Method to Determine the Structural Equivalent MRI for the United States Deterministic Load Case (NESC Rule 250B) and Case Study Results

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Abstract—**Transmission lines in the United States are designed to resist both deterministic loads and probabilistic loads. These load cases are specified in the National Electrical Safety Code (NESC). The deterministic weather criteria specified in NESC Rule 250B are criteria that have been "determined" to provide adequate safety performance. The NESC Rule 250B divides the continental United States into three districts (light, medium, and heavy) with each district assigned a unique set of radial ice thickness, wind speed, and temperature. For the structural design of transmission lines, the NESC also requires that load factors be applied to the NESC Rule 250B deterministic loads. The load factors are significant (1.5 on vertical loads, 2.5 on wind load, and 1.65 on the transverse component of the wire tension). The factored deterministic loads often control the design of a structure relative to the NESC specified probabilistic load cases. Since the NESC Rule 250B load case is deterministic, there are no mean recurrence intervals (MRIs) associated to this load case. Therefore, it is challenging to determine the reliability of a structure controlled by deterministic loads.**

The NESC also specifies two different probabilistic load cases. The 2023 NESC specifies Rule 250C, probabilistic extreme wind, with a 100-year MRI. The NESC also specifies Rule 250D, probabilistic extreme ice and concurrent wind, with a 50-year MRI. However, the NESC only requires load factors of 1.0 for both these probabilistic load cases. A brief history of the different NESC design load cases will be provided to give background on the origins and evolution of the specified loads that exist in the United States.

A method to determine an equivalent structural MRI for the deterministic NESC Rule 250B load case is presented herein. This involves determining an adjusted probabilistic radial ice thickness or an adjusted probabilistic wind speed that will yield structural loads that are equivalent to the structural load developed from NESC Rule 250B with the specified NESC load factors. The NESC Rule 250B equivalent MRIs can then be calculated for the adjusted ice thickness and adjusted wind speeds.

This method was applied to an example 230kV transmission line. This transmission line includes seven different structures each supporting different conductor line angles. This transmission line is modelled with the specific NESC Rule 250B loads for 26 different cities in the United States as well as seven cities in Canada. For the Canadian cities, we apply the NESC Rule 250B district loads and load factors based on the proximity to the closest 250B loading district. The adjusted ice thickness and adjusted wind speed are calculated for each city. For the cities in the United States, the adjusted ice thicknesses and adjusted wind speeds are compared to the NESC 100-year probabilistic ice thicknesses and wind speeds. For the Canadian cities, the adjusted ice thicknesses and adjusted wind speeds are compared to the CSA C22.3 100-year ice thicknesses and wind pressures. The equivalent MRIs for NESC Rule 250B are calculated for each structure type in each city and compared and differences are discussed.

Results from this analysis show that the equivalent MRIs not only vary based upon location but also vary upon the line angle of the supporting structure. Therefore, structures that support different line angles on the same transmission line have different equivalent MRIs. To a lesser extent, the equivalent MRIs are also dependent on the conductor type and the conductor design tensions.

Keywords— ***Deterministic Design Loads, Probabilistic Design Loads, NESC 250B Equivalent MRI, Extreme Wind, Extreme Ice with Concurrent Wind.***

I. Introduction

The United States does not currently specify a design code or a standard that provides structural design loads for overhead utility lines. The only code that specifies weather loads for overhead utility lines is the National Electrical Safety Code (NESC). In the United States, when adopted by a State, transmission lines shall meet or exceed the requirements stated within that code, including the weather loads. However, the NESC is a safety code, not a design code. The NESC Rule 010D states:

"This Code is not intended as a design specification or as an instruction manual."

The intent of this paper is to determine the varying ranges of equivalent mean recurrence intervals (MRIs) that transmission line structures are effectively designed to resist to meet the requirements of the NESC. This research can hopefully be applied to future transmission line design load standards to specify probabilistic weather loads with appropriate MRIs and load factors that will lead to design loads that are more consistent and accurate than the weather loads specified in the NESC.

