 899.82	$ 899.82	$ 899.82	$ 1,349.82	$1,124.82	$1,349.82	$1,349.82
20519	$ 12,934.96	$15,521.96	$12,934.96	$ 12,934.96	$12,934.96	$7,760.96	$ 5,173.96	$ 5,173.96	$ 5,173.96	$5,173.96	$ 7,760.96	$6,467.46	$7,760.96	$7,760.96
20516	$ 12,934.96	$15,521.96	$12,934.96	$ 12,934.96	$12,934.96	$7,760.96	$ 5,173.96	$ 5,173.96	$ 5,173.96	$5,173.96	$ 7,760.96	$6,467.46	$7,760.96	$7,760.96
21595	$ 12,934.78	$15,521.78	$12,934.78	$ 12,934.78	$12,934.78	$7,760.78	$ 5,173.78	$ 5,173.78	$ 5,173.78	$5,173.78	$ 7,760.78	$6,467.28	$7,760.78	$7,760.78
20017A	$ 2,249.75	$ 2,699.75	$ 2,249.75	$ 2,249.75	$ 2,249.75	$1,349.75	$ 899.75	$ 899.75	$ 899.75	$ 899.75	$ 1,349.75	$1,124.75	$1,349.75	$1,349.75
20317	$ 12,934.80	$15,521.80	$12,934.80	$ 12,934.80	$12,934.80	$7,760.80	$ 5,173.80	$ 5,173.80	$ 5,173.80	$5,173.80	$ 7,760.80	$6,467.30	$7,760.80	$7,760.80
20290	$ 7,508.90	$ 9,010.72	$ 7,508.90	$ 7,508.90	$ 7,508.90	$4,505.27	$ 3,003.45	$ 3,003.45	$ 3,003.45	$3,003.45	$ 4,505.27	$3,754.36	$4,505.27	$4,505.27
20611	$ 12,934.80	$15,521.80	$12,934.80	$ 12,934.80	$12,934.80	$7,760.80	$ 5,173.80	$ 5,173.80	$ 5,173.80	$5,173.80	$ 7,760.80	$6,467.30	$7,760.80	$7,760.80
21593	$ 12,934.75	$15,521.75	$12,934.75	$ 12,934.75	$12,934.75	$7,760.75	$ 5,173.75	$ 5,173.75	$ 5,173.75	$5,173.75	$ 7,760.75	$6,467.25	$7,760.75	$7,760.75
20435A	$ 2,249.90	$ 2,699.90	$ 2,249.90	$ 2,249.90	$ 2,249.90	$1,349.90	$ 899.90	$ 899.90	$ 899.90	$ 899.90	$ 1,349.90	$1,124.90	$1,349.90	$1,349.90
20615B	$ 2,249.88	$ 2,699.88	$ 2,249.88	$ 2,249.88	$ 2,249.88	$1,349.88	$ 899.88	$ 899.88	$ 899.88	$ 899.88	$ 1,349.88	$1,124.88	$1,349.88	$1,349.88
20022	$ 7,508.81	$ 9,010.63	$ 7,508.81	$ 7,508.81	$ 7,508.81	$4,505.17	$ 3,003.36	$ 3,003.36	$ 3,003.36	$3,003.36	$ 4,505.17	$3,754.26	$4,505.17	$4,505.17
20413	$ 2,249.98	$ 2,699.98	$ 2,249.98	$ 2,249.98	$ 2,249.98	$1,349.98	$ 899.98	$ 899.98	$ 899.98	$ 899.98	$ 1,349.98	$1,124.98	$1,349.98	$1,349.98
21589	$ 12,934.80	$15,521.80	$12,934.80	$ 12,934.80	$12,934.80	$7,760.80	$ 5,173.80	$ 5,173.80	$ 5,173.80	$5,173.80	$ 7,760.80	$6,467.30	$7,760.80	$7,760.80
20515	$ 12,934.94	$15,521.94	$12,934.94	$ 12,934.94	$12,934.94	$7,760.94	$ 5,173.94	$ 5,173.94	$ 5,173.94	$5,173.94	$ 7,760.94	$6,467.44	$7,760.94	$7,760.94
20419	$ 12,934.80	$15,521.80	$12,934.80	$ 12,934.80	$12,934.80	$7,760.80	$ 5,173.80	$ 5,173.80	$ 5,173.80	$5,173.80	$ 7,760.80	$6,467.30	$7,760.80	$7,760.80
20573	$ 12,934.97	$15,521.97	$12,934.97	$ 12,934.97	$12,934.97	$7,760.97	$ 5,173.97	$ 5,173.97	$ 5,173.97	$5,173.97	$ 7,760.97	$6,467.47	$7,760.97	$7,760.97
20435B	$ 2,249.84	$ 2,699.84	$ 2,249.84	$ 2,249.84	$ 2,249.84	$1,349.84	$ 899.84	$ 899.84	$ 899.84	$ 899.84	$ 1,349.84	$1,124.84	$1,349.84	$1,349.84
20320	$ 7,508.77	$ 9,010.59	$ 7,508.77	$ 7,508.77	$ 7,508.77	$4,505.13	$ 3,003.32	$ 3,003.32	$ 3,003.32	$3,003.32	$ 4,505.13	$3,754.23	$4,505.13	$4,505.13
20615A	$ 2,249.97	$ 2,699.97	$ 2,249.97	$ 2,249.97	$ 2,249.97	$1,349.97	$ 899.97	$ 899.97	$ 899.97	$ 899.97	$ 1,349.97	$1,124.97	$1,349.97	$1,349.97
20574	$ 12,934.95	$15,521.95	$12,934.95	$ 12,934.95	$12,934.95	$7,760.95	$ 5,173.95	$ 5,173.95	$ 5,173.95	$5,173.95	$ 7,760.95	$6,467.45	$7,760.95	$7,760.95
