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MARYLAND DEPARTMENT OF TRANSPORTATION
STATE HIGHWAY ADMINISTRATION

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RESEARCH REPORT

Structural Assessment for MD Sign Structures Project based on AASHTO LTS-6 Strength and Fatigue Criteria

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FINAL REPORT

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The purpose of this project is to conduct a structural assessment of Maryland sign structures based on the AASHTO LTS- 6 strength and fatigue criteria, using these criteria and methods to study and evaluate the Maryland Department of Transportation's State Highway Administration sign structure database and taking samples from the selected categories. The research developed a methodology for analyzing sampled sign structures, running selected sampled cases and verifying structural results. After evaluating sampled sign structures, a ranking category was established which led to prioritizing the whole population based on the evaluation. Finally, all information from the research was summarized and the findings were reported.</td></tr>
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Structural Assessment for MD Sign Structures Project based on AASHTO LTS-6 Strength and Fatigue Criteria

Executive Summary

Road-side infrastructures are part of the highway plan, and their safety is essential for maintaining traffic flow and traffic safety. The AASHTO Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals have gone through several evolutional/revolutionary changes since the year 2001 (LTS-4) and the latest editions are 2013 (LTS-6) and 2015 (LTS-LRFD) editions with their respective interims. The LTS-LRFD specifications adopted the ASCE/SEI 7-10 wind loads and considered wind as an extreme limit state, unified with the most used U.S. Standards. The LTS-LRFD specifications raised the wind load to stronger storms with lower Mean Recurrence Intervals (MRI) which requires new structural analyses of the old structures under the current wind loads. The Maryland Department of Transportation State Highway Administration (MDOT SHA) is developing a sign structure assessment approach in collaboration with the Bridge Engineering Software and Technology (BEST) Center, University of Maryland to understand the influence of the new wind loads on types of structures and if they should be categorized as at risk, marginal, or can remain in service. This research included six tasks.

Task 1: Study and evaluate MDOT SHA sign structure database

The data of sign structures in MD was collected and grouped. The MDOT SHA Traffic Structure Inventory Inspection Management (TSIIM) database was provided and permitted for the use for analytical purposes. Also, the Excel format file could be extracted and downloaded for our analysis. Types of sign structures, the years they were built, AASHTO versions adopted, material, dimensions, inspection record (if exists) were collected through the database. For more detailed information, GPS locations, roads, and traffic conditions (interstate, non-interstate, ADT/ADTT, etc.) were collected from the MDOT SHA Traffic Monitoring System (TMS).

All Maryland sign structures were summarized and then categorized based on 5 major categories (cantilever type, butterfly type, span-cantilever type, double type, and overhead type).

Task 2: Take samples from categories and analyze sampling sign structures

By studying the TSIIM database, several mis-coded recordings were found and extracted for further improvement. Based on the team's research, galloping was the most critical fatigue load of the three types specified by AASHTO (galloping, natural wind gust and truck gust). Then, 5 out of 19 types for a total of 736 galloping-influenced structures were left for consideration. Valid sampling techniques were adopted to determine the sign bridge sampling sizes for numerical modeling and evaluation.

Task 3: Run selected sampled cases and verify SABRE results

Sample models were established and run in Sign Bridge Analysis and Evaluation System (SABRE) software from 5 major categories for a total sample sign structure population. Five box type cantilever structures belonging to two categories (CN3 and CN5) were sampled and modeled in order to prove that without galloping, the other two fatigue loads (natural wind gust and truck gust) were not critical. Their fatigue details were carefully calculated, summarized and checked against the code or documents. Details are shown in Appendix C.

Task 4: Evaluate sampling sign structures

Sample sign structures were evaluated based on AASHTO LTS-6 with fatigue consideration for maximum fatigue life expectation. Although the LRFD criteria is not adopted for this study, the AASHTO LRFD-based development for wind and traffic volume (AADT) is considered in the risk analysis. The locations of the 736 sign structures, which are influenced by wind galloping, within different ranges of AADT were observed and studied from the Arc-GIS map. Moreover, tentative factors considered in ranking and prioritizing were tabulated.

Task 5: Rank and prioritize the whole population based on the evaluation

A semi-qualitative risk ranking approach and a reliability analysis approach were developed for the assessment of MD sign structures. In the sign structure rank system, four relevant factors, including structure analysis result, number of anchor bolts, average annual daily traffic volume (AADT), and sign structure age, were considered in the evaluation. The rank in each factor is assigned to a certain weight to obtain the final rank score. For the structure analysis portion, certain types of sign structures were summarized into groups according to the distribution of span lengths and post sizes. Subsequently, these samples were modeled and analyzed by the SABRE program. Their Combined Stress Ratio (CSR) of posts and arms, as well as their fatigue stress ranges, were obtained. When evaluating a structure based on one factor, a risk rank was given according to its condition data. Eventually, the ranking of all existing sign structures is generated to prioritize the structural replacement.

An Automated Sign Structure Ranking Program was developed as a tool by the BEST center to help maintain and monitor the current sign structure (CN2 and OH6 type). It imported the TSIIM database combined with the traffic information from the MDOT Traffic Monitoring System, then organized and analyzed the inventory condition. A total ranking from 1 to 5 was be provided in the end, whereas a default rank score (by following the TEDD, Traffic engineering Design Division, scoring system) of 5 indicated the least critical condition, and rank score 1 indicated the most dangerous condition. The Automated Sign Structure Ranking Program also allowed a reverse ranking with 5 as the most and 1 the least critical conditions by following the Pontis-based scoring system.

Moreover, a reliability analysis was provided as an alternative approach that gives an evaluation of the whole sign structure system. The failure probabilities obtained in the reliability analysis show the consistency with the risk ranking results.

Task 6: Summary and Report

A summary of all six tasks and a conclusion is included in this chapter. A report deliverable table is included.

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Chapter 1 Introduction

1.1 Research Problem Statement

Since 2001, the AASHTO Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals have gone through several evolutional/revolutionary changes, which are chronologically listed with a short description of the changes:

- 1994 (LTS-3 and earlier) edition – original; load combinations 1-3
- 2001 (LTS-4) edition – revamped; new wind criteria
- 2009 (LTS-5) edition – new wind; foundation/anchor bolts; fatigue introduced as load combination 4; retrofit/rehab; miscellaneous
- 2013 (LTS-6) edition – wind; fatigue (major revision); foundation
- 2015 (LTS-LRFD) edition – new wind; new load combination; load and resistance factors; same LTS-6 fatigue design.

The National Cooperative Highway Research Program (NCHRP) sponsored research in the problem areas and the AASHTO released the specifications. It is now the states' responsibility to accommodate their designs based on different versions of the codes. Specifications list three types of roadside structures: highway sign structures, high mast light poles, and traffic signal posts. The current status of Maryland structures is listed as follows:

- MD structural supports for highway signs: LTS-4
- MD structural supports for high mast light poles: LTS-5 (based on MDTA Standard)
- MD structural supports for traffic signals: LTS-3 (recently to LTS-6)

The question is where we stand now with all those old sign structures. The majority of the sign structures that currently owned are designed based on the ASD standards for 90 or 100 miles/hour of wind load where fatigue was not even considered as a major failing factor for these cyclically loaded structures. Unfortunately, the maximum expected service lives of these types of structures are unknown. The LTS-LRFD specifications adopted the ASCE/SEI 7-10 wind loads and considered wind as an extreme limit state, unified with the most used U.S. Standards. Also, the LTS-LRFD specifications raised the wind load to stronger storms with lower Mean Recurrence Intervals (MRI) which requires new structural analyses of the old structures under the current wind loads.

The MDOT SHA current sign structure standard is the 2001 AASHTO LTS- 4 (the majority of sign structures were designed after 2001 with wind speed of 100 MPH) and the older trichord and square tubular (box-type) sign structures were designed for 90 miles/hour. This wind speed was only applicable for Groups I-III load combinations, as fatigue was not part of the design criteria in the 1994 AASHTO Specifications.

1.2 Research Objectives

AASHTO updated the wind loads, design categories and fatigue stress thresholds for sign structures based on the most recent wind load studies performed by the American Society of Civil Engineers (ASCE/SEI 7-10).

MDOT SHA owns many sign structures which are designed based on the older AASHTO standards and most likely a few of them will not be able to resist the new wind load categories, even if maintenance and inspection criteria are followed closely. To be proactive, it is very important to know which categories (at risk, marginal, or can stay in service) the structures would fall under. The purpose of this project is stated in the title to conduct a structural assessment of MD sign structures based on the AASHTO LTS- 6 strength and fatigue criteria.

1.3 Benefits

After 2020, the sign structures inspection and maintenance budget will be based on the MDOT SHA's new asset management budget allocation policies since sign structures are considered "structural assets" here after. To be prepared for the upcoming budget allocation policies, the Office of Traffic and Safety (OOTS) needs to have a well-established inventory system in place, know the exact number of structures, their most current condition ratings, and the cost associated with repair or total replacement.

There are some old sign structures in service that are designed and built based on lower wind loads without considering fatigue as a failing factor. Also, the wind pressure calculations with their associated parameters are different from various specification editions. The OOTS needs to know the structural soundness of these sign structures under the new wind loads and their maximum expected service life to protect public safety.

1.4 Research Plan

Proposed tasks associated with the evaluation of the existing sign structures and their asset management:

Task 1: Study and evaluate the MDOT SHA sign structure database

Task 2: Take samples from categories and analyze sampling sign structures

Task 3: Run selected sampled cases and verify SABRE results

Task 4: Evaluate sampling sign structures

Task 5: Rank and prioritize the whole population based on the evaluation

Task 6: Summary and Report

Chapter 2 Task 1: Study and evaluate MDOT SHA sign structure database

Two steps were involved in this task, data collection and categorization.

2.1 Step 1: Data Collection

This step involved collecting data such as sign structural types, year built, AASHTO versions adopted, material, dimensions, inspection record from the MDOT SHA sign structure database. More detailed information such as GPS locations, road and traffic conditions (interstate, non-interstate, ADT/ADTT, etc.) was also collected.

Status: MDOT SHA categorized sign structural types, where 19 types were identified and are graphically shown in Appendix B. MDOT SHA also supplied the TSIIM database and all the research team members received permission to log in to the state system as users. The Excel format file could be extracted and downloaded for our analysis. Based on the team's research, galloping was the most critical fatigue load of the three types specified by AASHTO (galloping, natural wind gust and truck gust). The Excel sheet listed the extracted 2,451 sign structures (shown by type in Table 2.1 and Figs. 2.1 & 2.2). The MDOT SHA, by following the bridge rating, has rated the sign bridge in five categories, which are shown in Table 2.2 and Fig. 2.3. (Based on joint consensus, the structure condition rating was not fully reliable, and so it is considered in the evaluation, but should only be used as a reference.)

Table 2.1 – MDOT SHA Sign Structure Type

Type	Chord No.	Number	Ratio	Galloping	NW Gust	Truck Gust	Galloping	NW Gust	Truck Gust
CM1	Tri	7	0.29%	No	Yes	Yes	0	1	1
CM2	Tri	0	0.00%	No	Yes	Yes	0	1	1
CM3	Box	0	0.00%	No	Yes	Yes	0	1	1
CM4	Tri	7	0.29%	No	Yes	Yes	0	1	1
CM5	Box	23	0.94%	No	Yes	Yes	0	1	1
CM6	Box	47	1.92%	No	Yes	Yes	0	1	1
CM7	Tri	11	0.45%	No	Yes	Yes	0	1	1
CN1	Single	74	3.02%	Yes	Yes	Yes	1	1	1
CN2	Double	631	25.74%	Yes	Yes	Yes	1	1	1
CN3	Box	616	25.13%	No	Yes	Yes	0	1	1
CN4	Double	5	0.20%	Yes	Yes	Yes	1	1	1
CN5	Box	14	0.57%	No	Yes	Yes	0	1	1
CN6	Pedestal	12	0.49%	No	Yes	No	0	1	0
OH1	Single	18	0.73%	Yes	Yes	Yes	1	1	1
OH2	Double	8	0.33%	Yes	Yes	Yes	1	1	1
OH3	Tri	27	1.10%	No	Yes	Yes	0	1	1
OH4	Tri	275	11.22%	No	Yes	Yes	0	1	1
OH5	Tri	72	2.94%	No	Yes	Yes	0	1	1
OH6	Box	604	24.64%	No	Yes	Yes	0	1	1
Total		2451					736	2451	2439

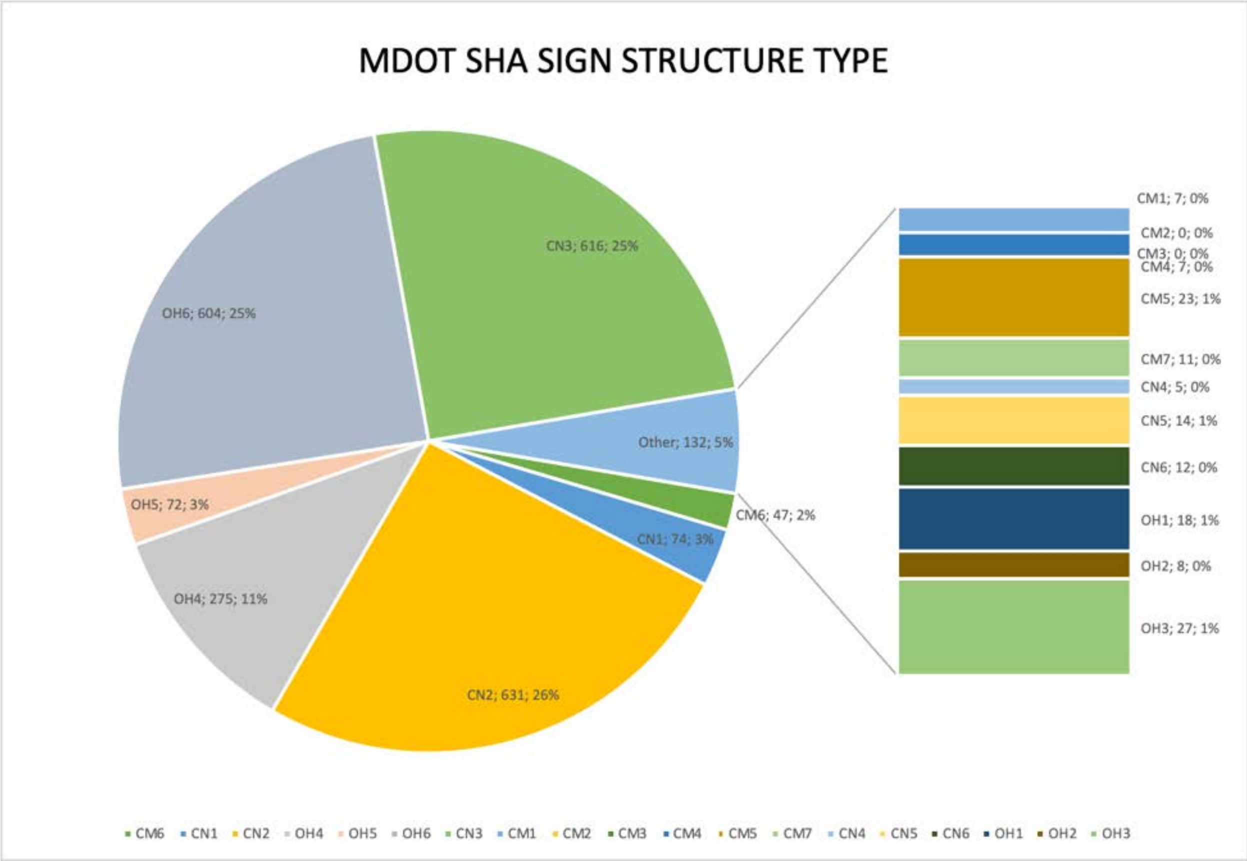


Figure 2.1 – MDOT SHA Sign Structure Type in Pie chart

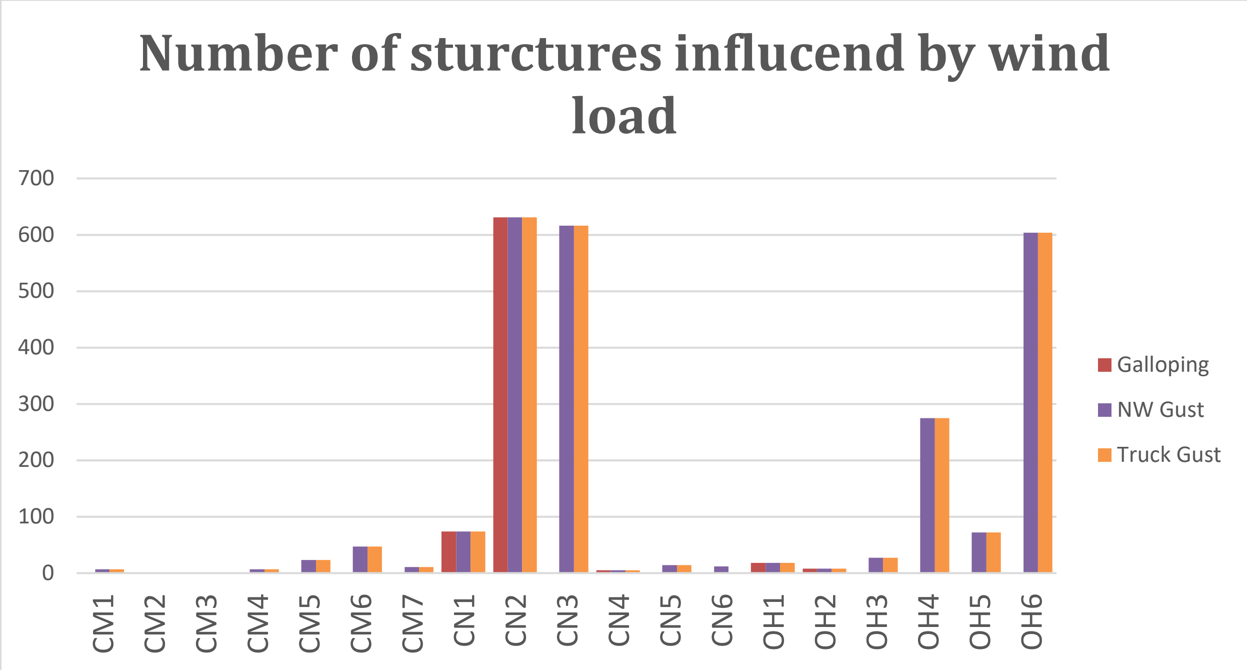


Figure 2.2- MDOT SHA Sign Structure Type due to Fatigue Wind Load in Bar chart

Table 2.2 - MDOT SHA Sign Structure Condition Rating

Rate	Deficient	Poor	Fair	Good	Excellent
	1	2	3	4	5
No.	70	107	564	1466	199
%	2.91%	4.45%	23.44%	60.93%	8.27%