A. National Electrical Safety Code [1] (NESC) Rule 250B

The NESC does provide three general loading cases that transmission line structures must be capable of resisting. These load cases are as follows:

- NESC Rule 250B – Combined ice and wind district loading (**Deterministic Load Case**)
- NESC Rule 250C – Extreme wind loading (**Probabilistic Load Case**)
- NESC Rule 250D – Extreme ice and concurrent wind load (**Probabilistic Load Case**)

The NESC specifies two probabilistic load cases: extreme wind and extreme ice with concurrent wind, known as NESC Rules 250C & 250D respectively. The NESC Rule 250B specifies a deterministic combined ice and wind district loading case. The term "deterministic" load case is derived from loads that have been "determined" to provide adequate safety performance. The weather data used to determine the specified loads of NESC Rule 250B is not known. The loads specified in NESC Rule 250B "*…and load factors do not have a strong theoretical basis. Some designers find their rules too restrictive, while others adopt a more conservative criteria.*" [2]. Comparisons of the specified loads of NESC Rule 250B and the probabilistic load case NESC Rule 250D show that the accuracy of the deterministic load case significantly varies across the country [3]. Below is a brief history of NESC Rule 250B.

B. Brief History of NESC Rule 250B

The first documented publication on transmission line loading was the "Fundamental Considerations Governing the Design of Transmission Line Structures" [4]. This document used the same wind load data that was being used for the design of steel windmill towers. This document discusses loading from wind pressure on wires and loading from freezing rain or sleet. Scholes discusses a storm that occurred in Chicago during a previous winter where over a half inch of radial ice was observed. Scholes recommends designing the conductor and the structure to resist a 0.5-inch radial ice and design the conductor and the structural components with a factor of safety of 2.0.

Another document discussing design loads for transmission lines was "Some Mechanical Considerations of Transmission Line Structures" [5]. In this document, Worcester states:

"The amount of ice which may form on wires has been a much-discussed topic and one which will probably never be settled to the satisfaction of all concerned."

It has been 110 years since Worcester published his document, and there is still much discussion on the appropriate radial ice thicknesses for design. For a more detailed history on NESC Rule 250B, 250C and 250D please refer to [3].

Figure 1 displays NESC Rule 250B's district load map. The district loading map breaks the continental United States into three loading districts: heavy, medium, and light. The boundaries between these different loading districts have changed slightly over the years. In the current NESC 2017, the specified radial ice thickness, wind pressures, and temperatures are shown in Table I.

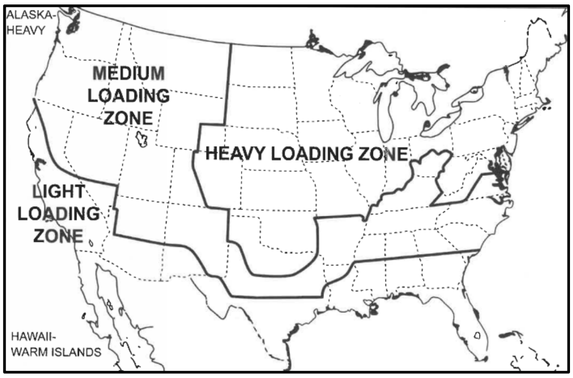


Figure 1: 2017 NESC - Rule 250B - District Load Map [1]

TABLE I. NESC RULE 250B - ICE, WIND PRESSURES, AND TEMPERATURES

NESC 2017 – Rule 250B – Ice, Wind Pressures, and Temperatures			
Region	**Radial Ice mm (in)**	**Wind Pressure Pa (psf)**	**Temp °C (°F)**
HEAVY	12.5 (0.5)	191.5 (4)	-20 (0)
MEDIUM	6.4 (0.25)	191.5 (4)	-10 (15)
LIGHT	0 (0)	431 (9)	-1.0 (30)

The NESC also specifies minimum load factors that are to be applied to the three weather load cases to create the required structural design loads. As shown in Table II, the NESC only requires load factors greater than 1.0 to be applied to the deterministic loads of NESC Rule 250B. For the two probabilistic load cases, NESC Rule 250C and 250D, the required load factors are 1.0. However, many utilities do apply load factors greater than 1.0 for the probabilistic load cases.