20515	$ 12,934.90	$15,521.90	$12,934.90	$ 12,934.90	$12,934.90	$7,760.90	$ 5,173.90	$ 5,173.90	$ 5,173.90	$5,173.90	$ 7,760.90	$6,467.40	$7,760.90	$7,760.90
20416	$ 12,934.80	$15,521.80	$12,934.80	$ 12,934.80	$12,934.80	$7,760.80	$ 5,173.80	$ 5,173.80	$ 5,173.80	$5,173.80	$ 7,760.80	$6,467.30	$7,760.80	$7,760.80
21310	$ 12,934.64	$15,521.64	$12,934.64	$ 12,934.64	$12,934.64	$7,760.64	$ 5,173.64	$ 5,173.64	$ 5,173.64	$5,173.64	$ 7,760.64	$6,467.14	$7,760.64	$7,760.64
20012	$ 2,249.89	$ 2,699.89	$ 2,249.89	$ 2,249.89	$ 2,249.89	$1,349.89	$ 899.89	$ 899.89	$ 899.89	$ 899.89	$ 1,349.89	$1,124.89	$1,349.89	$1,349.89
20417	$ 12,934.80	$15,521.80	$12,934.80	$ 12,934.80	$12,934.80	$7,760.80	$ 5,173.80	$ 5,173.80	$ 5,173.80	$5,173.80	$ 7,760.80	$6,467.30	$7,760.80	$7,760.80
20013	$ 7,509.00	$ 9,010.81	$ 7,509.00	$ 7,509.00	$ 7,509.00	$4,505.36	$ 3,003.54	$ 3,003.54	$ 3,003.54	$3,003.54	$ 4,505.36	$3,754.45	$4,505.36	$4,505.36
20613	$ 12,934.73	$15,521.73	$12,934.73	$ 12,934.73	$12,934.73	$7,760.73	$ 5,173.73	$ 5,173.73	$ 5,173.73	$5,173.73	$ 7,760.73	$6,467.23	$7,760.73	$7,760.73
20517	$ 12,934.94	$15,521.94	$12,934.94	$ 12,934.94	$12,934.94	$7,760.94	$ 5,173.94	$ 5,173.94	$ 5,173.94	$5,173.94	$ 7,760.94	$6,467.44	$7,760.94	$7,760.94
20770	$ 12,934.83	$15,521.83	$12,934.83	$ 12,934.83	$12,934.83	$7,760.83	$ 5,173.83	$ 5,173.83	$ 5,173.83	$5,173.83	$ 7,760.83	$6,467.33	$7,760.83	$7,760.83
21600E	$ 2,249.59	$ 2,699.59	$ 2,249.59	$ 2,249.59	$ 2,249.59	$1,349.59	$ 899.59	$ 899.59	$ 899.59	$ 899.59	$ 1,349.59	$1,124.59	$1,349.59	$1,349.59
20576	$ 12,934.96	$15,521.96	$12,934.96	$ 12,934.96	$12,934.96	$7,760.96	$ 5,173.96	$ 5,173.96	$ 5,173.96	$5,173.96	$ 7,760.96	$6,467.46	$7,760.96	$7,760.96
20268	$ 12,934.83	$15,521.83	$12,934.83	$ 12,934.83	$12,934.83	$7,760.83	$ 5,173.83	$ 5,173.83	$ 5,173.83	$5,173.83	$ 7,760.83	$6,467.33	$7,760.83	$7,760.83
20384	$ 7,508.71	$ 9,010.52	$ 7,508.71	$ 7,508.71	$ 7,508.71	$4,505.07	$ 3,003.25	$ 3,003.25	$ 3,003.25	$3,003.25	$ 4,505.07	$3,754.16	$4,505.07	$4,505.07
21613E	$ 2,249.62	$ 2,699.62	$ 2,249.62	$ 2,249.62	$ 2,249.62	$1,349.62	$ 899.62	$ 899.62	$ 899.62	$ 899.62	$ 1,349.62	$1,124.62	$1,349.62	$1,349.62
21309	$ 12,934.58	$15,521.58	$12,934.58	$ 12,934.58	$12,934.58	$7,760.58	$ 5,173.58	$ 5,173.58	$ 5,173.58	$5,173.58	$ 7,760.58	$6,467.08	$7,760.58	$7,760.58
20298	$ 7,508.90	$ 9,010.72	$ 7,508.90	$ 7,508.90	$ 7,508.90	$4,505.26	$ 3,003.44	$ 3,003.44	$ 3,003.44	$3,003.44	$ 4,505.26	$3,754.35	$4,505.26	$4,505.26
20510	$ 7,508.76	$ 9,010.58	$ 7,508.76	$ 7,508.76	$ 7,508.76	$4,505.12	$ 3,003.30	$ 3,003.30	$ 3,003.30	$3,003.30	$ 4,505.12	$3,754.21	$4,505.12	$4,505.12
20421A	$ 2,249.86	$ 2,699.86	$ 2,249.86	$ 2,249.86	$ 2,249.86	$1,349.86	$ 899.86	$ 899.86	$ 899.86	$ 899.86	$ 1,349.86	$1,124.86	$1,349.86	$1,349.86
20415	$ 12,934.78	$15,521.78	$12,934.78	$ 12,934.78	$12,934.78	$7,760.78	$ 5,173.78	$ 5,173.78	$ 5,173.78	$5,173.78	$ 7,760.78	$6,467.28	$7,760.78	$7,760.78
20017B	$ 2,249.54	$ 2,699.54	$ 2,249.54	$ 2,249.54	$ 2,249.54	$1,349.54	$ 899.54	$ 899.54	$ 899.54	$ 899.54	$ 1,349.54	$1,124.54	$1,349.54	$1,349.54