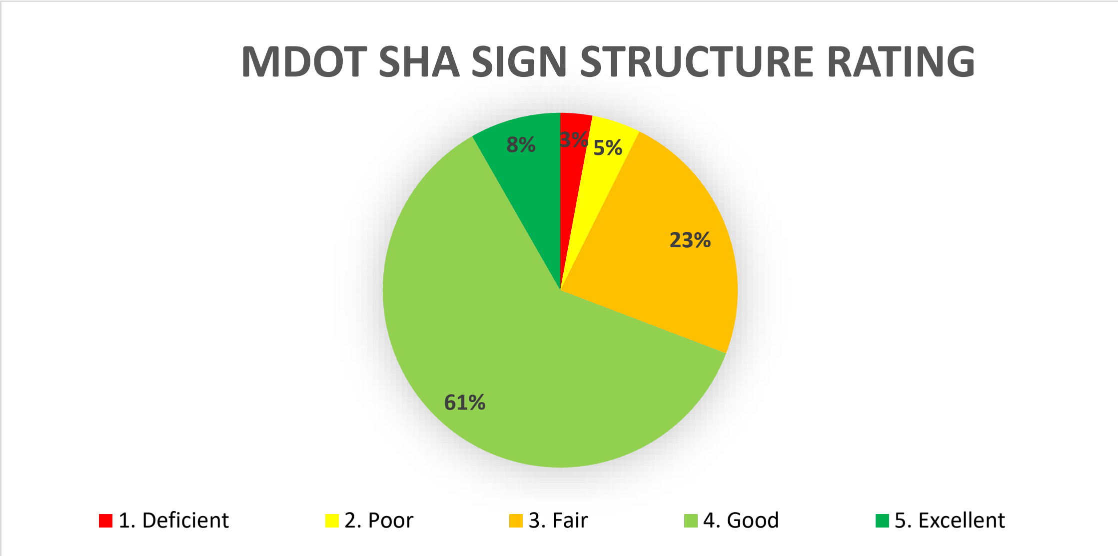


Figure 2.3 - MDOT SHA Sign Structure Rating in Pie Chart

2.2 Step 2: Categorizing

This step involved categorizing all MD sign structures based on 5 major categories of (1) cantilever type (CN1-3), (2) butterfly type (CN4-5 may include CN6), (3) span-cantilever type (CM1-3, may include CM7), (4) double type (CM4-5, may include CM6), and (5) overhead type (OH1-6).

Status: Out of the five major categories, the box-type sign structure evaluation can be waived for both cantilever (CN1-6), cantilever overhang (CM1-3) and overhead (OH1-4). Galloping-influenced sign structures are shown as bar 1 in Fig. 2.4, whereas bars 2 (affected by Natural Wind Gust) and 3 (affected by Truck Gust) represent nearly all the structures

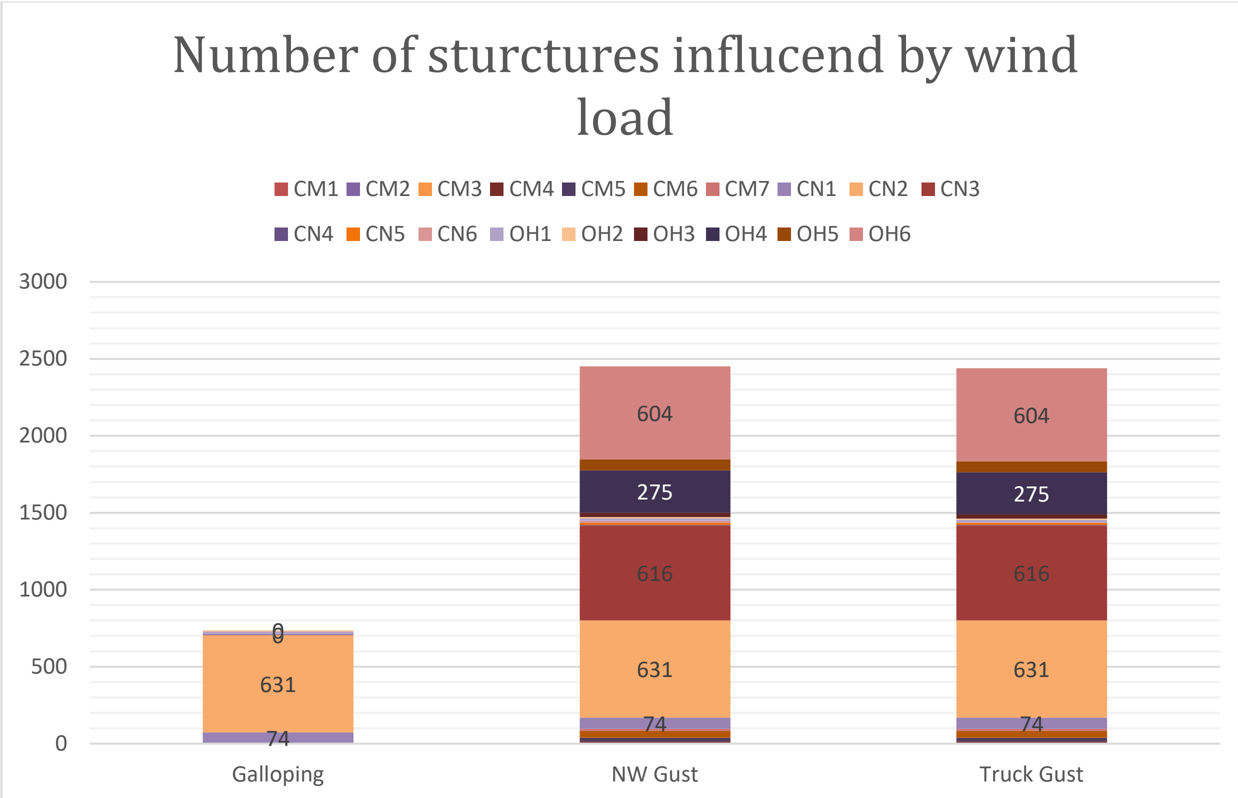


Figure 2.4 - Numbers and Types of Structures Influenced by Three Fatigue Loads

Chapter 3 Task 2: Take samples from categories and analyze sampling sign structures

Two steps are involved in this task: categorizing and analyzing samples,

3.1 Step 3: Major categories

In this step, the total MD sign structure population was taken, and subtotal numbers were calculated for the 5 major categories.

Status: The AADT of the route where a sign structure situates is critical in the analysis of a structure. Although Maryland AADT is available as a GIS feature layer, as shown in Fig. 3.1, a special spatial analysis program was developed to snap a structure to the closest AADT feature segment and thus associate an AADT value to each structure. A special mapping program was then developed to show all the sign structures on the base maps as shown in Fig. 3.2.

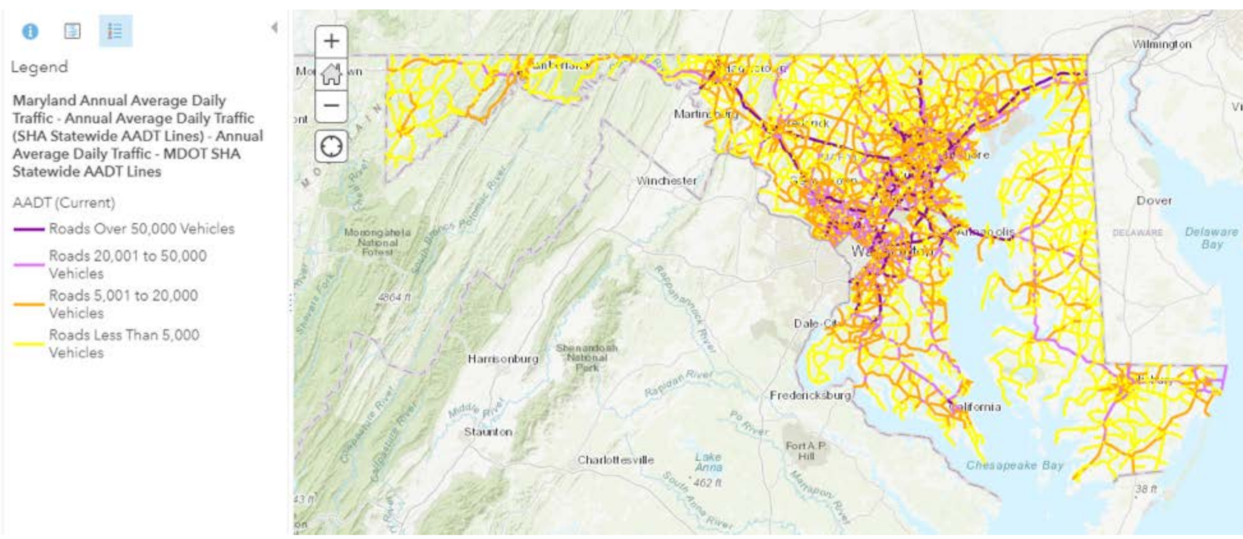


Figure 3.5 - Maryland AADT Traffic Volume Map (ArcGIS-MD online)

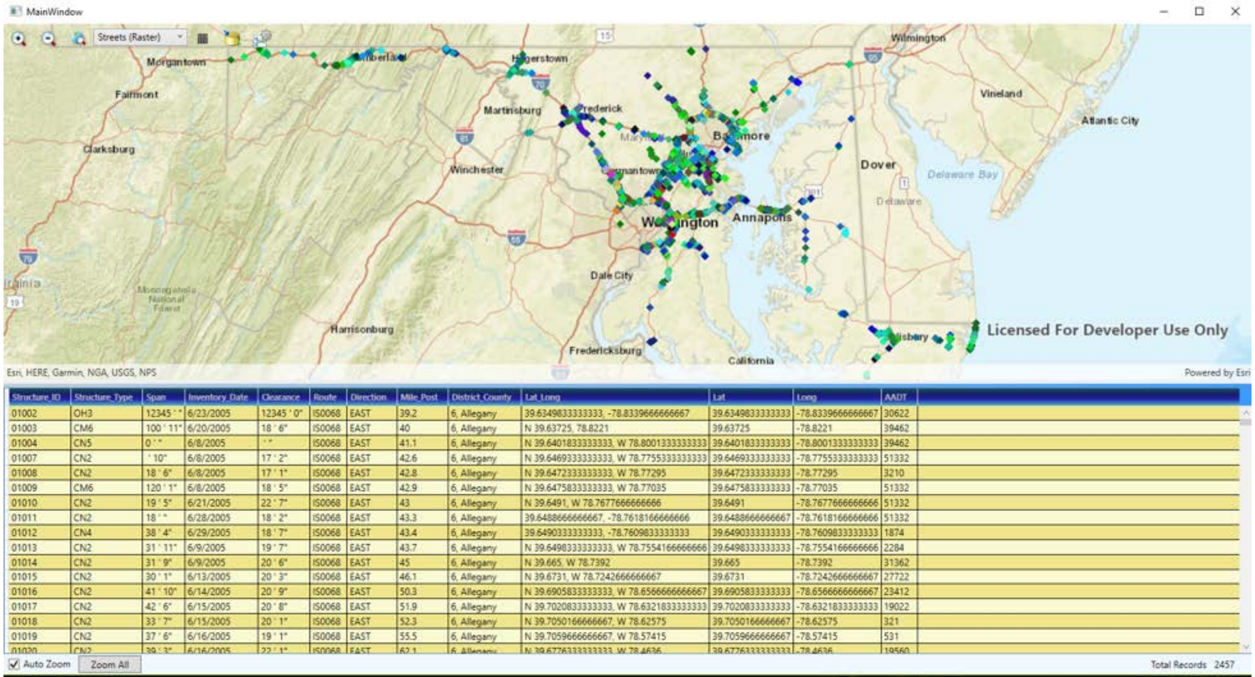


Figure 3.6 - Main Program with Whole Structure information (2,457 in total)

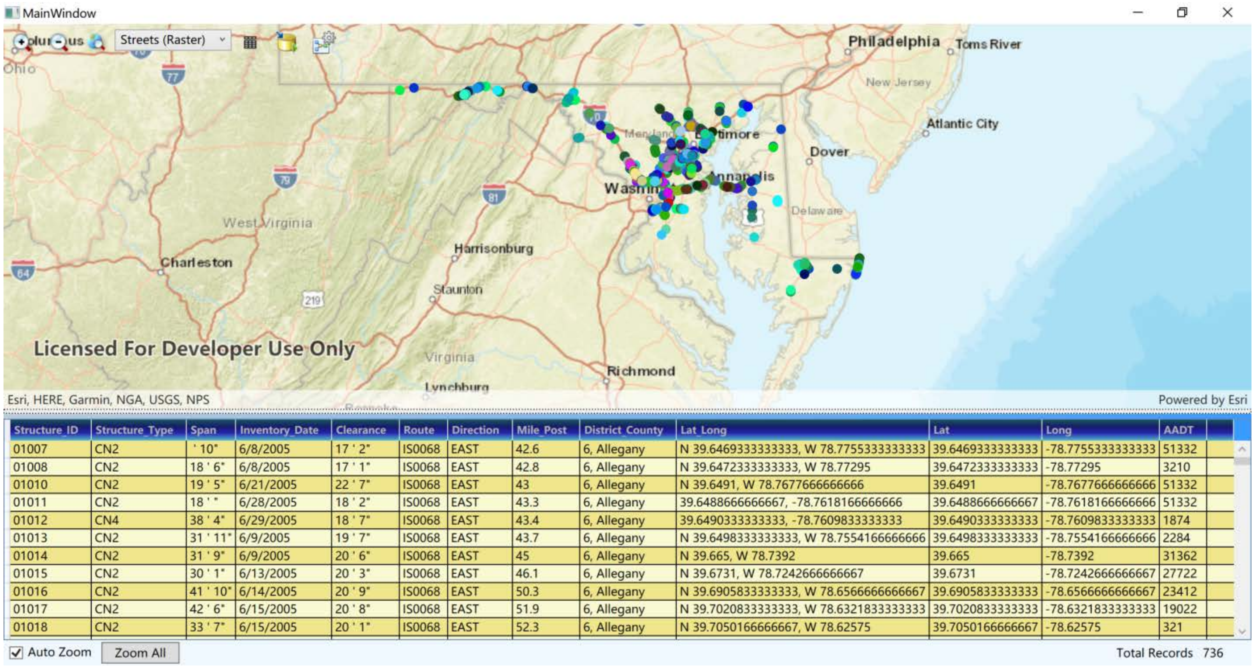
Findings of the TSIIM database include:

- The locations of some structures in the database supplied by MDOT SHA seemed incorrect, and here is a short list of the detected items:
    - Structure ID 15147, located in Greenland, near to the north pole.
    - Structure ID 10084, located in Portugal.
    - Structure ID 15523, located in Atlantic Ocean.
    - Structure ID 15057, located in Atlantic Ocean.
    - Structure ID 01073, location near to Raleigh, NC.
    - Structure ID 15318, location near to Arlington, VA.
    - Structure ID 16200, location near to York, PA.
    - Structure ID 02131, location near to Susquehanna River, PA.