TABLE II: NESC RULE 253 – STRUCTURAL LOAD FACTORS

Structural Load Factors for Grade B					
Load Case	**Vert. Loads**	**Transverse Loads**		**Longitudinal Loads**	
		Wind	**Wire tension**	**In general**	**At Dead -ends**
NESC 250B - District Load (Deterministic)	1.50	2.50	1.65	1.10	1.65
NESC 250C - Extreme Wind (Probabilistic)	1.00	1.00	1.00	1.00	1.00
NESC 250D - Extreme Ice & Concurrent Wind (Probabilistic)	1.00	1.00	1.00	1.00	1.00

As shown in Table II, there are different load factors for transverse loads and longitudinal loads. Figure 2 illustrates a plan view of a structure that supports a turn of the conductors (turning structure). As the line angle increases the resulting transverse wire load also increases and the 1.65 factor for transverse wire tensions greatly increases the transverse design load applied to the structure. Therefore, the load factors of NESC 250B have varying impacts for different structure types. Structures with very small line angles are not significantly affected by the 1.65 factor on wire tensions. The design of these structures is often controlled by the probabilistic extreme wind speeds. However, for structures supporting larger line angles or dead-end structures, the 1.65 factor applied to the NESC 250B transverse wire tensions can often cause the factored deterministic Rule 250B to control the design of the structure relative to the design loads from NESC Rules 250C, or 250D.

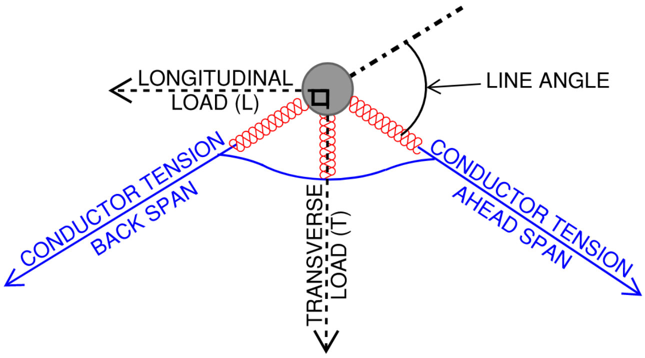


Figure 2: Transmission Line Structure Loading Terminology – Plan View of Self-Supporting Dead-end Structure

For structural design loads for overhead utility lines selected in The United States, utilities often rely on past experience to set additional design load conditions and/or load factors that are used to supplement NESC specified weather loads. There are numerous different utilities across the United States, and the structural design loads specified by each utility often varies.

C. Reliability Based Design Methodology (RBD)

There are other manuals and guidelines that provide recommendations on transmission line structure loading. One such guideline is the American Society of Civil Engineers (ASCE) Manual of Practice No. 74 – Guidelines for Electrical Transmission Line Structural Loading [6]. Currently, ASCE No. 74 is a design guide, not a code or standard. Therefore, the loadings stated in ASCE No. 74 are recommendations, not requirements.

The ASCE No. 74 recommends designing transmission line structures following a Reliability Based Design (RBD) methodology and in Section 1.3.2 states the following: *"Load and resistance factor design methodology is a simplified approach to RBD which uses factors to account for the uncertainty in the loading and strength."* The equation below displays the basic LRFD concept.

$$\emptyset R_n \geq \sum \gamma_i Load_i \quad (1)$$

Where:

$$\emptyset R_n = Design\ capacity\ of\ structural\ component$$
$$\emptyset = Strength\ reduction\ factor$$
$$R_n = Nominal\ strength\ of\ the\ component$$
$$\Sigma\gamma_i Load_i = Design\ load\ combination.\ applied\ to\ structure$$
$$\gamma_i = Load\ factor, unique\ for\ each\ load\ type$$
$$Load_i = \ Load\ type\ (Dead\ loads, wire\ tensions, weather\ loads, etc.)$$

ASCE No. 74 4th edition recommends designing structures to probabilistic weather cases. It provides two weather related load cases with 100-year MRIs: Extreme wind and extreme ice with concurrent wind. ASCE No. 74 also provides numerous additional load conditions to supplement the NESC weather related loads. These include recommendations for differential ice loading, construction loads, broken wire loads as well as many others.