When evaluating the impact of sign support failure, it is crucial to also take the human factor into consideration. The impact of a sign support failure in a rural area is likely to be less significant compared to that of a sign support in a densely populated urban area like downtown Hartford, CT. To estimate the number of commuters affected by the failure, population data from the 2020 census can be combined with average daily traffic (*ADT*) data to calculate an accurate estimate of the number of commuters (*CMT*). The equation used to estimate CMT involves combining the *ADT* and population data to obtain an average.

$$CMT = \frac{ADT+POP}{2} \qquad \text{Eq. 7}$$

The accuracy of the data can be validated by examining the towns with the highest estimated impact on commuters and verifying that they are significant commuter hubs, such as New Haven and Hartford, CT. The impact of sign support failure on commuters (*iCMT*) is determined by multiplying the likelihood of failure by the average number of commuters. *iCMT* offers a visual representation of which sign supports are the most critical for preserving and preventing disruption to commuters.

$$iCMT = p(f) * CMT \qquad \text{Eq. 8}$$

It should be noted that the structures with the greatest impact do not necessarily have the highest probability of failure. For instance, the structure with the highest impact (No. 21311, a tubular span support located near Exit 32-A in Hartford (Figure 3.12) has a *p(f) = 0.673*, which is only in the middle range of *p(f)* values. Despite this, it is important to give this support more attention due to the high traffic and population density in the Hartford area. *iCMT* can be viewed as a "priority of inspection and replacement/repair" metric for each asset. It represents the risk, as it is determined by the combination of the probability of failure and the number of commuters. Consequently, sign supports with higher *iCMT* values should be prioritized for repair and maintenance to minimize the impact on commuters.