- These structures are located out of MD on the map, and items on the list that might be in error but still listed within MD are:
    - Structure ID 21001, 21033, 21034, 21035, 21036, 03163, 15287, 15345, 16473, 16104, & 16106.

- The common characteristic of these structures is that AADT=0 (on both two lists), and they did not appear beside roads on the map. The *Query* function has noted that AADT should be from 71 to 267,232, so there might cause an error in locating these structures.

- Only 5 out of 19 types for a total 736 galloping-influenced structures remain for consideration. Those structures are shown in the Arc-GIS map by their categories (Fig. 3.3).



Structure_ID	Structure_Type	Span	Inventory_Date	Clearance	Route	Direction	Mile_Post	District_County	Lat_Long	Lat	Long	AADT
01007	CN2	' 10"	6/8/2005	17 ' 2"	IS0068	EAST	42.6	6, Allegany	N 39.6469333333333, W 78.7755333333333	39.6469333333333	-78.7755333333333	51332
01008	CN2	18 ' 6"	6/8/2005	17 ' 1"	IS0068	EAST	42.8	6, Allegany	N 39.6472333333333, W 78.77295	39.6472333333333	-78.77295	3210
01010	CN2	19 ' 5"	6/21/2005	22 ' 7"	IS0068	EAST	43	6, Allegany	N 39.6491, W 78.7677666666666	39.6491	-78.7677666666666	51332
01011	CN2	18 ' "	6/28/2005	18 ' 2"	IS0068	EAST	43.3	6, Allegany	39.6488666666667, -78.7618166666666	39.6488666666667	-78.7618166666666	51332
01012	CN4	38 ' 4"	6/29/2005	18 ' 7"	IS0068	EAST	43.4	6, Allegany	39.6490333333333, -78.7609833333333	39.6490333333333	-78.7609833333333	1874
01013	CN2	31 ' 11"	6/9/2005	19 ' 7"	IS0068	EAST	43.7	6, Allegany	N 39.6498333333333, W 78.7554166666666	39.6498333333333	-78.7554166666666	2284
01014	CN2	31 ' 9"	6/9/2005	20 ' 6"	IS0068	EAST	45	6, Allegany	N 39.665, W 78.7392	39.665	-78.7392	31362
01015	CN2	30 ' 1"	6/13/2005	20 ' 3"	IS0068	EAST	46.1	6, Allegany	N 39.6731, W 78.7242666666667	39.6731	-78.7242666666667	27722
01016	CN2	41 ' 10"	6/14/2005	20 ' 9"	IS0068	EAST	50.3	6, Allegany	N 39.6905833333333, W 78.6566666666667	39.6905833333333	-78.6566666666667	23412
01017	CN2	42 ' 6"	6/15/2005	20 ' 8"	IS0068	EAST	51.9	6, Allegany	N 39.7020833333333, W 78.6321833333333	39.7020833333333	-78.6321833333333	19022
01018	CN2	33 ' 7"	6/15/2005	20 ' 1"	IS0068	EAST	52.3	6, Allegany	N 39.7050166666667, W 78.62575	39.7050166666667	-78.62575	321

Figure 3.7 - Program with the Galloping-influenced Structure information (736 in total)

3.2 Step 4: Stratified sampling

This step adopted stratified sampling methodology based on 5 sub-populations. Valid sampling techniques were adopted to determine the sign bridge sampling sizes for numerical modeling and evaluation.

Status: 736 vulnerable (galloping-influenced) structures belonged to 5 categories (CN1, 2, 4 and OH1-2). Their sizes were 74 for CN1, 631 for CN2, 5 for CN4, 18 for OH1, and 8 for OH2. Statistically, one was taken from CN4, OH1, and OH2, two (2) from CN1, and 10 from CN2 to represent the whole population.

Chapter 4 Task 3: Run selected sampled cases and verify SABRE results

Two steps were involved in this task: on strength evaluation and fatigue evaluation.

4.1 Step 5: Verification

This step verified (SABRE software using STADD-Pro based on the examples adopted from NCHRP reports 718 (2012) and 796 (2014) and the NJDOT report (2015).

Status: SABRE was verified using STAAD-Pro. Several input and assumption errors were found in the four sample problems from NCHRP reports 718 (2012) and 796 (2014) and the NJDOT report (2015). Their summary report is in Appendix C.

4.2 Step 6: SABRE model samples

This step established SABRE models and ran samples from 5 major categories (for instance, five samples selected from category 1, three from category 2, and so on) for a total sample population of 30 sign structures.

Status: In order to prove that without considering galloping, other two fatigue loads (natural wind gust and truck gust) are not governing the fatigue design, 5 box-type cantilever structures belonging to two categories, CN3 (total = 616) and CN5 (total =14), were taken as samples. Their fatigue details were carefully calculated, summarized and checked against the code or documents. Appendix A shows that even with the equation limitation, 2.7 ksi can be conservatively adopted as the fatigue limit for the post base and the 5 sample problems (out of 630) shows they are within the fatigue limit. The next step was to find the sizes for the modeling of eight (8) sample overhead sign structures out of a total of 978 (27 for OH-3, 275 for OH4, 72 for OH5, 604 for OH6) to prove that without considering galloping, those overhead structures were also not critical and could be waived for further evaluation as planned.

Chapter 5 Task 4: Evaluate sampled sign structures

The one step involved in this task was to obtain the performance of the sampled sign structures.

5.1 Step 7: Sample evaluation

This step evaluated the sampled sign structures based on the AASHTO LTS-6 with fatigue consideration for maximum fatigue life expectation.

Status: 736 sign structures and sample problems had to be established in order to determine their fatigue stress that was entered into the Arc-GIS as one of the determining factors for ranking and prioritizing. Based on the AASHTO LRFD development for wind, traffic volume (AADT) was considered in the risk analysis. Table 5.1 shows the risk categories by traffic volume considered by AASHTO and was also be considered in our analysis.

Table 5.3 - Risk Category by Traffic Volume (AASHTO-LRFD 2015)

	Risk Category		
	Typical	High	Low
Traffic Volume	<35	N/A	N/A
ADT < 100	300	1,700	300
100 < ADT ≤ 1,000	700	1,700	300
1,000 < ADT ≤ 10,000	700	1,700	300
ADT > 10,000	1,700	1,700	300
Typical: Support failure could cross travelway.			
High: Support failure could stop a lifeline travelway.			
Low: Support failure could not cross travelway.			
Roadside sign supports: use 10-year MRI.			

It can be seen that ADT<100 can be considered Category I, combining 100<ADT<1,000 and 1,000<ADT<10,000 can be considered Categories II and III, ADT>10,000 can be considered Category IV where their corresponding maps are shown in Figs. 5.1 – 5.4, respectively.

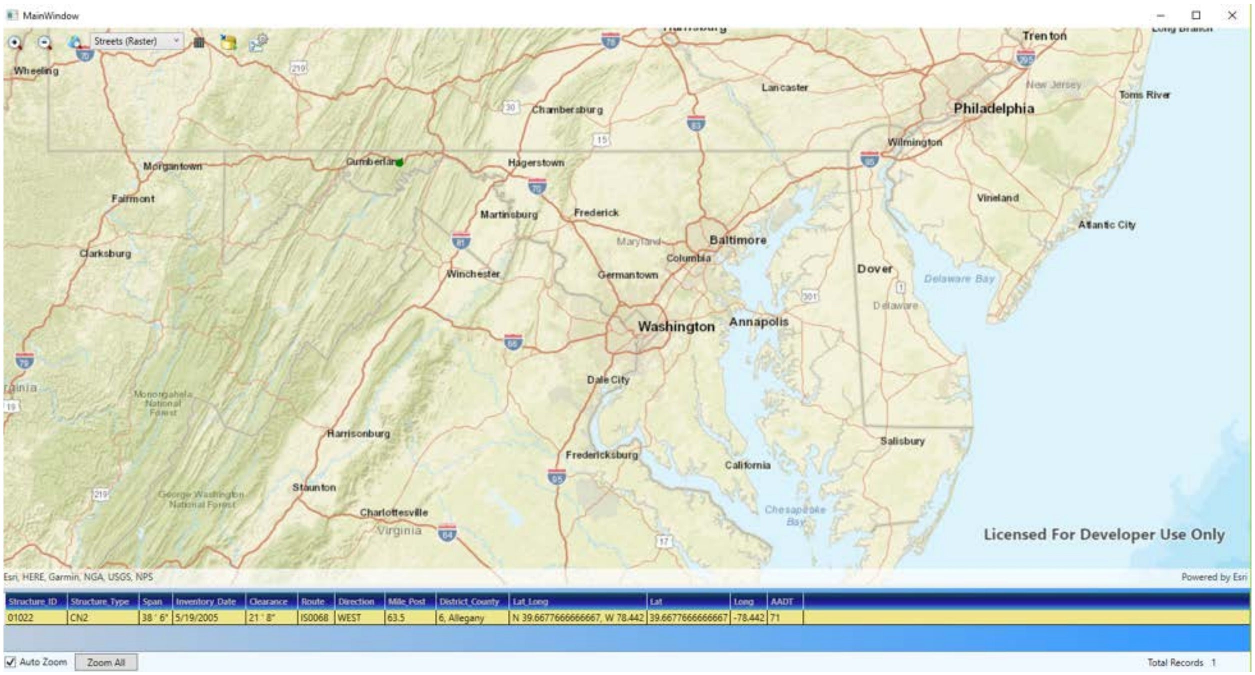


Figure 5.8 - Structures with ADT less than 100 (Category I), 1 in total

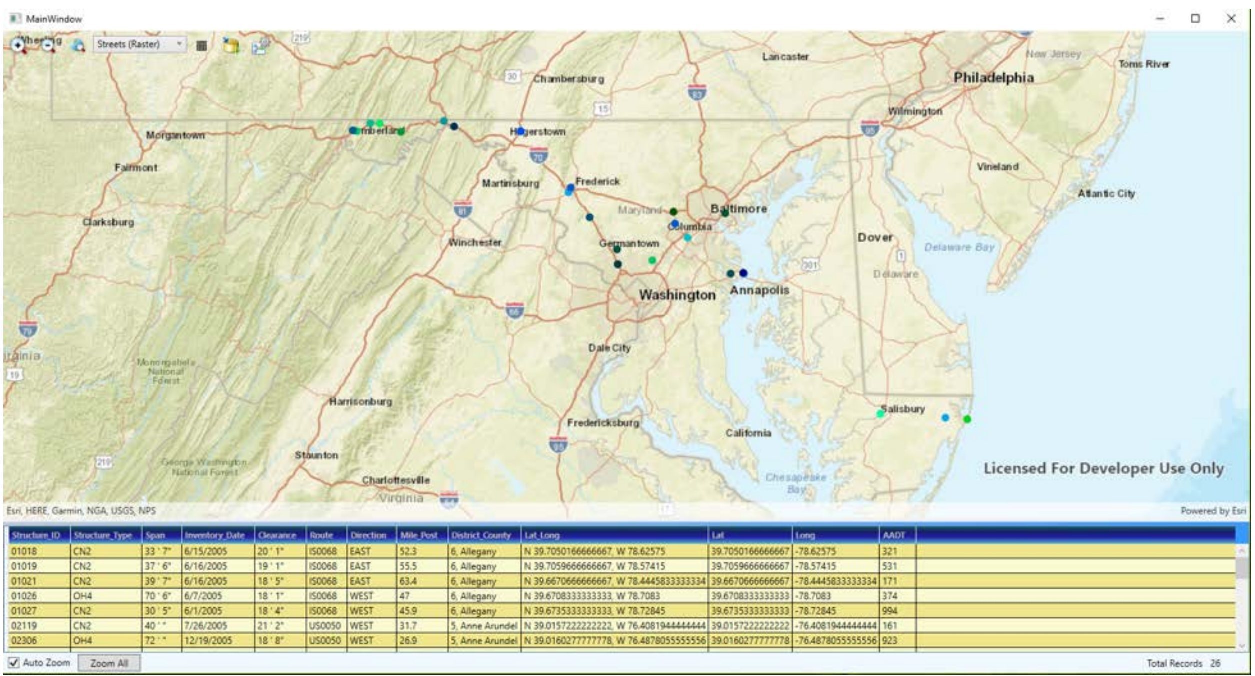


Figure 5.9 - Structures with ADT between 100 and 1,000 (Category II), 26 in total

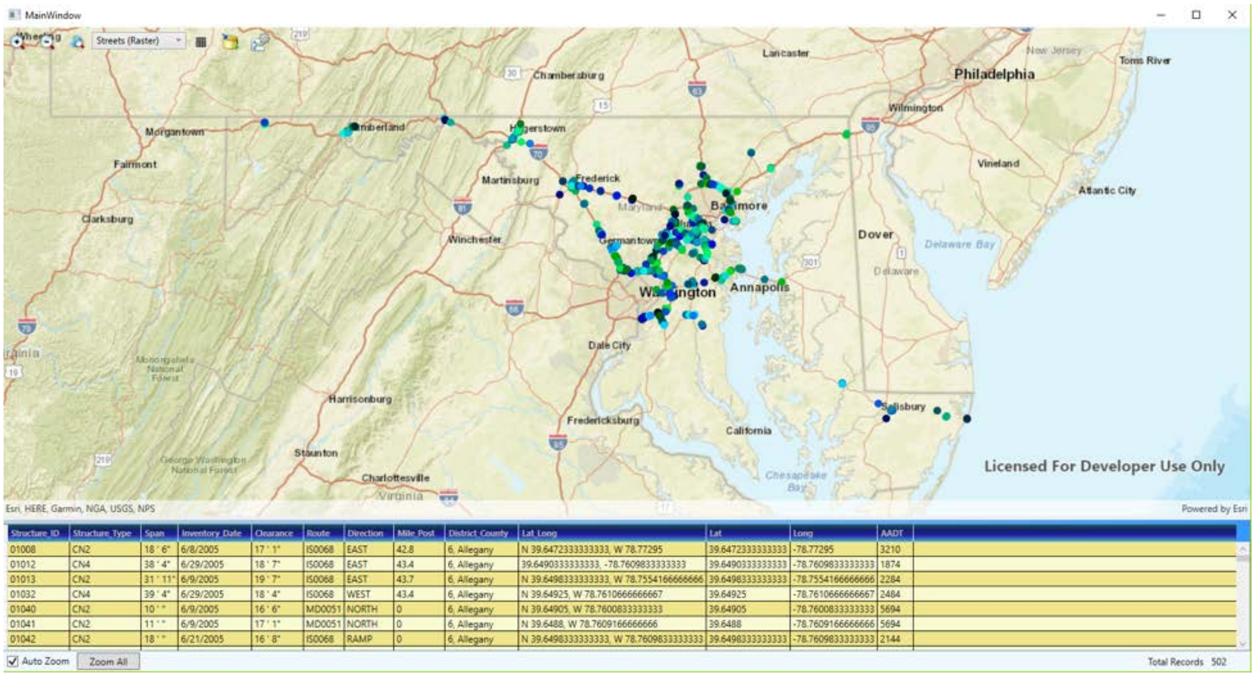


Figure 5.10 - Structures with ADT between 1,000 and 10,000 (Category III), 502 in total