In contrast, the 2017 NESC Rules 250C for extreme wind, specifies 50- to 90-year MRI. The 2017 NESC Rule 250D for extreme ice and concurrent wind, specifies 50-year MRI.

As shown in Equation (1), there are two sides of the equation to satisfy structural reliability: the structural design capacity and the applied design loads. This study focuses on the applied design loads.

There are many other good references on reliability-based design of utility structures that discuss both the applied design loads and the structural design capacity, such as ASCE No. 111 [7] and [2].

II. METHOD

For many transmission structure types in many locations across the United States, the controlling NESC design loads are from Rule 250B load case with the load factors from NESC Rule 253. For these transmission line structures, there has been no way of knowing what sort of MRI weather event the structures have the capacity to resist since the deterministic load case NESC Rule 250B does not have an associated MRI.

D. Method to Calculate "Equivalent" MRIs from the Deterministic Loads of NESC RULE 250B

Our proposed method relies on structural calculations of transmission line structures (Figure 3). We determine the structural loads from load case NESC Rule 250B including the load factors from NESC Rule 253, then we determine the probabilistic weather conditions that would be needed to develop the same structural loads. Then, we determine the MRIs of these probabilistic loads.

Step-by-step methods to determine the "Equivalent" MRI from the deterministic loads and load factors from NESC Rule 250B and 253 are outlined below and shown in Figure 3.

1) For a transmission line structure, determine the required structural capacity to resist the design loads from NESC Rule 250B and the load factors from NESC Rule 253. For a self-supporting monopole structure calculate the base moment reaction from NESC Rule 250B with Load Factors.
2) Determine what "Adjusted" wind speed would be required to create an equivalent base moment reaction. (Equiv. $\mathrm{Wind}_{\mathrm{ADJ}}$)
3) Determine what "Adjusted" freezing rain radial ice thickness would be required, in combination with concurrent wind speed, to create an equivalent base moment reaction. (Equiv. $\mathrm{Ice}_{\mathrm{ADJ}}$)
4) Calculate the "Equivalent" MRI from the adjusted wind speed and an "Equivalent" MRI from the adjusted Ice thickness.
5) The lower of the two MRIs in step 3) and 4) above is the condition that is more likely to occur and create a structural load equal to the structural loads form NESC Rule 250B with Load Factor. This will be referred to as the structural "Equivalent" MRI for NESC Rule 250B with Load Factor.