Figure 3.12. Support 21311 leading into Hartford, CT

To express the risk of sign support failure in terms of financial value, it is necessary to convert the affected commuters into a monetary value. This can be achieved by using census data to calculate the impact cost per commuter. This cost is determined by dividing the average individual income of the city by the average number of commuters. It is assumed that the income of commuters contributes to the overall average income of the city.

$$iCMT\$ = \frac{iCMT}{Per\ Capita\ Income} \qquad \text{Eq. 9}$$

Table 3.4, which displays the commuter impact, along with the intermediate calculations needed to determine the values. Finally, a risk factor can be determined by multiplying the impact in dollars by the probability of failure.

$$Risk\ per\ Capita = \frac{iCMT}{capita\ income} = iCMT\$ \qquad \text{Eq. 10}$$

Table 3.4. Commuter Impact of Sign Support Failure (showing only selected data)

Asset Name	NBI 4: City or Town	Lanes	Description	Description	Average Daily Traffic	Per capita income	Median household income	Median Family Incon	Average Personal Income per Town	Population '20	Avg. Commuters	p(f)	Commuter Impact (Persons)	Commuter Impact (Dollars per Person)
21311	Hartford	4	A-36 Steel	Tubular Span Bridge Sign Support	235,100	$ 16,798.00	$ 28,970.00	$ 32,820.00	$ 26,196.00	121,026	178,063	0.673	119,755	$ 7.13
21671	Hartford	5	A-36 Steel	Box Truss Span Bridge Sign Support Type III	169,300	$ 16,798.00	$ 28,970.00	$ 32,820.00	$ 26,196.00	121,026	145,163	0.777	112,841	$ 6.72
20292	Stamford	2	A-36 Steel	Structure-Mounted Sign Support	147,600	$ 44,667.00	$ 75,579.00	$ 88,050.00	$ 69,432.00	135,511	141,556	0.792	112,085	$ 2.51
20519	Bridgeport	5	Other	Box Truss Span Bridge Sign Support Type III	89,600	$ 19,854.00	$ 41,047.00	$ 47,894.00	$ 36,265.00	148,698	119,149	0.933	111,157	$ 5.60
20516	Bridgeport	4	Other	Box Truss Span Bridge Sign Support Type III	90,050	$ 19,854.00	$ 41,047.00	$ 47,894.00	$ 36,265.00	148,698	119,374	0.930	111,050	$ 5.59
21595	Hartford	5	A-36 Steel	Box Truss Span Bridge Sign Support Type II	171,390	$ 16,798.00	$ 28,970.00	$ 32,820.00	$ 26,196.00	121,026	146,208	0.758	110,844	$ 6.60
20017A	Stamford	2	A-36 Steel	Structure-Mounted Sign Support	149,600	$ 44,667.00	$ 75,579.00	$ 88,050.00	$ 69,432.00	135,511	142,556	0.730	104,018	$ 2.33
20317	New Haven	4	A-36 Steel	Non-Standard Box Truss Span Bridge Sign Support	127,650	$ 21,789.00	$ 38,963.00	$ 47,432.00	$ 36,061.33	134,052	130,851	0.777	101,715	$ 4.67
20290	Stamford	1	A-36 Steel	Single Arm Tubular Cantilever Sign Support	121,950	$ 44,667.00	$ 75,579.00	$ 88,050.00	$ 69,432.00	135,511	128,731	0.787	101,248	$ 2.27
20611	Bridgeport	5	A-242 Steel	Box Truss Span Bridge Sign Support Type III	110,700	$ 19,854.00	$ 41,047.00	$ 47,894.00	$ 36,265.00	148,698	129,699	0.777	100,820	$ 5.08