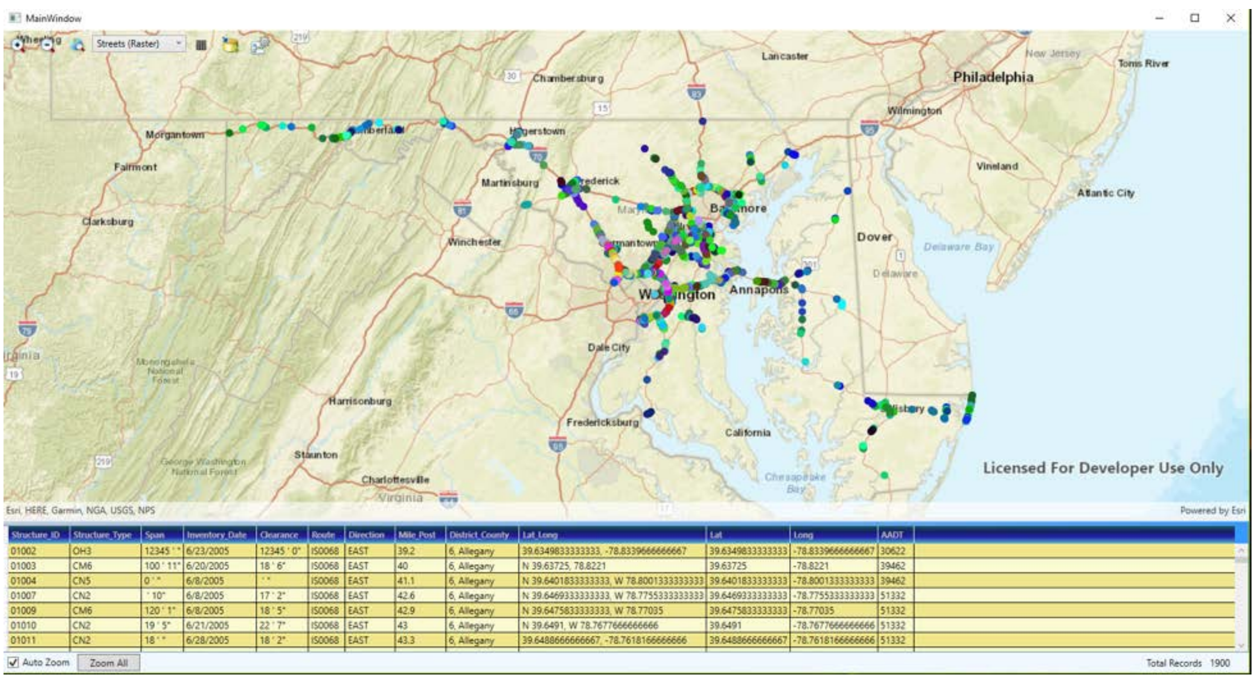
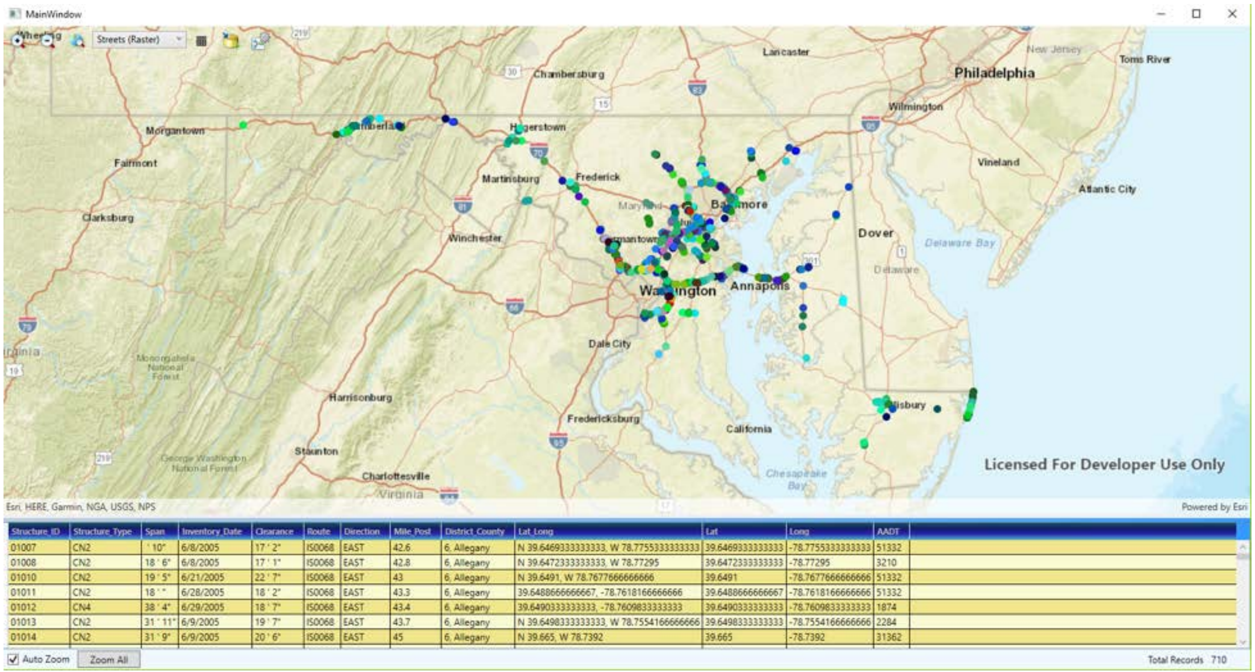


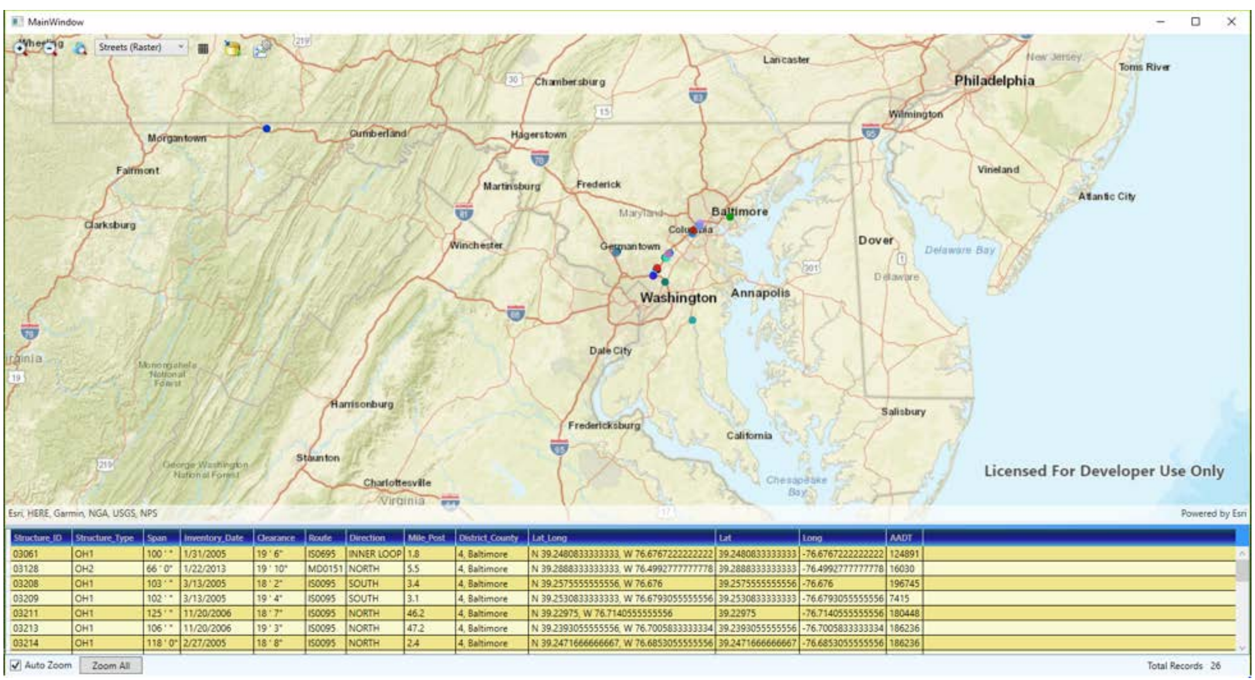
Figure 5.11 - Structures with ADT over 10,000 (Category IV), 1900 in total

As mentioned in Step 4, 736 galloping-influenced structures were considered vulnerable and belonged to 5 categories (710 CN1, 2, & 4 in Fig. 5.5 and 26 OH1 & 2 in Fig. 5.6). By combining two databases, those structures of 5 categories for AADT over 10,000 are shown in Fig. 5.7; for AADT over 1000 are shown in Fig. 5.9 with symbology, and Fig. 5.8 lists the symbology used in Fig. 5.9.



Structure_ID	Structure_Type	Span	Inventory_Date	Clearance	Route	Direction	Mile_Post	District_County	Lat_Long	Lat	Long	AADT
01007	CN2	' 10"	6/8/2005	17 ' 2"	IS0068	EAST	42.6	6, Allegany	N 39.6469333333333, W 78.7755333333333	39.6469333333333	-78.7755333333333	51332
01008	CN2	18 ' 6"	6/8/2005	17 ' 1"	IS0068	EAST	42.8	6, Allegany	N 39.6472333333333, W 78.77295	39.6472333333333	-78.77295	3210
01010	CN2	19 ' 5"	6/21/2005	22 ' 7"	IS0068	EAST	43	6, Allegany	N 39.6491, W 78.7677666666666	39.6491	-78.7677666666666	51332
01011	CN2	18 ' "	6/28/2005	18 ' 2"	IS0068	EAST	43.3	6, Allegany	39.6488666666667, -78.7618166666666	39.6488666666667	-78.7618166666666	51332
01012	CN4	38 ' 4"	6/29/2005	18 ' 7"	IS0068	EAST	43.4	6, Allegany	39.6490333333333, -78.7609833333333	39.6490333333333	-78.7609833333333	1874
01013	CN2	31 ' 11"	6/9/2005	19 ' 7"	IS0068	EAST	43.7	6, Allegany	N 39.6498333333333, W 78.7554166666666	39.6498333333333	-78.7554166666666	2284
01014	CN2	31 ' 9"	6/9/2005	20 ' 6"	IS0068	EAST	45	6, Allegany	N 39.665, W 78.7392	39.665	-78.7392	31362

Figure 5.12 - Galloping-influenced Structure Types CN1, CN2, and CN4 (710 in total)



Structure_ID	Structure_Type	Span	Inventory_Date	Clearance	Route	Direction	Mile_Post	District_County	Lat_Long	Lat	Long	AADT
03061	OH1	100 ' "	1/31/2005	19 ' 6"	IS0695	INNER LOOP	1.8	4, Baltimore	N 39.2480833333333, W 76.6767222222222	39.2480833333333	-76.6767222222222	124891
03128	OH2	66 ' 0"	1/22/2013	19 ' 10"	MD0151	NORTH	5.5	4, Baltimore	N 39.2888333333333, W 76.4992777777778	39.2888333333333	-76.4992777777778	16030
03208	OH1	103 ' "	3/13/2005	18 ' 2"	IS0095	SOUTH	3.4	4, Baltimore	N 39.2575555555556, W 76.676	39.2575555555556	-76.676	196745
03209	OH1	102 ' "	3/13/2005	19 ' 4"	IS0095	SOUTH	3.1	4, Baltimore	N 39.2530833333333, W 76.6793055555556	39.2530833333333	-76.6793055555556	7415
03211	OH1	125 ' "	11/20/2006	18 ' 7"	IS0095	NORTH	46.2	4, Baltimore	N 39.22975, W 76.7140555555556	39.22975	-76.7140555555556	180448
03213	OH1	106 ' "	11/20/2006	19 ' 3"	IS0095	NORTH	47.2	4, Baltimore	N 39.2393055555556, W 76.7005833333334	39.2393055555556	-76.7005833333334	186236
03214	OH1	118 ' 0"	2/27/2005	18 ' 8"	IS0095	NORTH	2.4	4, Baltimore	N 39.2471666666667, W 76.6853055555556	39.2471666666667	-76.6853055555556	186236

Figure 5.13 - Galloping-influenced Structure Types OH1 and OH2 (26 in total)

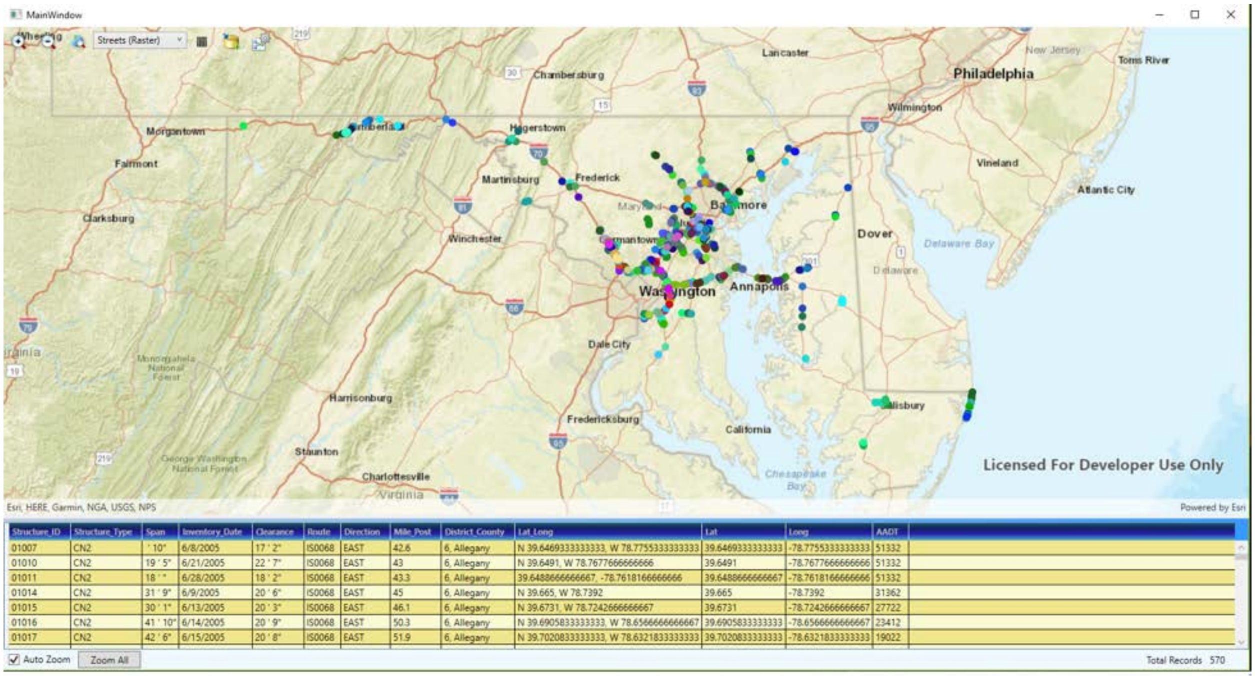


Figure 5.14 - Galloping-influenced Structures in Types CN1, CN2, CN4, OH1, and OH2, AADT over 10,000 (570 in total)