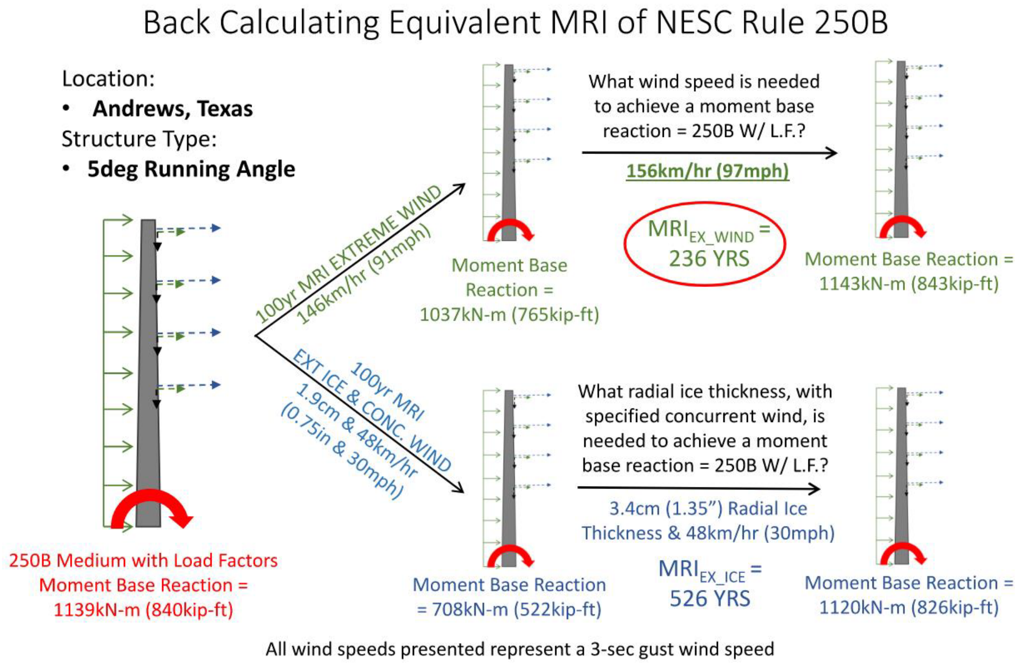


Figure 3. Method to Determine “Equivalent” MRI for NESC Rule 250B with Load Factors

E. Implementing this Methodology in our Analysis

We can follow this methodology to calculate the equivalent MRIs of NESC Rule 250B using the transmission line design software PLS-CADD. This involved creating numerous incremental weather cases for both wind speeds and for radial ice thicknesses.

To determine the equivalent adjusted wind speed, incremental weather cases were created. Incremental wind speeds that ranged from 121 kilometers per hour (km/hr) (75 miles per hour [mph]) to 402 km/hr (250 mph) in 1.6 km/hr (1.0 mph) increments. This created 176 incremental wind speed cases. Base moment reactions were then calculated for each one of these incremental wind speeds cases. The wind speed case that created a base moment reaction that was closest to the base moment reaction from NESC Rule 250B with load factors was set as the equivalent adjusted wind speed.

A similar process was followed to determine the equivalent adjusted ice thickness, in combination with concurrent wind speed. However, to determine the equivalent adjusted ice thickness was more complex. This is due to the two different conditions that are applying load to the transmission line structure, radial ice, and concurrent wind. The concurrent wind speeds specified for the probabilistic extreme ice and concurrent wind load case are as follows: 48 km/hr (30 mph), 64 km/hr (40 mph), 80 km/hr (50 mph), 97 km/hr (60 mph), 113 km/hr (70 mph) and 129 km/hr (80 mph), per ASCE 7-22, Figure 10.5-1 [8]. These concurrent wind speeds are a 3-second gust and represent the wind speed that could occur while ice remains on the structure. These specific concurrent wind speeds are associated only with different regions of the country and are independent of MRI.

The Canadian Overhead Transmission Line Design Criteria, CSA C22.3 [9] specifies concurrent wind speeds in a slightly different way. Condition C1 states to model *“…the highest value of ice load to be combined with the average of yearly maximum wind speed during ice persistence.”* Without specific annual wind data, the CSA recommends a concurrent wind speed that is (0.4 to 0.5) × (CSA specified design wind speeds). The design wind speeds in CSA C22.3 were converted from a 10-minute mean wind speed to a 3-second gust wind speed using the Durst relationship provided in ASCE 7 (approximately a factor of 1.43 on the 10-minute mean wind speed) [8].

The factors of 0.4 and 0.5 were then applied to give a range of concurrent wind speeds. We then assigned the ASCE concurrent wind speed that was within this CSA specified range. For example, in Abbotsford B.C., the specified 3-second gust 100-year MRI wind speed of 151 km/hr (94 mph). The 0.4 and 0.5 factors were applied [0.4 × Wind Speed = 60.4 km/hr (37.7mph)] and [0.5 × Wind Speed = 75.5 km/hr (47.1 mph)] we then assigned a 64.3 km/hr (40 mph) concurrent wind speed because this incremental concurrent wind speed fits within the CSA recommended range of (0.4 to 0.5) × (Design wind speed). Following this method allowed us to model and process the data from the United States and the Canadian locations in the same way and that greatly simplified our analysis.