21593	Hartford	4	A-36 Steel	Box Truss Span Bridge Sign Support Type II	151,250	$ 16,798.00	$ 28,970.00	$ 32,820.00	$ 26,196.00	121,026	136,138	0.735	100,083	$ 5.96
20435A	Waterbury	1	A-36 Steel	Structure-Mounted Sign Support	111,150	$ 21,545.00	$ 40,254.00	$ 47,077.00	$ 36,292.00	114,426	112,788	0.866	97,677	$ 4.53
20615B	Bridgeport	2	A-36 Steel	Structure-Mounted Sign Support	79,700	$ 19,854.00	$ 41,047.00	$ 47,894.00	$ 36,265.00	148,698	114,199	0.849	96,963	$ 4.88
20022	Stamford	1	A-36 Steel	Single Arm Tubular Cantilever Sign Support	137,850	$ 44,667.00	$ 75,579.00	$ 88,050.00	$ 69,432.00	135,511	136,681	0.706	96,554	$ 2.16
20413	Waterbury	2	A-36 Steel	Structure-Mounted Sign Support	80,100	$ 21,545.00	$ 40,254.00	$ 47,077.00	$ 36,292.00	114,426	97,263	0.959	93,301	$ 4.33
21589	Hartford	4	A-595 Steel	Box Truss Span Bridge Sign Support Type I	118,750	$ 16,798.00	$ 28,970.00	$ 32,820.00	$ 26,196.00	121,026	119,888	0.777	93,193	$ 5.55
20515	Bridgeport	5	A-36 Steel	Box Truss Span Bridge Sign Support Type III	54,800	$ 19,854.00	$ 41,047.00	$ 47,894.00	$ 36,265.00	148,698	101,749	0.911	92,653	$ 4.67
20419	Waterbury	3	A-595 Steel	Box Truss Span Bridge Sign Support Type I	123,750	$ 21,545.00	$ 40,254.00	$ 47,077.00	$ 36,292.00	114,426	119,088	0.777	92,571	$ 4.30
20573	Waterbury	3	Other	Box Truss Span Bridge Sign Support Type III	80,700	$ 21,545.00	$ 40,254.00	$ 47,077.00	$ 36,292.00	114,426	97,563	0.941	91,853	$ 4.26
20435B	Waterbury	2	A-36 Steel	Structure-Mounted Sign Support	111,150	$ 21,545.00	$ 40,254.00	$ 47,077.00	$ 36,292.00	114,426	112,788	0.811	91,446	$ 4.24
20320	New Haven	1	A-36 Steel	Single Arm Tubular Cantilever Sign Support	132,750	$ 21,789.00	$ 38,963.00	$ 47,432.00	$ 36,061.33	134,052	133,401	0.673	89,718	$ 4.12
20615A	Bridgeport	1	A-36 Steel	Structure-Mounted Sign Support	39,850	$ 19,854.00	$ 41,047.00	$ 47,894.00	$ 36,265.00	148,698	94,274	0.940	88,592	$ 4.46
20574	Waterbury	4	Other	Box Truss Span Bridge Sign Support Type III	77,700	$ 21,545.00	$ 40,254.00	$ 47,077.00	$ 36,292.00	114,426	96,063	0.919	88,260	$ 4.10
20515	Bridgeport	5	A-36 Steel	Box Truss Span Bridge Sign Support Type III	54,800	$ 19,854.00	$ 41,047.00	$ 47,894.00	$ 36,265.00	148,698	101,749	0.867	88,196	$ 4.44
20416	Waterbury	3	A-36 Steel	Box Truss Span Bridge Sign Support Type III	111,900	$ 21,545.00	$ 40,254.00	$ 47,077.00	$ 36,292.00	114,426	113,163	0.777	87,966	$ 4.08
21310	Hartford	4	A-36 Steel	Tubular Span Bridge Sign Support	154,200	$ 16,798.00	$ 28,970.00	$ 32,820.00	$ 26,196.00	121,026	137,613	0.637	87,636	$ 5.22
20012	Greenwich	2	A-36 Steel	Structure-Mounted Sign Support	140,150	$ 90,087.00	$ 128,153.00	$ 167,825.00	$ 128,688.33	63,502	101,826	0.860	87,616	$ 0.97
20417	Waterbury	3	A-595 Steel	Box Truss Span Bridge Sign Support Type I	108,850	$ 21,545.00	$ 40,254.00	$ 47,077.00	$ 36,292.00	114,426	111,638	0.777	86,780	$ 4.03
20013	Greenwich	1	A-36 Steel	Single Arm Tubular Cantilever Sign Support	134,250	$ 90,087.00	$ 128,153.00	$ 167,825.00	$ 128,688.33	63,502	98,876	0.874	86,372	$ 0.96