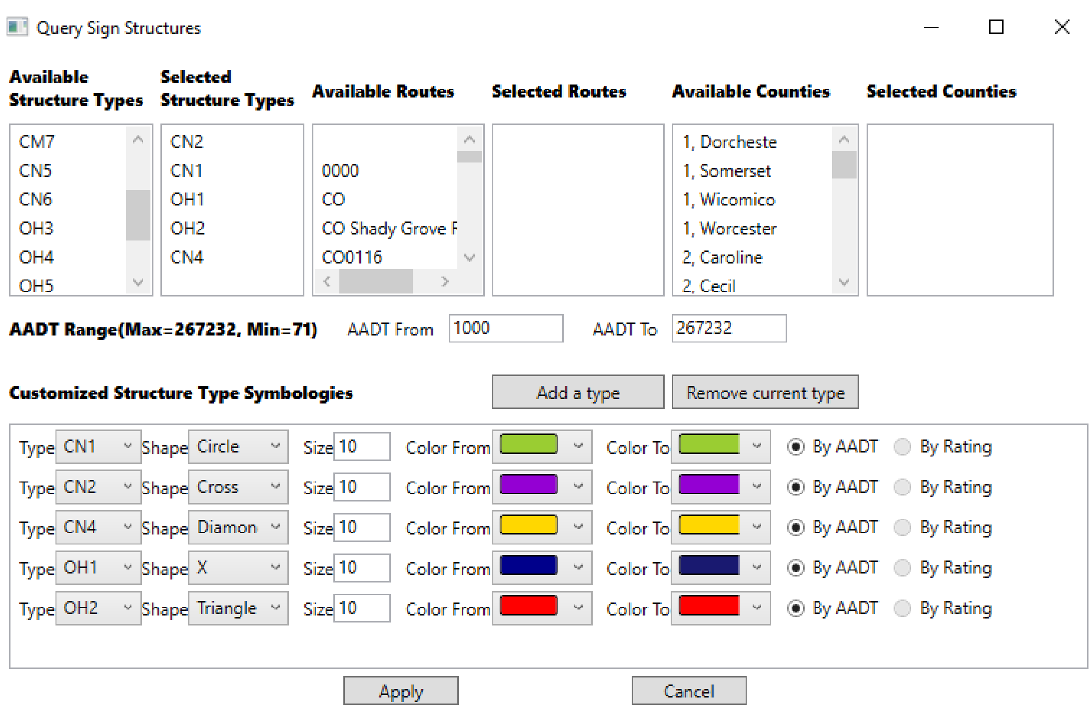
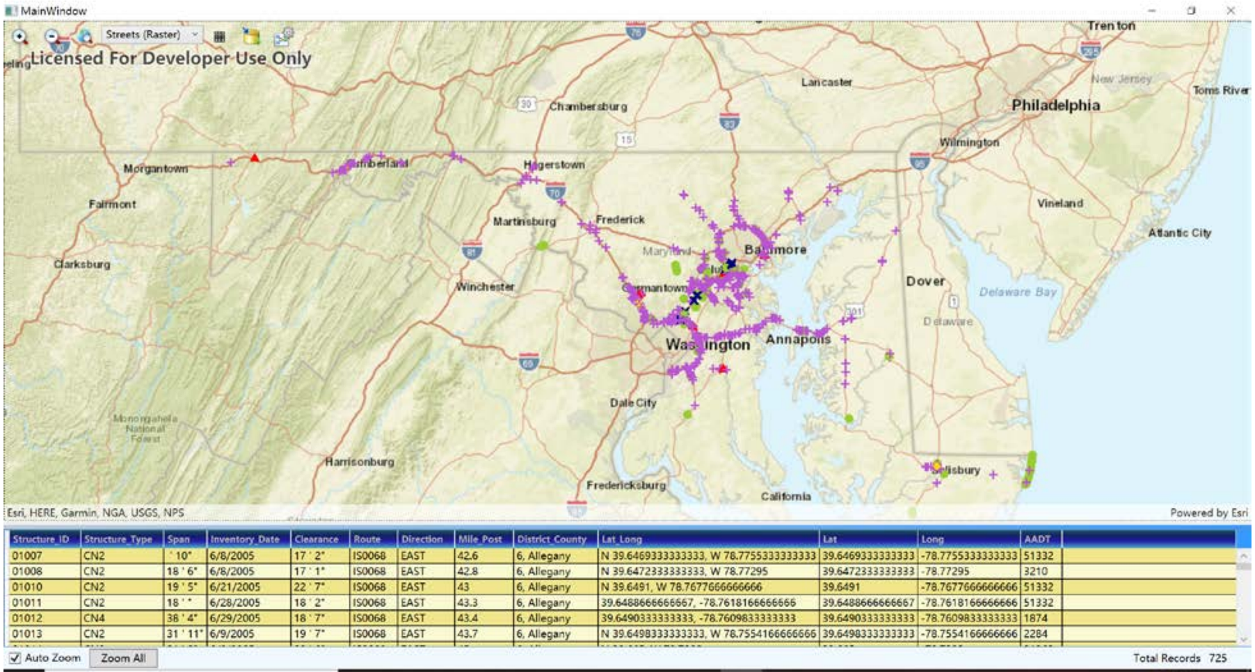


Figure 5.15 - Symbology for Galloping Influenced Structures



Structure_ID	Structure_Type	Span	Inventory_Date	Clearance	Route	Direction	Mile_Post	District_County	Lat_Long	Lat	Long	AADT
01007	CN2	' 10"	6/8/2005	17 ' 2"	IS0068	EAST	42.6	6, Allegany	N 39.6469333333333, W 78.7755333333333	39.6469333333333	-78.7755333333333	51332
01008	CN2	18 ' 6"	6/8/2005	17 ' 1"	IS0068	EAST	42.8	6, Allegany	N 39.6472333333333, W 78.77295	39.6472333333333	-78.77295	3210
01010	CN2	19 ' 5"	6/21/2005	22 ' 7"	IS0068	EAST	43	6, Allegany	N 39.6491, W 78.7677666666666	39.6491	-78.7677666666666	51332
01011	CN2	18 ' "	6/28/2005	18 ' 2"	IS0068	EAST	43.3	6, Allegany	39.6488666666667, -78.7618166666666	39.6488666666667	-78.7618166666666	51332
01012	CN4	38 ' 4"	6/29/2005	18 ' 7"	IS0068	EAST	43.4	6, Allegany	39.6490333333333, -78.7609833333333	39.6490333333333	-78.7609833333333	1874
01013	CN2	31 ' 11"	6/9/2005	19 ' 7"	IS0068	EAST	43.7	6, Allegany	N 39.6498333333333, W 78.7554166666666	39.6498333333333	-78.7554166666666	2284

Figure 5.16 - Galloping-influenced Structures in Types CN1, CN2, CN4, OH1, and OH2, AADT over 1000 (with Symbology; 725 in total)

Based on the evaluation, the tentative factors considered in ranking and prioritizing were:

1. Structure type
2. Structure age (year built)
3. Traffic Volume in AADT
4. Structural analysis results, especially fatigue analysis
5. Structural condition (rating)

Chapter 6 Task 5: Rank and prioritize the whole population based on the evaluation

Two steps were involved in this task to rank and prioritize the sign structures in the MD

6.1 Step 8: Sign structure ranking

This step ranked all MD sign structures based on the evaluation.

Status:

A semi-qualitative method was used to assess the performance of sign structures MD. Four relevant factors, including sign structure analysis result, number of anchor bolts, AADT and sign structure age, were used to evaluate each sign structure.

When evaluating a sign structure based on one factor, a risk rank was given according to its condition data (which can be obtained from database), ranging from 1 to 5. The system, by default, allowed a ranking with 1 as the most and 5 as the least critical conditions by following the TEDD scoring system. This risk ranking system also allowed the Pontis-based health index system used for US bridges where risk rank 1 meant the least dangerous while risk rank 5 meant the most dangerous.

To obtain the risk rank in the structural analysis factor, the MDOT SHA (TSIIM database was studied and then grouped and analyzed by the (SABRE software as a preliminary calculation. Then, the rank in each factor was assigned to a certain weight to obtain the final rank score. The ranking process of the CN2 type structure is demonstrated in this report. Fig. 6.1 shows the relevant factors that affect the CN2 type sign ranking system and their weights, respectively.

Figure 6.17 - Ranking system structure (CN2) breakdown

MDOT SHA categorized sign structures into 19 types for a total 2,186 sign structures where CN2 is designated as double box-type cantilever structure. Inspired by the Sign/Luminaire Standard Drawing MD 803.08 released in 2002, 527 round tube CN2 structures were summarized into 20 groups with their respective typical samples according to the distribution of span lengths and post sizes. Then, these 20 samples were modeled and analyzed by the SABRE program and their Combined Stress Ratio (CSR) of posts and arms, as well as their fatigue stress ranges of galloping, natural wind gust and truck induced gust were obtained. Since the arm information was not available in the database, the CSR of the arm was omitted in the structural ranking. The fatigue stress range due to galloping was considered as the most critical and used to rank fatigue risk. For OH6 type structures, the galloping fatigue was no longer considered in the AASHTO specification, the fatigue risk rank for all items in this category were given the “Least dangerous” score of 5. Next, the results were sorted from low to high and assigned a risk rank score from 5 to 1 accordingly, as shown in Table 6.1.

Table 6.4 - CN2 Structure ranking

Span	Post		Max CSR	Fatigue stress limit (ksi)	CSR Risk Rank	Fatigue Risk Rank
ft	Dia (in)	thk (in)	Pole	Galloping		
25	16	0.313	1.009	11.94	1	2
	18	0.438	0.529	6.8	4	4
	20	0.500	0.371	4.86	5	5
	24	0.438	0.288	3.91	5	5
	25	0.500	0.228	3.15	5	5
30	18	0.438	0.594	8.27	3	3
	20	0.500	0.499	6.73	4	4
	24	0.438	0.451	6.5	4	4
	25	0.500	0.408	6.18	5	5
35	16	0.313	1.072	9.78	1	2
	18	0.438	0.809	9.64	2	2
	20	0.500	0.752	9.84	3	2
	24	0.438	0.616	8.52	3	3
	25	0.500	0.569	7.74	4	4
	26	0.531	0.761	8.56	3	3
50	18	0.500	0.776	8.72	2	3
	20	0.500	1.156	18.95	1	1
	24	0.438	0.991	13.46	2	1
	25	0.500	0.999	14.32	1	1
	26	0.531	0.846	12.27	2	1

The research used inventory number 01021 from TSIIM database as example and took the following steps.

1) Collect span/post information, determine its structure ranking. R1: CSR=1, Fatigue=2
2) Collect number of anchor bolts, determine its bolt ranking. R2=5
3) Collect traffic information, determine its AADT ranking. R3=3
4) Use construct year, determine its age ranking. R4=4
5) Combine the final structural ranking using different weight for each rank type. R=**3.1**

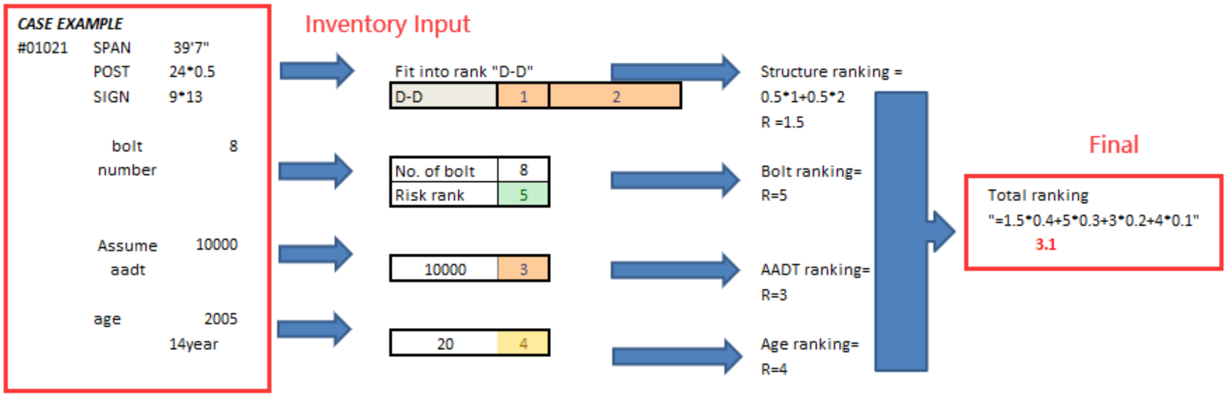


Figure 6.18 - Process flow chart

Based on this approach, the entire MDOT SHA sign structure inventory was ranked. Every item had its overall ranking score for management decision making. Additionally, an automated ranking program was developed for CN2 and OH6 type sign structures in case of future data updates. The results of previous UT tests are also implemented in the automated ranking program. Those structures failed the UT test will be rank as “Critical” with a score of 1.0 (TEDD system) in the final ranking summary.

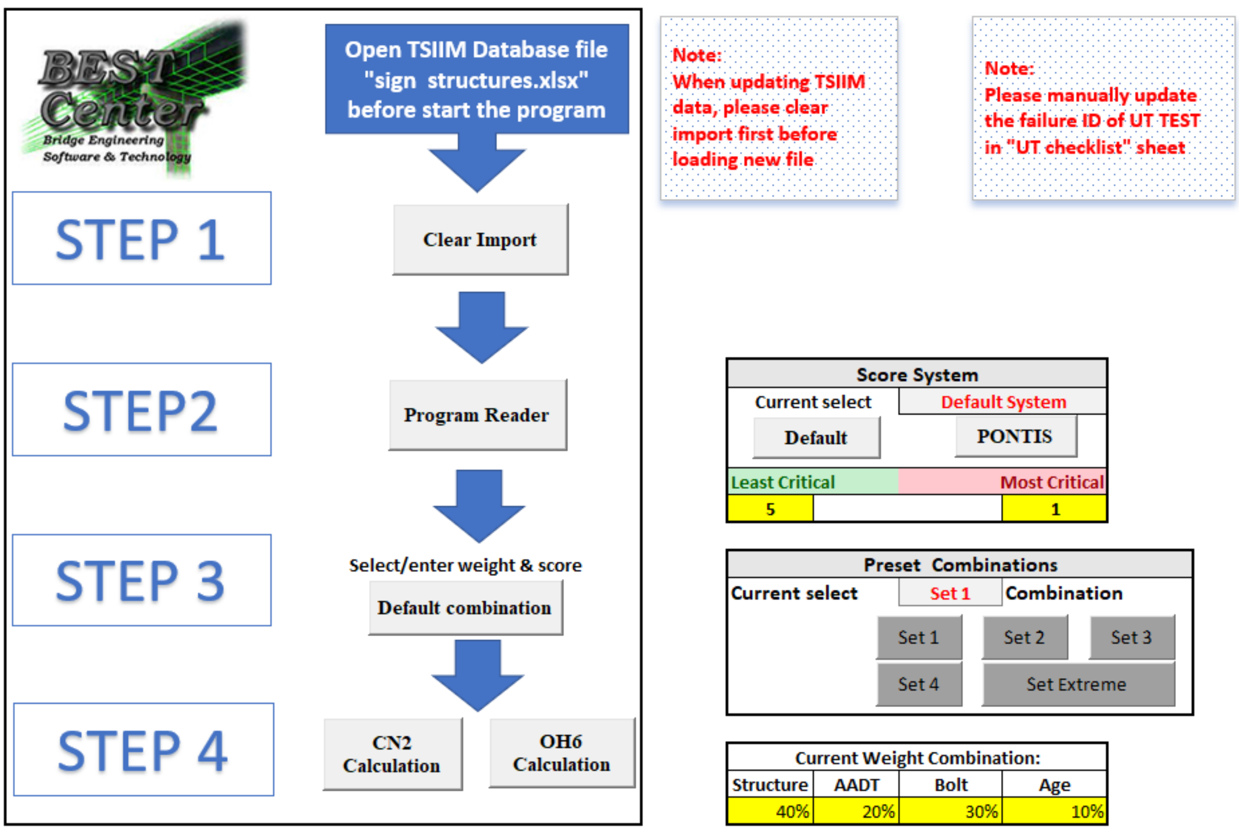


Figure 6.19 - Automated sign structure ranking program

6.2 Step 9: Prioritizing

This step prioritized all MD sign structures based on budget and risk.

Status:

Alternative analysis

An analytical performance-based reliability assessment was conducted to calculate the reliability of the MD sign structure system. The reliability of an engineering system can be defined as the ability to fulfill its design purposes defined as performance requirements for certain time period and environmental conditions (Ayyub, 2014).

Different types of signs have different force analysis, so the reliability analysis was conducted in the same manner. The analyses of types CN2 and OH6 were conducted in this study. The flow chart of MATLAB (version R2018a) code is attached in Appendix D. The Monte Carlo (MC) simulation, a widely used method in reliability analysis, was used in this study.

In the MC simulation, samples of the basic correlated variables were randomly drawn according to their corresponding probabilistic characteristics and fed into the performance function, which in this study is expressed as Eq. 1 and Eq. 2 for Combined Stress Ratio (CSR) and fatigue load induced stress range σ_f, respectively:

$$CSR < 1.0 \quad (1)$$

$$\sigma_f < 7.0ksi \quad (2)$$

The failure event happens when it reaches one of the two criteria, $CSR > 1.0$ or $\sigma_f > 7.0ksi$. Therefore, the probability of failure and reliability can be expressed as:

$$\overline{P_f} = P(CSR > 1.0 \ or \ \sigma_f > 7.0) = \frac{N_f}{N} \quad (3)$$

$$\overline{R} = 1 - \overline{P_f} \quad (4)$$

Where N_f is the number of simulation cycles for which the failure event happens in total N cycles of a simulation. According to the law of large numbers, the probability of failure approaches the true value when N approaches infinity.

Performance function

In this study, span length, height, sign area and the moment of inertia were selected as the variables in the MC simulation.

The most possible used CSR and fatigue load induced stress range were calculated based on the AASHTO code of Structural Supports for Highway Signs, Luminaries, and Traffic Signals (2013).

- For the cantilever type CN2, the equations are:

$$CSR[I(S),S,L,A] = \frac{f_a}{0.6F_y} + \frac{f_b}{C_A F_b} + \left(\frac{f_v}{F_v}\right)^2 \tag{5}$$

$$\sigma_f[I(S),S,L,A] = \frac{Max(M_G, M_{WG}, M_{TG})y}{I} \tag{6}$$

Where *I* is the moment of inertia; *S* is the span length; and *L* is the height of the post; *A* is the area of the sign panel. Among the four variables, *S, L*, and *A* are independent random variables based on the 571 samples, while I is the conditional random variables related to the span length range (grouped by $S \le 25\text{ft}$, $25\text{ft} < S \le 30\text{ft}$, $30\text{ft} < S \le 35\text{ft}$, and $35\text{ft} < S \le 50\text{ft}$). f_a, f_b, f_v are the axial, bending and shear stresses based on random variables; M_G, M_{WG}, M_{TG} are the moment ranges induced by galloping, wind gust and truck gust fatigue loads on random variables *I(S), S, L*, and *A*. C_A is the coefficient of amplification to estimate the second order effects (AASHTO 2016), and *y* is the perpendicular distance from the neutral axis to a point on the cross section, which is equal to the radius of the tube in this case.