For each of these concurrent wind speeds, incremental ice thickness was modelled. These incremental ice thicknesses ranged from 0.0 to 6.4 cm (2.5 inches) in 1.27 mm (0.05 inch) increments (51 adjusted ice thickness cases) and these incremental ice thickness cases were applied to each of the six concurrent wind speeds (6 × 51 = 306 cases). Base moment reactions were calculated for all 306 of these adjusted ice and concurrent wind cases. However, if the structures analysed were in a region that specified a 50-mph concurrent wind speed, for example, then only the 51 adjusted ice thicknesses cases associated with the 50 mph concurrent wind speeds were used to determine the adjusted ice thickness that creates an equivalent base moment reaction to the base moment reaction from NESC Rule 250B with load factors. It is important to note that the adjusted ice thicknesses represent ice thicknesses from freezing rain only. This methodology does not provide MRIs for “in-cloud icing” or “wet snow” events.

F. Calculation of Equivalent MRIs

In the United States, extreme ice thicknesses from freezing rain are calculated using the 3-parameter generalized Pareto distribution with location parameter φ, scale α, and tail shape *k*. The three parameters of the distribution are calculated from the sample of extremes using L-moments (Hosking and Wallis 1997) [10]. Here we use parameters for the extreme value distributions based on the station groupings that were created for calculating the extremes for the maps in ASCE Standard 7-2022. For a specified ice thickness *t*, the mean recurrence interval Y_{MRI} is

$$Y_{MRI} = \frac{1}{r}\left[1 - \frac{k}{\alpha}(t-\varphi)\right]^{-1/k} \quad (2)$$

The occurrence rate r=1 where the number of values in the sample of extremes is the same as the number of years of record. This is the case for most of the United States. Where freezing rain occurs rarely, however, r (the number of values in the sample of extremes divided by the number of years of record) may be less than one. In the United States, extreme wind speeds are estimated based on historical data and the statistical approaches described by Lombardo et al. (2016) [11]. The results from this analysis are such that the wind speeds at various MRI can be estimated as approximately following a Gumbel distribution for any location of interest in the United States. It is worth noting that due to the contoured nature of the maps, these parameters and their interaction vary with location. This is true for wind speed maps in versions of ASCE Standard 7-16 and later editions. The nominal wind speed map in ASCE Manual No. 74 (100-year MRI) is based on this analysis.

For the purposes of this study, the ASCE Hazard Tool (available at https://asce7hazardtool.online/) was used to obtain the extreme wind speeds over a range of MRI (10 to 3,000 years) for each location and the corresponding Gumbel parameters were calculated. Based on the equivalent adjusted wind speed obtained for each of the structure types, the corresponding equivalent MRI could then be calculated directly from the Gumbel parameters. Note that for some locations, relatively small increases in wind speed results in large differences in MRI as the relationship is logarithmic.

In Canada, both extreme wind speeds and ice thicknesses are calculated using the Gumbel distribution. Factors for calculating the wind speed and ice thickness for MRI up to 500 years from the nominal 50-year MRI values are in Table CA.2 in CAN/CSA (2019). Note that the parameters of the Gumbel distribution differ for wind and ice; these relationships are shown in the **Error! Reference source not found.**. For the Canadian locations, these values were used in place of the estimates based on the location-specific Gumbel parameters described for the United States.

The factors for any MRI are then:

wind: $f_{MRI} = 0.281 + 0.184\ln(Y_{MRI})$

ice: $f_{MRI} = 0.675 + 0.085\ln(Y_{MRI})$

which can be used to modify the specified 50-year values in CSA C22.3.

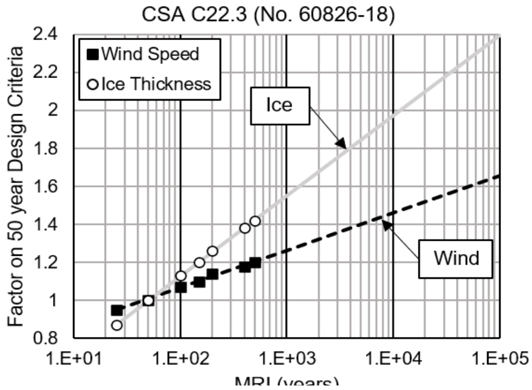


Figure 4. Plot of Factors on 50-year values and extrapolation based on Gumbel parameters