20613	Bridgeport	3	Other	Box Truss Span Bridge Sign Support Type III	91,100	$ 19,854.00	$ 41,047.00	$ 47,894.00	$ 36,265.00	148,698	119,899	0.716	85,807	$ 4.32
20517	Bridgeport	5	Other	Box Truss Span Bridge Sign Support Type III	39,550	$ 19,854.00	$ 41,047.00	$ 47,894.00	$ 36,265.00	148,698	94,124	0.911	85,709	$ 4.32
20770	Waterbury	4	A-36 Steel	Box Truss Span Bridge Sign Support Type III	95,900	$ 21,545.00	$ 40,254.00	$ 47,077.00	$ 36,292.00	114,426	105,163	0.801	84,285	$ 3.91
21600E	Hartford	2	A-36 Steel	Structure-Mounted Sign Support	161,350	$ 16,798.00	$ 28,970.00	$ 32,820.00	$ 26,196.00	121,026	141,188	0.597	84,254	$ 5.02
20576	Waterbury	5	Other	Box Truss Span Bridge Sign Support Type III	65,100	$ 21,545.00	$ 40,254.00	$ 47,077.00	$ 36,292.00	114,426	89,763	0.937	84,072	$ 3.90
20268	Norwalk	6	A-595 Steel	Box Truss Span Bridge Sign Support Type I	111,500	$ 43,303.00	$ 76,161.00	$ 93,009.00	$ 70,824.33	91,194	101,347	0.806	81,716	$ 1.89
20384	New Haven	1	A-36 Steel	Single Arm Tubular Cantilever Sign Support	130,250	$ 21,789.00	$ 38,963.00	$ 47,432.00	$ 36,061.33	134,052	132,151	0.617	81,584	$ 3.74
21613E	East Hartford	2	A-588 Steel	Structure-Mounted Sign Support	211,750	$ 24,373.00	$ 48,613.00	$ 57,848.00	$ 43,611.33	51,016	131,383	0.618	81,228	$ 3.33
21309	Hartford	4	A-36 Steel	Tubular Span Bridge Sign Support	156,200	$ 16,798.00	$ 28,970.00	$ 32,820.00	$ 26,196.00	121,026	138,613	0.586	81,180	$ 4.83
20298	Greenwich	1	A-36 Steel	Single Arm Tubular Cantilever Sign Support	143,300	$ 90,087.00	$ 128,153.00	$ 167,825.00	$ 128,688.33	63,502	103,401	0.782	80,876	$ 0.90
20510	Bridgeport	2	A-36 Steel	Single Arm Tubular Cantilever Sign Support	93,450	$ 19,854.00	$ 41,047.00	$ 47,894.00	$ 36,265.00	148,698	121,074	0.663	80,283	$ 4.04
20421A	Waterbury	1	A-36 Steel	Structure-Mounted Sign Support	78,000	$ 21,545.00	$ 40,254.00	$ 47,077.00	$ 36,292.00	114,426	96,213	0.831	79,955	$ 3.71
20415	Waterbury	3	A-36 Steel	Box Truss Span Bridge Sign Support Type III	95,900	$ 21,545.00	$ 40,254.00	$ 47,077.00	$ 36,292.00	114,426	105,163	0.758	79,727	$ 3.70
20017B	Stamford	2	A-36 Steel	Structure-Mounted Sign Support	149,600	$ 44,667.00	$ 75,579.00	$ 88,050.00	$ 69,432.00	135,511	142,556	0.553	78,825	$ 1.76
21603A	Hartford	2	A-36 Steel	Structure-Mounted Sign Support	88,050	$ 16,798.00	$ 28,970.00	$ 32,820.00	$ 26,196.00	121,026	104,538	0.749	78,338	$ 4.66
21600D	Hartford	2	A-36 Steel	Structure-Mounted Sign Support	122,250	$ 16,798.00	$ 28,970.00	$ 32,820.00	$ 26,196.00	121,026	121,638	0.642	78,082	$ 4.65
21313F	Hartford	1	A-588 Steel	Structure-Mounted Sign Support	134,600	$ 16,798.00	$ 28,970.00	$ 32,820.00	$ 26,196.00	121,026	127,813	0.611	78,052	$ 4.65
21313G	Hartford	1	A-588 Steel	Structure-Mounted Sign Support	134,600	$ 16,798.00	$ 28,970.00	$ 32,820.00	$ 26,196.00	121,026	127,813	0.611	78,052	$ 4.65