- For the overhead type OH6, the equations are:

$$CSR[I(S),S,L] = \frac{f_a}{0.6F_y} + \frac{f_b}{F_b} + \left(\frac{f_v}{F_v}\right)^2 \tag{7}$$

$$\sigma_f[I(S),S,L] = \frac{Max(M_{WG}, M_{TG})y}{I} \tag{8}$$

Where *I* is the moment of inertia; *S* is the span length; and *L* is the height of the post. *S* and *L* are independent random variables based on the 998 samples, while *I* is the conditional random variable related to the span length range (grouped by $S \le 65\text{ft}$, $65\text{ft} < S \le 100\text{ft}$, and $100\text{ft} < S$). f_a, f_b, and f_v are the axial, bending and shear stresses based on random variables; for box truss, the galloping effect was not considered. M_{WG} and M_{TG} are the moment ranges induced by wind gust and truck gust fatigue loads on random variables *I(S*), *S*, and *L*. *y* is the perpendicular distance from the neutral axis to a point on the cross section, which is equal to the radius of the tube in this case.

Probability distribution of variables

The probability of variables was based on the bar charts, which were generated from the database. Mean values and standard deviations were based on the samples of the cantilever planar (CN2) and overhead box (OH6) sign structures, respectively. The probability density function (PDF) of the variables were generated through MATLAB, and their fitted distribution curves are obtained.

- Cantilever type CN2

The span length S, height L, and part of the moment of inertia I (when $S \leq 25\text{ft}$ and $25\text{ft} < S \leq 30\text{ft}$) were assumed to follow the normal distribution, while the sign area A and I (when $30 < S \leq 35\text{ft}$ and $35 < S \leq 50\text{ft}$) followed the lognormal distribution. The density and fitted curve of height L and sign area A are shown in Figs. 6.4 and 6.5 as examples. All the other distribution figures can be found in the Appendix D.

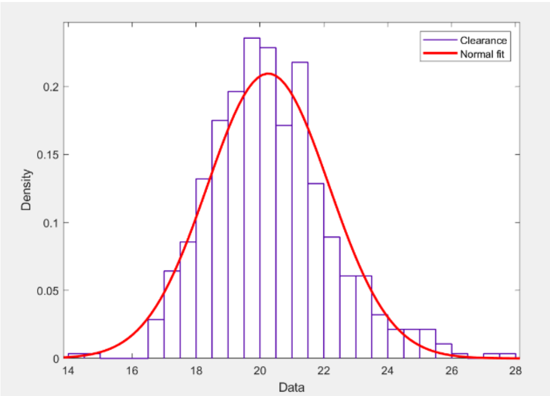


Figure 6.20 - CN2 Height L PDF and normal fitted curve

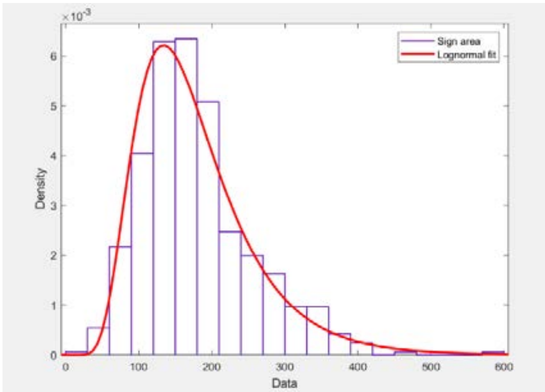


Figure 6.21-CN2 Sign area A PDF and Lognormal fitted curve

The mean values and standard deviations for each variable could be summarized based on the data of 559 samples, as listed in Table 6.2.

Table 6.5 - Probability distribution of variables for group CN2

Variable	Units	Type	Mean	Variance
S	Ft	Normal	29.58	7.95
L	Ft	Normal	20.26	1.90
A	ft^2	Lognormal	178.11	81.44
I($S \leq$25ft)	in^4	Lognormal	1065.50	967.70
I(25ft< $S \leq$30ft)	in^4	Lognormal	1498.05	908.92
I(30ft< $S \leq$35ft)	in^4	Normal	1938.90	792.81
I(35ft< $S \leq$50ft)	in^4	Normal	2208.37	722.64

- Overhead type OH6

In the OH6 group, the span length S and the height L were assumed to follow the normal and lognormal distribution, respectively. Moment of inertia I (when $S \leq 65\text{ft}$ and $100\text{ft} < S$) were assumed to follow the lognormal distribution, while I ($65\text{ft} < S \leq 100\text{ft}$) followed a bimodal distribution . The density and fitted curve of height L and sign area A are shown in Figs. 6.6 and 6.7 as examples. All the other distribution figures can be found in Appendix D.

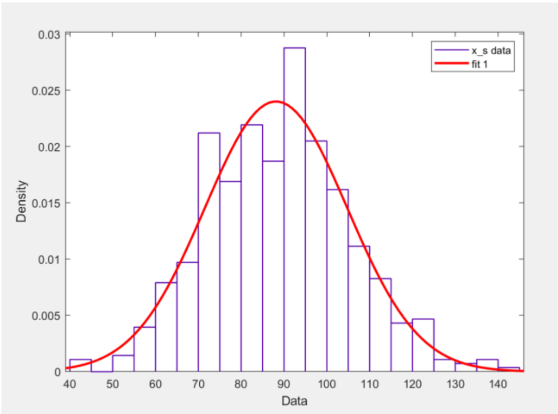


Figure 6.22 - OH6 Span length S PDF and normal fitted curve

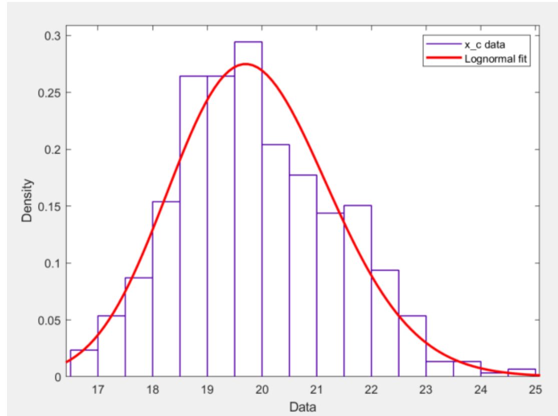


Figure 6.23 - OH6 Height L PDF and Lognormal fitted curve

The mean values and standard deviations for each variable of the 998 samples are summarized, as listed in Table 6.3.

Table 6.6- Probability distribution of variables for group OH6

Variable	Units	Type	Mean	Variance
S	Ft	Normal	88.14	275.788
L	Ft	Lognormal	19.86	2.13
I($S \leq$65ft)	in^4	Lognormal	358.84	120962
I(65ft < $S \leq$100ft)	in^4	Bimodal	/	/
I(100ft< S)	in^4	Lognormal	630.64	149562

Monte-Carlo simulation

After the determination of performance function as well as the probability of distribution for variables, quantities of groups of variables were drawn based on the assumed distribution. Then, based on the failure numbers N_f according to Eq. 3 and Eq. 4, it was:

$$\overline{R} = 1 - \frac{N_f}{10^5} \tag{9}$$

Where $\overline{R}$ is the reliability of the whole sign structure system.

Results comparison

The results of reliability analysis of CN2 and OH6 were compared with the ones of risk ranking. For CN2 in Table 6.4, the CSR failure probability was 19.0%, and the fatigue stress probability was 51.0%. Since it is presumed that either failed in CSR or fatigue stress may cause the structure fail, the total failure probability of the sign structure system was 51.0%. The risk ranking results were used to compare with the failure probabilities here. The ratio of structures in CSR risk rank 1 to the whole structure inventory was compared with the CSR failure probability; the ratio of structures in fatigue stress risk rank 1,2 and 3 to the whole structure inventory was compared with the fatigue stress failure probability. For OH6 in Table 6.5, both reliability analysis and risk ranking results showed that the performance of the box truss sign structure was very safe. Under the code criterion (CSR>1, fatigue stress>7 ksi), the failure probability was quite low. The ratio of CSR>0.726, which meant that the structures were in CSR risk rank 1, 2 and 3, were compared to check the consistency of the two methods. The results were close, and the errors were acceptable.

Table 6.7 - Comparison of the failure probabilities of two methods-CN2

	Reliability analysis	Risk ranking	Errors
CSR	19.0%	21.95%	2.95%
Fatigue Stress	51.0%	55.3%	4.3%

Table 6.8 - Comparison of the results of two methods-OH6

	Reliability analysis		Risk ranking	Errors
CSR	Failure PR.	0%	0%	0%
	CSR>0.726	1.31%	1.40%	0.09%
Fatigue Stress	Failure PR.	0%	0%	0%

Chapter 7 Task 6: Summary and Report

This task involved one step.

7.1 Step 10: Summary

This step summarized and drew the conclusion of the study.

Status:

The purpose of the project was to conduct a structural assessment of MD sign structures due to the change of the AASHTO LTS-6 strength and fatigue criteria.

In this study, the MD sign structure database was studied and summarized. A preliminary risk assessment and classification of the structure was given first according to the galloping fatigue. Based on the team’s research, galloping was the most critical fatigue load of all three types of fatigue loads, and 5 (CN1, 2, & 4 and OH1 & 2) out of 19 types were galloping-influenced structures. Those structures were left for careful assessment and prioritizing. Also, the remaining types of structures were sampled and modeled and proved that those overhead structures were not critical and could be waived for further analysis.

For the galloping-influenced sign structures, a semi-qualitative method was used to assess the performance. Four relevant factors, including a sign structure analysis result, number of anchor bolts, AADT, and sign structure age, were used to evaluate each sign structure. The default risk rank ranged from 1 to 5, which designated 1 as the most dangerous while 5 indicated the least dangerous by following the TEDD scoring system. An automated ranking program was developed for CN2 and OH6 type sign structures in case of future data updates. Moreover, an alternative analysis, an analytical performance-based reliability assessment was performed to calculate the reliability of the sign structure in types CN2 and OH6. The results of fail probabilities matched the ratio of high-risk structures in risk ranking program.

With this risk ranking method, all existing MD sign structures could be ranked and sorted. It helped to understand the current condition of the sign structure system under the new standards and provided guidance for maintenance and management.

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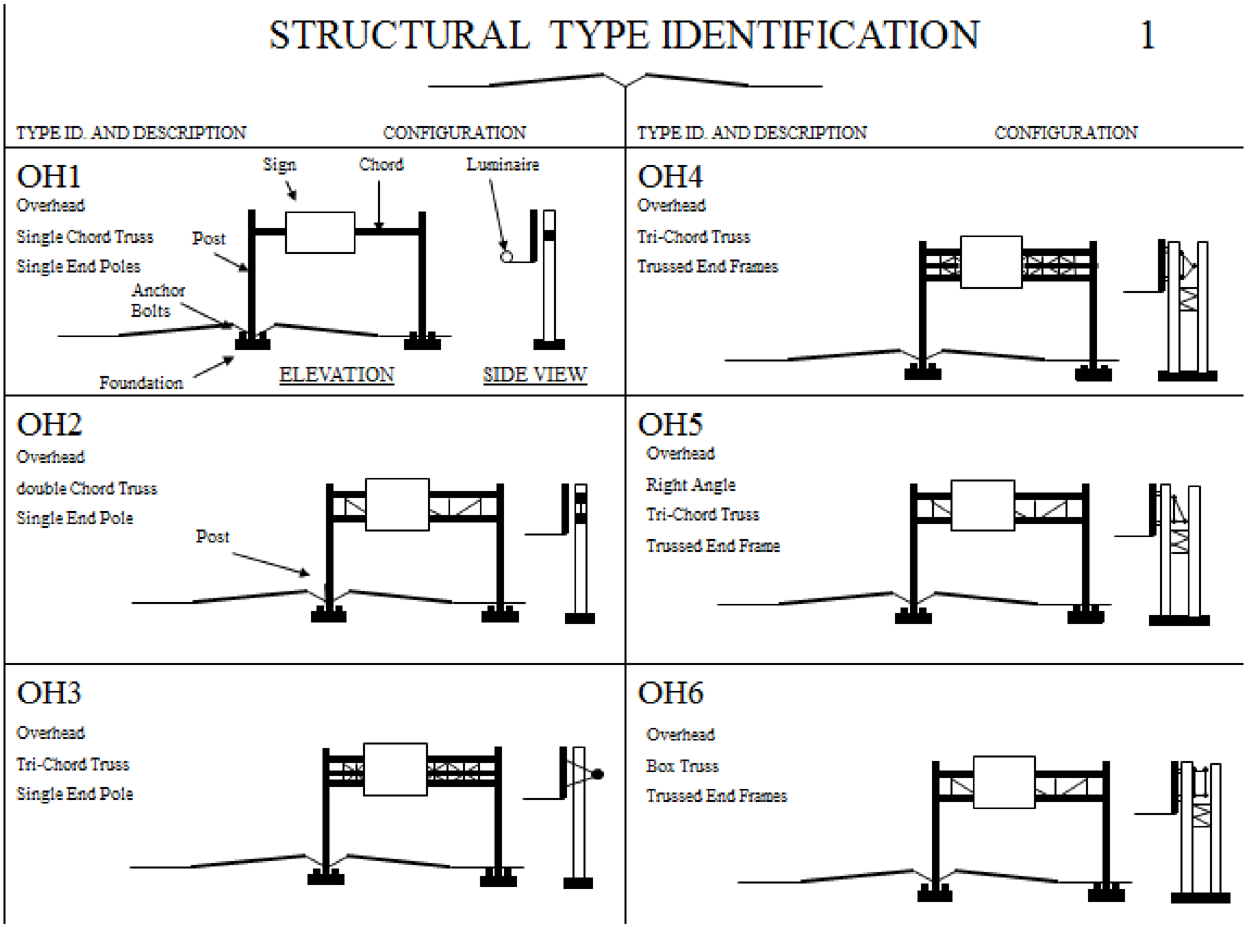
Roda, A., Najm, H., Choi, H., (2015), “Fatigue Study on Structural Supports for Luminaries, Traffic Signals, Highway Signs,” CAIT/Rutgers, NJDOT report

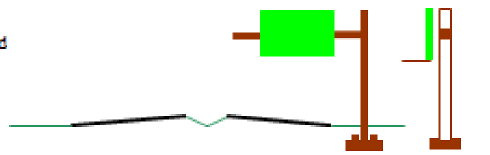
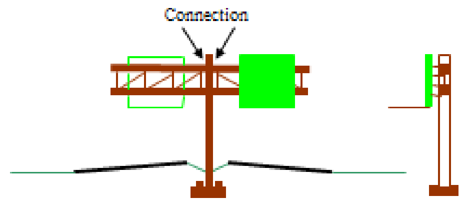
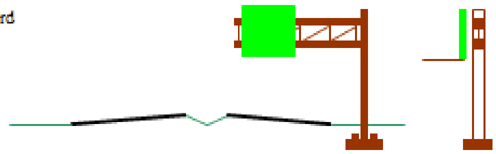
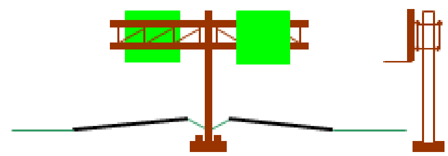
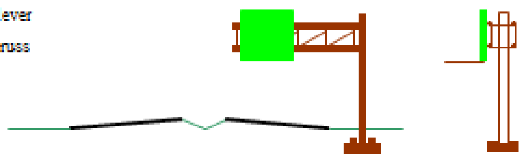
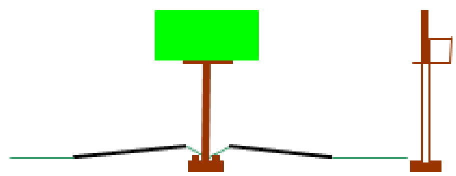
Roy, S., Park, Y.C., Sause, R., Fisher, J.W. and Kaufmann, E.J. (2011), Cost-effective connection details for highway sign, luminaire, and traffic signal structures, Transportation Research Board. National Cooperative Highway Research Program (NCHRP) Web-Only Document 176.