Figure 3.13 presents a 3D representation of the impact on commuters in terms of dollars. The data shows a normalized distribution trending towards an increase in the commuter impact in dollars as the age of the structure increases. This means that the risk increases as the structures age and *p(f)* approaches the limit of *1*. The increase in risk is indicated by the color of the cubes transitioning from green to red. This 3D graph demonstrates that each factor affecting the outcome (commuter impact) is related to the support factors and not a linear curve. When using this graph and maintenance schedules, it is essential to consider the full picture.

It is noticeable that the deterioration prediction curve largely depends on the age and materials of the structure. However, considering the impact of the structure's failure, maintenance priority is not always linearly proportional to the risk of failure. The replacement prioritization can be performed according to the Risk that is calculated by the Probability of Failure and the Impact of the failure. As shown in the Figure 3.13, most assets with high age have a high probability of failure, but not all old assets are prioritized for maintenance. Those with a high impact of failure are given high maintenance priority and are marked in red.

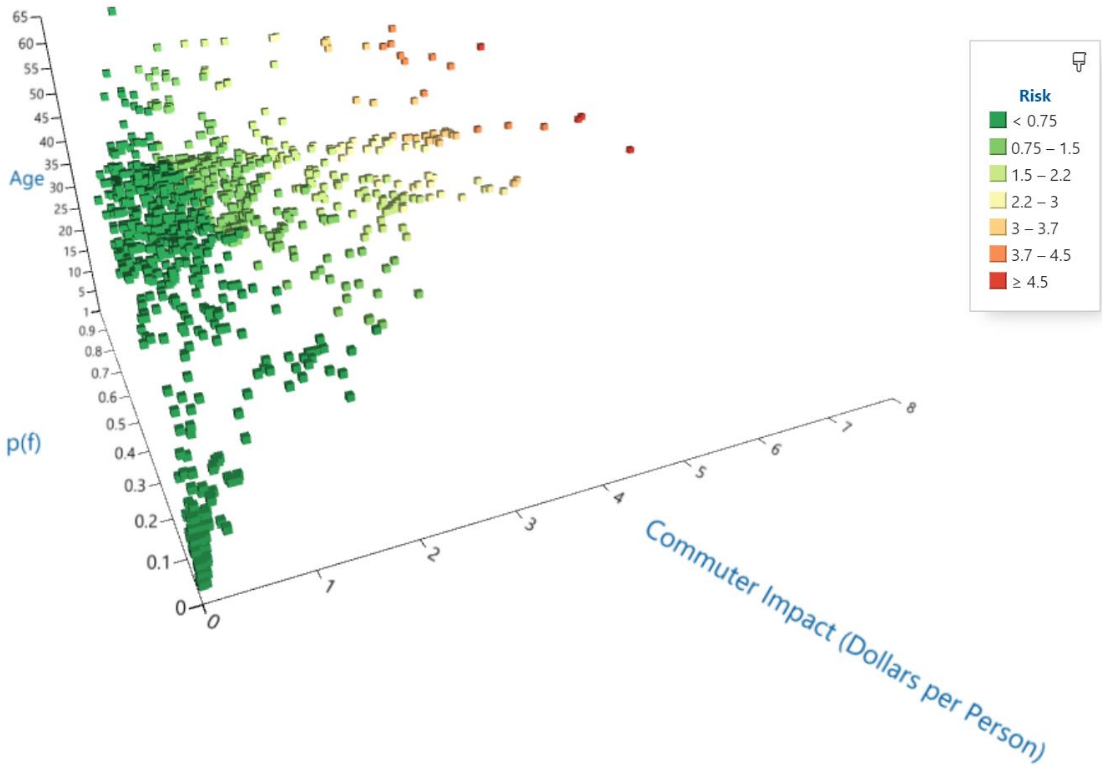

Figure 3.13. Risk by commuter impact, likelihood of failure (p(f)), and ages of assets

Results of Risk Analysis

Sign support assets have been analyzed by the size, type, material, age, and location based on the population of the area. Using a simplified deterioration model and factors that affect the failure probability, asset failure risk and impacts have been calculated, resulting in data-based asset management and repair/replacement prioritization planning. Not all the old assets require immediate attention. By material, type, and commuter impacts, repair/replacement priority varies.

Upon analyzing the data and conducting the calculations, the results indicate that the structure's age and other factors that determine *MTTF* are the primary contributors to the failure rate. This study identified two main categories of sign support failures: (1) structural damage and (2) readability or accessibility damage. Structural damage results from physical factors, such as anchor bolts, while accessibility damage refers to the clarity and reflectivity of the signs.

When determining the mean time to failure (*MTTF*), taking into account multiple factors provides a more nuanced probability of failure and a more focused replacement/repair recommendation list. These factors can be divided into two categories: categorical and multiplicative. The categorical values establish a baseline probability of failure (*p(f)*), which is then modified by the multiplicative factors. The categorical factors primarily affect the shape parameter in the Weibull function, while the multiplicative factors primarily affect the scale parameter. These principles apply to both Weibull functions used to calculate the rate of failure (*r(f)*) and the probability of failure (*p(f)*). The findings from the different contributing factors that led to sign degradation are outlined below.

1. **Average Daily Traffic** - The modification of this multiplicative statistic did not significantly impact the shape of the p(f) curve. All sign supports in the data set had a reasonable amount of ADT.
2. **Lanes Under structure** - The number of lanes under the structure was a factor that multiplied the *p(f)* curve. A structure spanning over more lanes had more points of potential failure and therefore, a higher *p(f)* value.
3. **Material Type** - The material used in constructing the sign support was a categorical factor affecting the probability of failure (*p(f)*) of each sign support. The yield strength of the material played a role in determining the overall stability of the structure.
4. **Support Type** - The type of support was a key categorical factor in determining the *p(f)* value for each sign support. Structures supported by box trusses were found to have a higher number of potential points of failure compared to those supported by monotubes or structure mounted signs, leading to a higher *p(f)* value. Additionally, the cost of replacing each type of structure varied.
5. **Year Installed** - The year a structure was installed was a significant factor in determining its *p(f)* value. This factor had the most impact on a structure, affecting the shape of the curve the most in testing.

The reliability curve shows a consistent trend towards the 40-year mark, with noticeable fluctuations in its progression. These fluctuations indicate that secondary factors have a greater impact on the reliability curve compared to the probability of failure curve.

Figure 3.13 illustrates that as the age of the structure increases, the risk of failure also increases, tending towards a maximum value of 1. The graph does not display a strong curvature, indicating that the failure rate is relatively constant with age. However, the variations and mild bumps in the graph are due to the additional factors contributing to the failure rate, such as average daily traffic, number of lanes under the structure, material type, and support type. The lowest failure rates are for signs that were installed less than two years ago, with deviations from the mean-time-to-failure coming from other factors.

CHAPTER 4 Conclusions, Recommendations and Suggested Research

The research effort evaluated sign support management strategies, including repair manuals, Transportation Asset Managements Plans, standardized drawings, and structure selection criteria. The researchers gathered and analyzed survey feedback from DOTs throughout the US. This effort initiated the second phase of the research work that involved the instrumentation and testing of a highway sign support structure. The data acquisition system, including the various sensors, were installed on the sign support asset No. 21740, on Highway 384, in Manchester, CT. The installation was in November 2022 and the data was collected and analyzed over the next six months.

The field test showed that the sign support structure only experienced significant wind loading on a few occasions, and during such activities the stress due to the load only reached about 20% of the elastic limit of the structure. A finite element model was developed, and its accuracy verified by comparing the model to the experimental field test data. The model was then subjected to the AASHTO LTS-15 (LRFD) complete design load that showed the structure reaching its design capacity if fatigue loading was considered. This demonstrated the importance of designing the sign support structures to resist long-term fatigue stresses.

Specific critical details can be most impacted by fatigue failure since the fatigue limits have been surpassed from natural wind or truck-induced wind gusts. If a particular sign support structure starts to exhibit fatigue failure, then it is recommended that all equivalent structures be inspected as soon as possible since they would have similar designs that might not be effective against long-term fatigue stresses caused by fluctuating loads. Furthermore, since sign replacement occurs at a more often rate than the support, the new sign size should not exceed the former sign so not to increase the area that the wind would be impacting, creating higher fatigue stresses that designed for.

The next phase of the project was risk analysis and developing a deterioration model for sign supports. As the amount of failure data collected over time increases, the accuracy of the data analytics will proportionally improve. A larger data set will allow for a higher degree of confidence in the results. However, it is worth noting that the database used in this study was not complete at the time of collection. To further strengthen the findings, additional factors such as precipitation and weather data could be included in future studies, as these supports are stationary objects and Connecticut experiences a range of severe weather conditions.

The results give us a replacement/repair prioritized list that was created by calculating the impact on commuter and likelihood of failure of assets. The highest risk assets are the ones that combine the factors above. The supports serving single-lane roads going into or out of Hartford are the most at risk for structural or readability damage. Rural sign supports in the outside corridor of the state are not subject to as many adverse conditions and, thus, would not need to be replaced/repaired as frequently.

In conclusion, it is cost-effective to prioritize sign support replacement/repairs based on the findings. While the overall failure rate of these signs is low, preventative replacements/repairs should be considered starting with the oldest supports and working towards the newest.

CHAPTER 5 Implementation of Research Results

The current service life of sign support structures in the State of Connecticut is 34 years. The research effort conducted in this project show that there is potential to increase the current service life significantly. This has been demonstrated by the field test, finite element analysis, risk assessment and the deterioration model. However, to have a more conclusive recommendation, further future research is required on other types of sign support structures. Similar to the work done in this project, the future work would involve field testing and FE analysis of the different types of sign supports. Since the experimental work for this research grant was limited to only one sign support, the researchers acknowledge that this one sign support is not sufficient to attempt to develop broad conclusions on the 1600 sign supports in Connecticut. Therefore, it is recommended that more experimental work on several more sign support is required to assist the researchers to determine a trending pattern of behavior which would help them develop actionable recommendations.

Looking into the future, it is also worth noting that some DOT's are opting out of sign panels and replacing it by the variable message displays to be mounted to sign support structures. These variable message displays require support structures with significantly higher capacity. For example, the cantilever structure selected for this project used a two chord cantilever arm, whereas a cantilever structure supporting a variable message display would probably require four chord cantilever arms.

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