Appendix

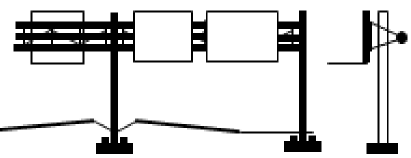
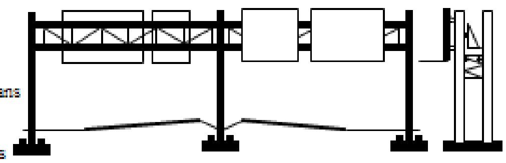
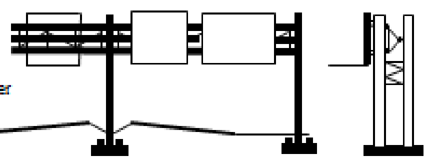
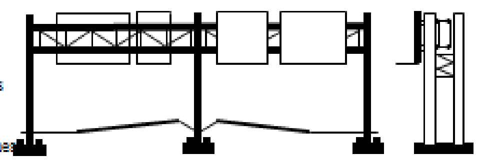
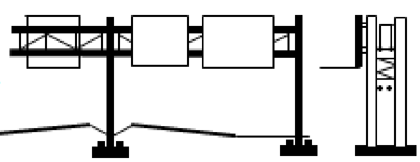
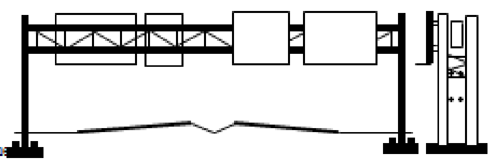
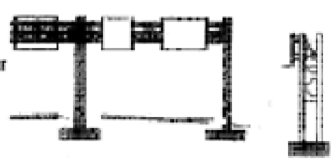
1.1 Appendix A – MD Structural Type Identification



STRUCTURAL TYPE IDENTIFICATION 2

TYPE ID. AND DESCRIPTION	CONFIGURATION	TYPE ID. AND DESCRIPTION	CONFIGURATION
CN1 Cantilever Single Chord		CN4 Cantilever Butterfly Double Chord	
CN2 Cantilever Double Chord		CN5 Cantilever Butterfly Box Truss	
CN3 Cantilever Box Truss		CN6 Pedestal DMS	

STRUCTURAL TYPE IDENTIFICATION 3

TYPE ID. AND DESCRIPTION	CONFIGURATION	TYPE ID. AND DESCRIPTION	CONFIGURATION
CM1 Combined Single Span & Cantilever Tri-Chord Truss Single End Pole		**CM4** Combined Two Single Spans Right Angle Tri-Chord Truss Trussed End Frames	
CM2 Combined Single Span & Cantilever Tri-Chord Truss Trussed End Frame		**CM5** Combined Two Single Spans Box Truss Trussed End Frames	
CM3 Combined Single Span & Cantilever Box Truss Trussed End Frame		**CM6** Combined Single Span Box Truss Trussed End Frames Over Two Way Traffic	
CM 7 Combined Single Span & Cantilever Right Angle Tri-Chord Truss Trussed End Frames			

1.2 Appendix B – Verification of SABRE Fatigue Analysis using Reports and STAAD

Example 1 – Planal cantilever sign structure (NJDOT Report Chapter 8 Example 1)

Results are very close after correct the errors shown in the report

Example I	(Fatigue II)	Sabre	Report	STAAD
Joint load (kips)	**Gallop**	**7.056**	**7.056**	**7.056**
	Natural wind total	**3.761**	**3.2551***	**3.237***
	sign	2.534	2.545	2.544
	chord	0.703	0.17	0.17
	column	0.525	0.5401	0.522
	Truck.W	**0.408**	**0.271**	**0.271**
	TW sign	0.134	0.134	0.134
	TW chord	0.274	0.137**	0.137**
Moment (K-ft)	Gallop	169.9	169	169.3
	Natural.W	63.6	57.65	61.1
	Truck.W	13.92	8.87	9.21

*The NJDOT report misused the sign C_d as 1.7, which should be C_d=1.2. Corrected result is listed in the table

**The NJDOT report misused the chord C_d as 1.1 and applied to the full arm.

Correct calculation should pick Cd as 0.45 and applied to the last 12ft of the arm. Corrected result is listed in the table.

Example 2 - Signal pole structure (NCHRP Report 796, Appendix C, Example 2.)

Results are very close among SABRE, Repot and STAAD

EX-2	(Fatigue II)	Sabre	Report	STAAD
Joint Load (kips)	**Wind Load Strength Total**	**3.378**	**3.28**	**3.287**
	Sign	-	2.311	2.326
	Pole and Arm	-	0.969	0.961
	Gallop Total	**0.89**	**0.852**	**0.852**
	Sign	0.89	0.852	0.852
	Pole and Arm	-	-	-
	Natural wind Total	**0.781**	**0.78**	**0.758**
	Sign	0.393	0.404	0.389
	Pole and Arm	0.388	0.376	0.369
	Truck induced Total	**0.106**	**0.1**	**0.105**
	Sign	0.042	0.0385	0.038
	Pole and Arm	0.064	0.0615	0.067

Example 3 – Cantilever monotube sign structure (NCHRP Report 796, Appendix C, Example 9.)

Results are very close among SABRE, Repot and STAAD

EX-9	(Fatigue I)	Sabre	Report	STAAD
Joint Load (kips)	**Wind Load Strength Total**	**8.157**	**8.833**	**8.849**
	Sign	-	7.32	7.397
	Pole and Arm	-	1.513	1.452
	Natural wind Total	**1.72**	**1.491**	**1.497**
	Sign	1.192	1.188	1.188
	Pole and Arm	0.528	0.303	0.309
	Truck induced Total	**1.286**	**1.288**	**1.58**
	Sign	1.083	1.085	1.085
	Pole and Arm	0.203	0.203	0.202

EX-9	(Fatigue I)	Sabre	Report	STAAD
Moment (K-ft)	**Wind Load Strength Total (bending)**	**157.93**	**148.21**	**158.918**
	Sign	-	146	147.947
	Pole and Arm	-	2.21	10.971
	Wind Load Strength Total (torsion)	**135.72**	**138.63**	**135.753**
	Sign	-	132	133.152
	Pole and Arm	-	6.63	2.601
	Natural wind Total	**31.57**	**29.8**	**27.504**
	Sign	23.84	23.8	23.8
	Pole and Arm	7.73	6.05	6.05
	Truck induced Total	**30.806**	**30.912**	**30.896**
	Sign	-	26.04	26.035
	Pole and Arm	-	4.872	4.861

Example 4 – HMLT structure (NCHRP Report 718, Example 1.)

Results are very close among SABRE, Repot and STAAD

HMLT	(Fatigue II)	Sabre	Report	STAAD
Joint Load (kips)	**Total**	**0.628**	**0.622**	**0.632**
	Sign	0.091	0.093	0.093
	Pole	0.537	0.529	0.539
Bending moment (K-ft)	Base	**27.59**	**25.4**	**25.83**

1.3 Appendix C – Discussion of Fatigue Details and Stress Limit

Five runs of C-35-30-f, C-34-e, C40-34-e, C45-32-f and C-45-34-a were made with low stresses due to natural wind fatigue stress analyses. Following is the discussion of setting stress limits.

The fatigue details Table 11.9.3.1 in new code LTS-6 and LTS-LRFD follows the NCHRP Web-Only Document 176 (2011), which detected no fatigue crack under the stress 2.6 ksi for main members. Also, on page 171 of the NCHRP Web-Only Document 176 (2011), it states "The stiffened fillet-welded tube-to-transverse plate connections in the test geometry exhibited a lower bound fatigue resistance exceeding AASHTO Category E. These specimens developed fatigue cracking at the stiffener-to-tube weld on the tube at the termination of the stiffener, where the predicted fatigue resistance was AASHTO Category E'. The predicted fatigue resistance against crack growth at the tube -to-transverse plate weld toe on the tube at the pole base was greater than AASHTO Category E'."

Two figures in the NCHRP Web-Only Document 176 (2011) are attached here. In actuality, the lowest category in the experiment fell in the rage of category D, with stress limit 7 ksi. 2.6 ksi is a conservative value for a stiffened connection.

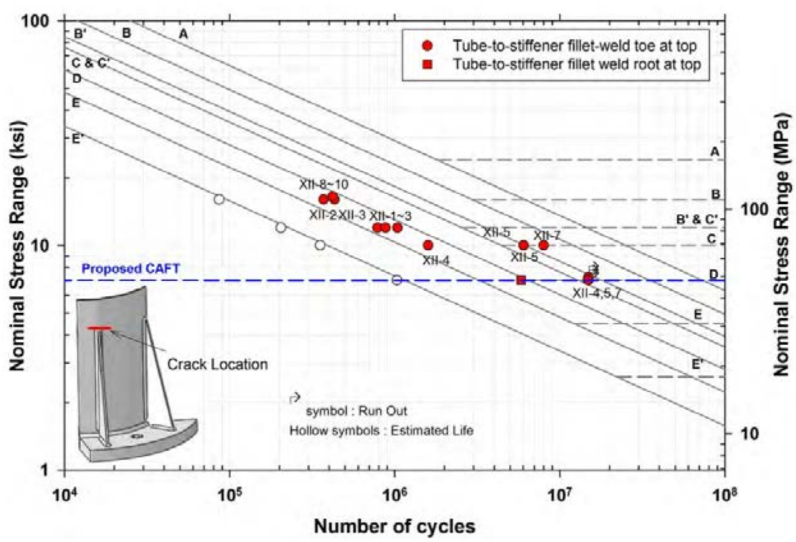


Figure 130 Fatigue test results for specimen Type XII at stiffener top

(Ref. NCHRP Web-Only Document 176 (2011))

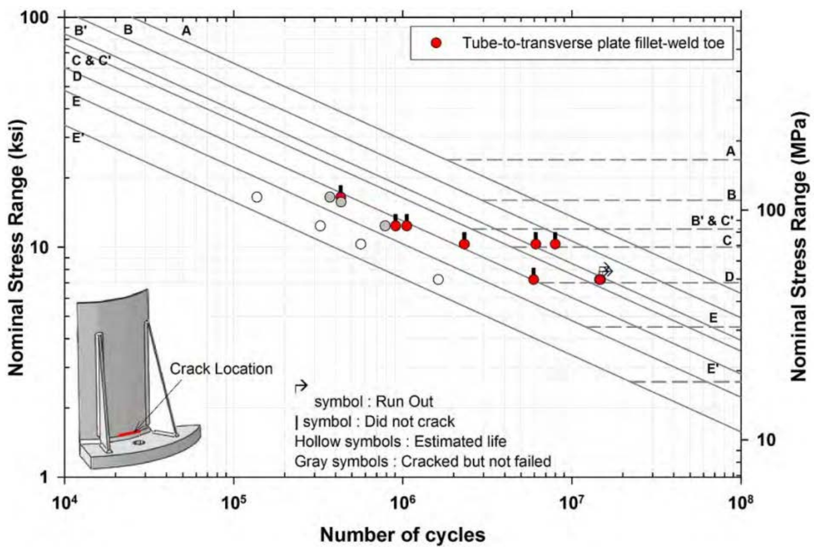


Figure 131 Fatigue test results for specimen Type XII at pole base

(Ref. NCHRP Web-Only Document 176 (2011))

The old code (LTS-5) also stated that the stiffened filled-weld tube-to-transvers plate connection takes the Category E', which has the fatigue limits 2.6. Please see the following table in LTS-5:

Fillet-Welded Connections	13. Fillet-welded lap splices.	*E*	Column or mast arm lap splices.	3
	14. Members with axial and bending loads with fillet-welded end connections without notches perpendicular to the applied stress. Welds distributed around the axis of the member so as to balance weld stresses.	*E*	Angle-to-gusset connections with welds terminated short of plate edge. Slotted tube-to-gusset connections with coped holes (see note e).	2, 6
	15. Members with axial and bending loads with fillet-welded end connections with notches perpendicular to the applied stress. Welds distributed around the axis of the member so as to balance weld stresses.	*E'*	Angle-to-gusset connections. Slotted tube-to-gusset connections without coped holes.	2, 6
	16. Fillet-welded tube-to-transverse plate connections (see note j).	*E'*	Column-to-base-plate or mast-arm-to-flange-plate socket connections.	7, 8, 16
	17. Fillet-welded connections with one-sided welds normal to the direction of the applied stress.	*E'*	Built-up box mast-arm-to-column connections.	8, 16
	18. Fillet-welded mast-arm-to-column pass-through connections.	*E'* (See note f)	Mast-arm-to-column pass-through connections.	9

By combining the statements in the new and old codes, it is reasonable to take the fatigue stress limit as 2.6 ksi (Category E') for the member with concentration factor KI out of the ranges in Table 11.9.3.1.

1.4 Appendix D – Alternative Analysis Details

- Alternative analysis (reliability analysis) flow chart

The flow chart of MATLAB code for CN2 is shown below. The calculation steps for OH6 are similar, only the distributions and equations are different, which is stated in a previous section.

Some parameters used in the calculation are listed here.

F_y=52ksi, E=29000ksi, γ_{steel}=490lb/ft^3, $\lambda_p = 0.13\frac{E}{F_y}$, $t_{post} = 0.4in$

N=100000, N: the number of MC simulation

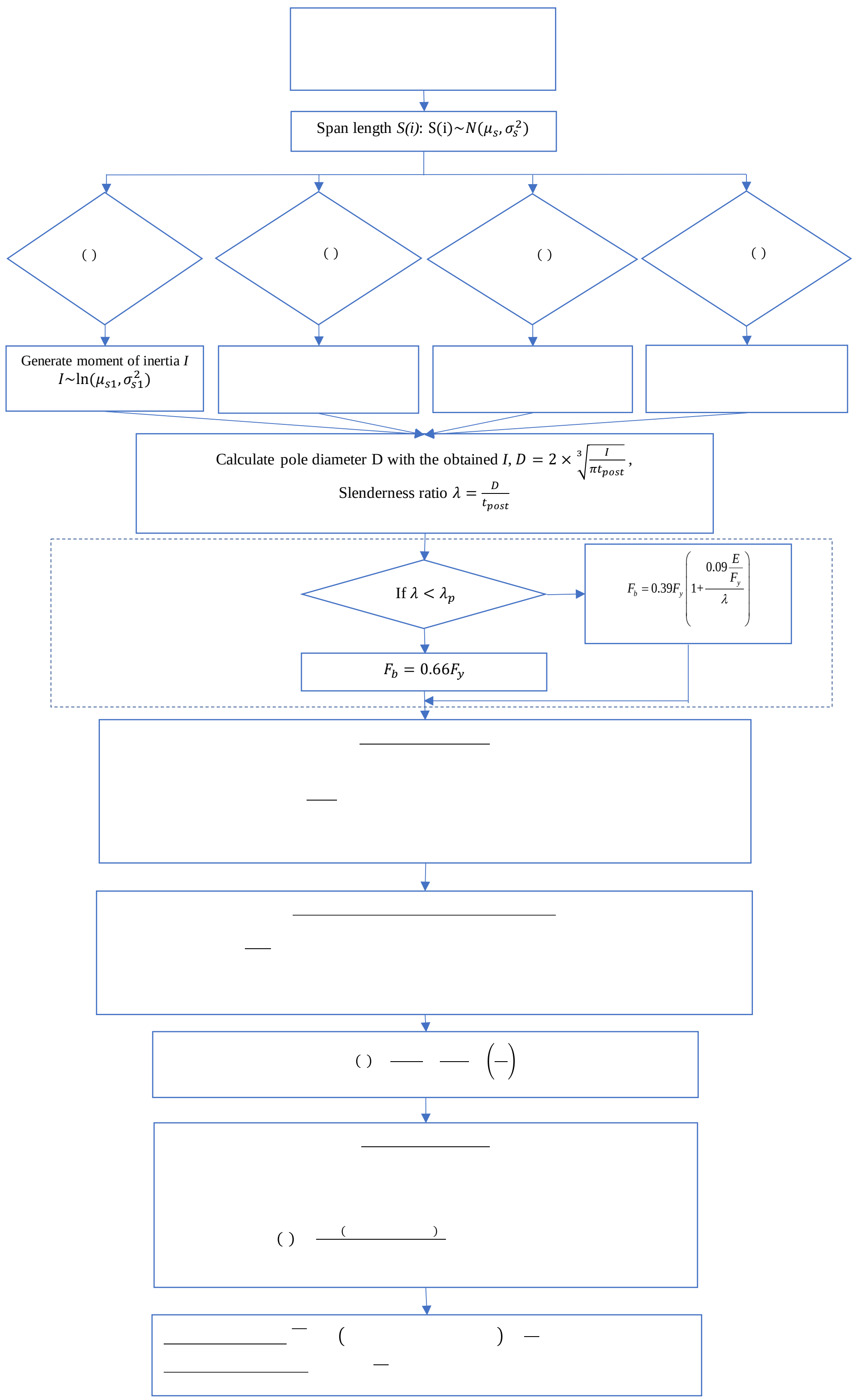
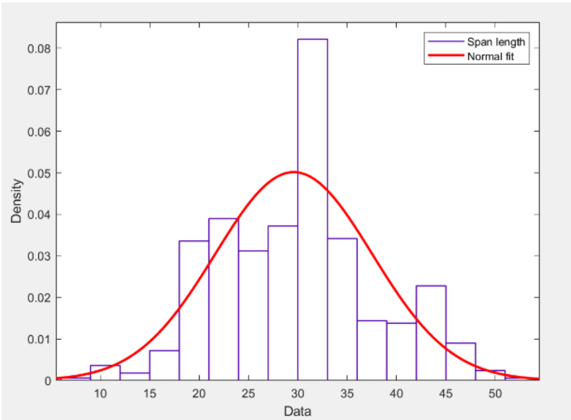
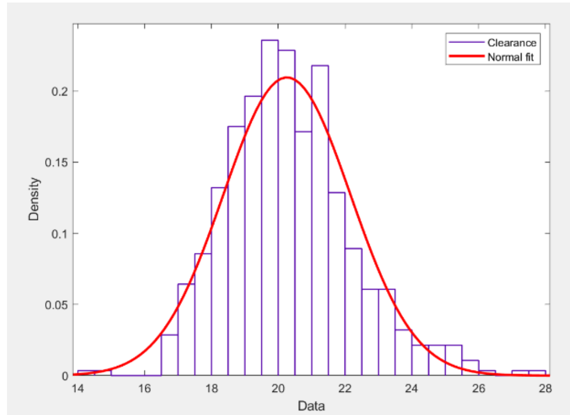


Figure A.1- Reliability analysis flow chart

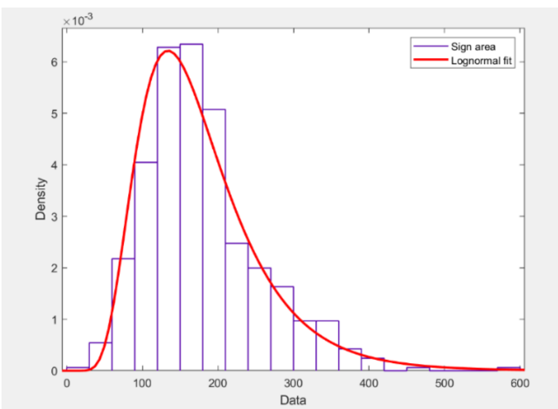
- PDF distributions and fitted curves of the variables of CN2:



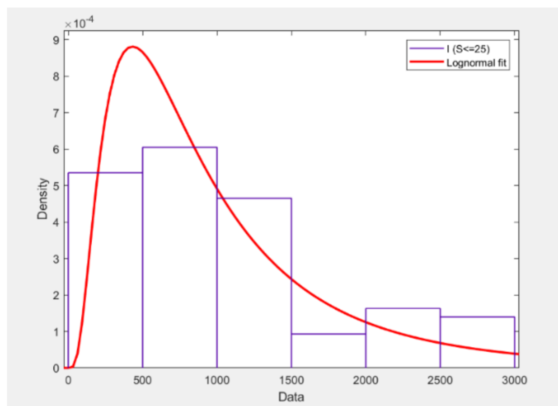
(a) Span length S PDF and fitted curve



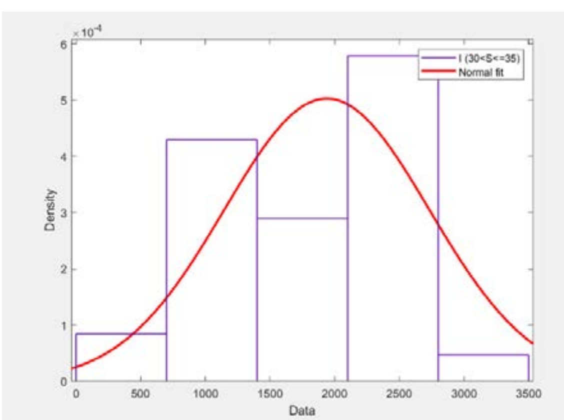
(b) Height L PDF and fitted curve



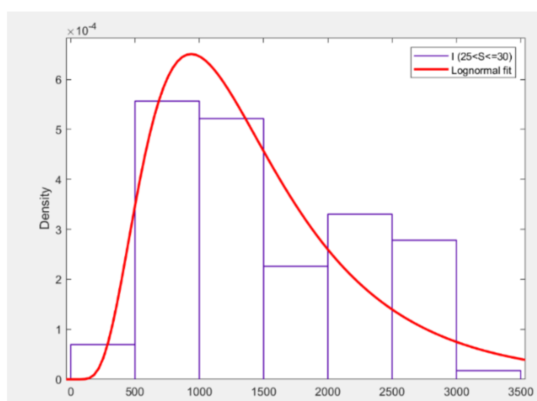
(c) Sign area A PDF and fitted curve



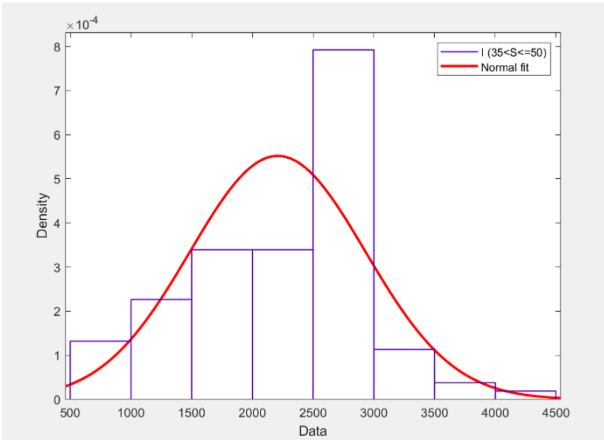
(d) I ($S \le 25$ft) PDF and fitted curve



(e) I (25ft $< S \le$ 30ft) PDF and fitted curve



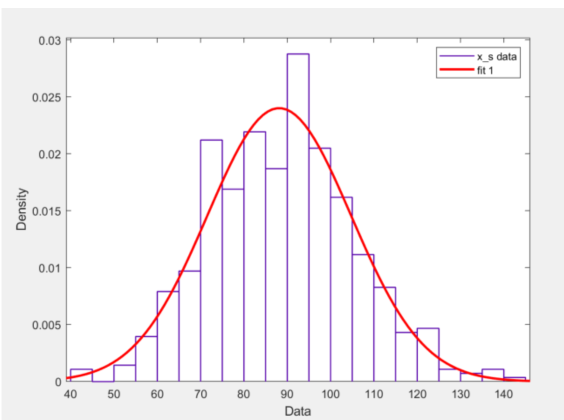
(f) I (30ft $< S \le$ 35ft) PDF and fitted curve

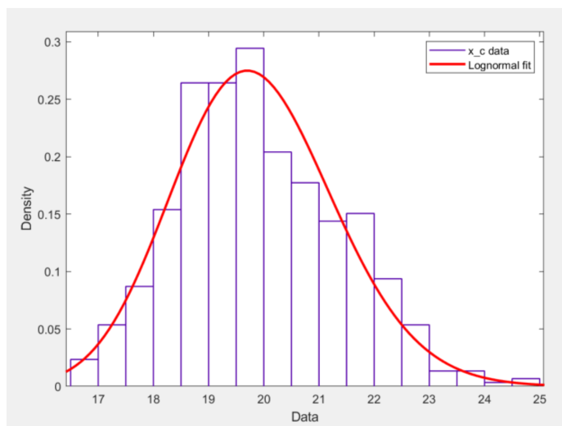


(g) I (35ft $< s \le$ 50ft) PDF and fitted curve

Figure A.2- PDF and fitted curves of variables of CN2

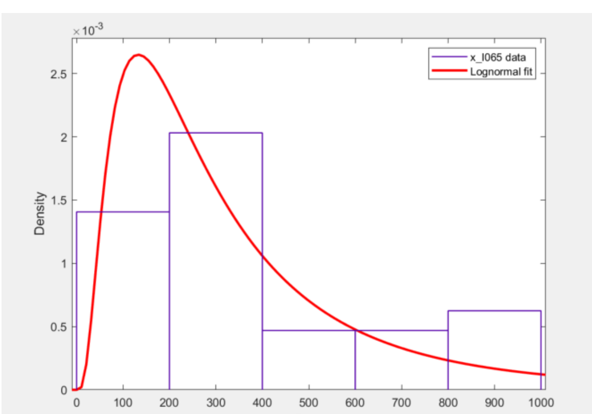
- PDF distributions and fitted curves of the variables of OH6:

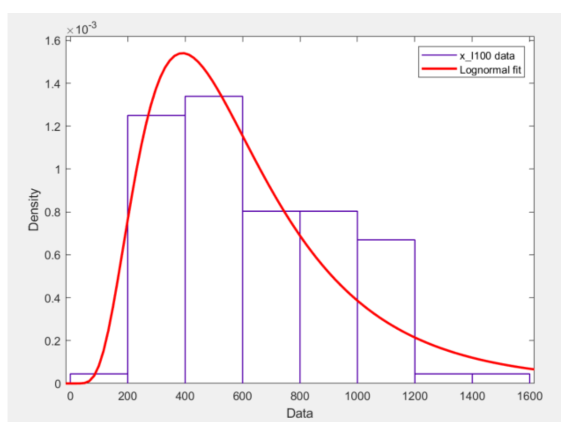




(a) Span length S PDF and fitted curve

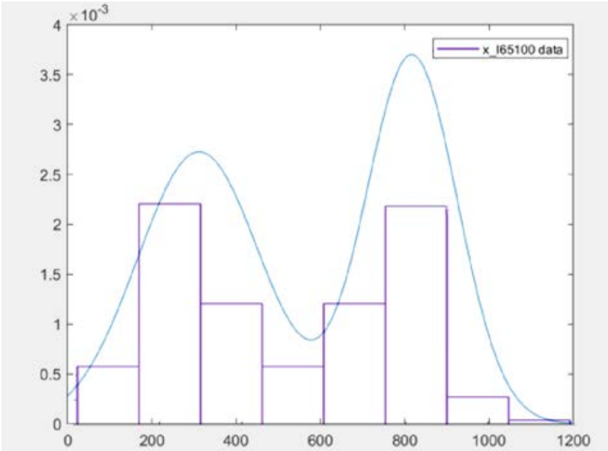
(b) Structure height PDF and fitted curve





(c) I ($s \le$ 65ft) PDF and fitted curve

(d) I (100ft $< s$) PDF and fitted curve



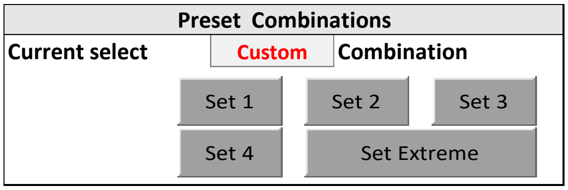
(e) I (65ft $< S \leq$ 100ft)) PDF and fitted curve

Figure A.3- PDF and fitted curves of variables of OH6

1.5 Appendix E: Demonstration of Maryland Sign Structure Automation Program

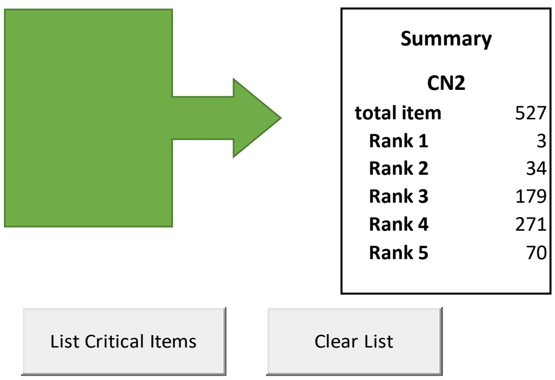
1. Score System Selection: Default (5: least critical; 1: most critical)

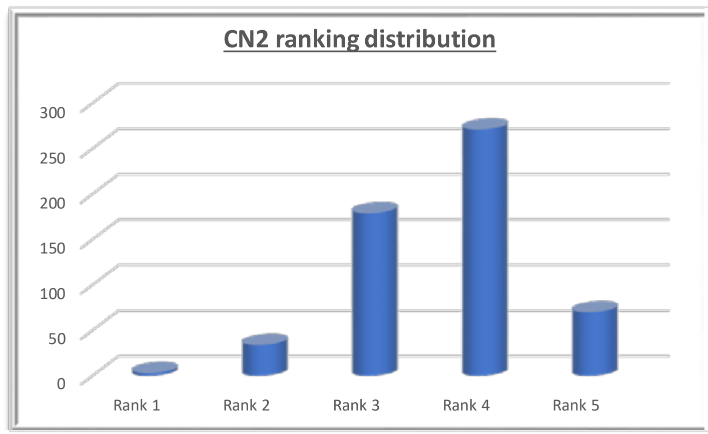
2. Panel Combination: Set 1



Current Weight Combination:			
Structure	**AADT**	**Bolt**	**Age**
40%	20%	30%	10%

3. Summary of CN2 Results where structures total ranking scores below 2 are listed in the summary

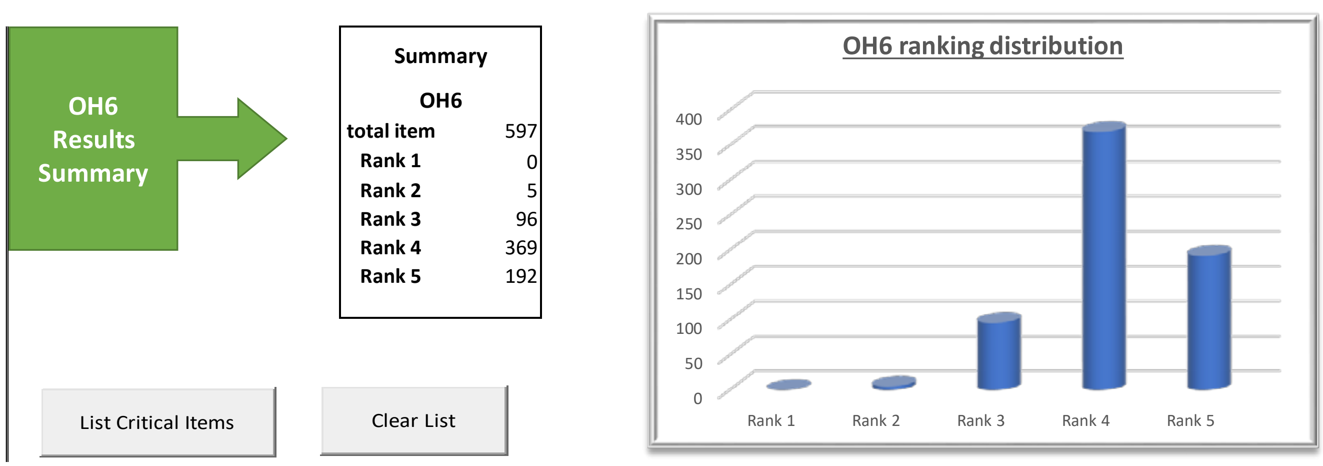




Structure ID	Total ranking score
1007	1.5
1011	1.5
1017	2
1060	1.8
1067	2
2019	1.8
2166	1.9
2172	1.8
2179	2
2333	1.9
3012	1.6
3075	1.8
3196	1.9
3262	2
3316	1.9

10031	1.8
12036	1.9
12054	1.9
15012	1
15028	1.8
15080	1.8
15132	1
15231	2
15234	1.7
15282	1.8
15284	1.8
15504	2
15510	2
16078	2
16086	1.8
16207	1.8
16256	1.5
17004	1.9
17020	1.9
17029	1
17051	1.7
21049	2

4. Summary of OH6 Results where structures total ranking scores below 2 are listed in the summary



Structure ID	Total ranking score
3490	2
10158	1.9
12056	1.9
13335	1.9
15423	1.9

5. Alternate Panel Combinations: If Set 2, 3, 4 or Extreme is selected, slightly different lists may be obtained. Beside the preset combinations, user can custom the weight combination in the input table.

Set 2

Current Weight Combination:			
Structure	**AADT**	**Bolt**	**Age**
30%	20%	40%	10%

or

Set 3

Current Weight Combination:			
Structure	**AADT**	**Bolt**	**Age**
35%	20%	35%	10%

Set 4

Current Weight Combination:			
Structure	**AADT**	**Bolt**	**Age**
40%	30%	20%	10%

or

Set Extreme

Current Weight Combination:			
Structure	**AADT**	**Bolt**	**Age**
100%	0%	0%	0%

Custom combination

Preset Combinations			
Current select	Custom	**Combination**	
	Set 1	Set 2	Set 3
	Set 4	Set Extreme	

Current Weight Combination:			
Structure	**AADT**	**Bolt**	**Age**
35%	35%	15%	15%