Another useful calculation is the Probability of Exceedance over a specified design life of n years [$PE_{(n\text{-}YR)}$]. This probability is calculated using

$$PE_{(n\text{-}YR)} = \left[1\text{-}\left(1\text{-}\frac{1}{MRI_{EQ}}\right)^{n}\right] \quad (3)$$

as described in ASCE 74 [6]:

$$PE_{(n-YR)} = \left[1 - \left(1 - \frac{1}{MRI_{EQ}}\right)^{n}\right] \quad (3)$$

$$PE_{n-YR} = Probability\ of\ Load\ Exceedance\ in\ n\ years$$

$$MRI_{EQ} = Equivalent\ MRI\ for\ NESC\ Rule\ 250B$$

$$n = Design\ life\ in\ years$$

The length of the design life has a major impact on the likelihood of exceeding the design load. For example, structures that are designed using 100-year MRI design loads and designed to a 50-year design life will have a likelihood of exceedance of 39.5%. Using the same design loads but designing to a 100-year design life, the likelihood of exceedance increases to 63.4%. The design life for transmission line structures can vary. Many renewable energy projects have a project design life of 25 to 30 years, whereas many utility lines may specify a design life of 100 years. In our analysis, we chose a 50-year design life to calculate the likelihood of load exceedance. As stated above, structural reliability is dependent on both design loads and structural design capacity. This study focuses on the accuracy and magnitude of the transmission line design loads, and does not focus on the design capacity of the transmission line structures. However, the paragraph below provides a brief background about how design capacity is specified in RBD methodology.

It is important to note that exceeding the design load does not ensure a structural failure would occur. Following RBD methodology, the design capacity of a structure ($\emptyset R_n$) is associated with a lower exclusion limit (LEL). Most design capacities are in the range of a 5% to 10% LEL. A steel pole that that has a LEL of 5% design capacity, $(\emptyset R_n)_{LEL5\%}$, is represented by the following example: on average, if 100 poles were tested to failure, five would fail under the $(\emptyset R_n)_{LEL5\%}$ design capacity, and 95 would exhibit a capacity higher than the $(\emptyset R_n)_{LEL5\%}$ design capacity. Also, most transmission line structures are not designed to push the structural utilization right up to 99.9%. There is generally some small margin between the applied loads and the design capacity. For these reasons, the likelihood of structural failure is generally lower than the probability of load exceedance.

G. Sample Set of Locations

The intent was to select cities that that would display wide array of both 100-year extreme wind speeds and extreme ice thicknesses across all three NESC districts (Figure 5). It is important to recognize that any calculated average or median results are tied only to these selected locations; a different set of cities would produce different results. In future revisions of this research, other cities will be analysed.

Figure 5. Selected Locations in United States and in Canada

H. Modelled Line and Structure Types Analysed

A 230kV transmission line with seven different structure types were modelled for our case study (Figure 6).

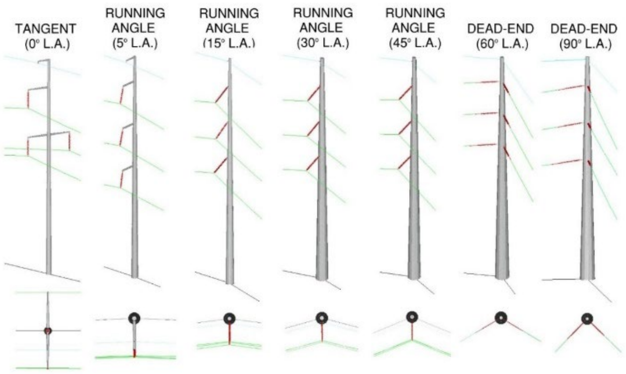


Figure 6. Analysed Self-Supporting Structure Types

Tangent structures are the most common structure type. Tangents are designed to support the conductor at a safe vertical clearance off the ground and to resist vertical conductor and ice loads as well as transverse wind loads. Many utilities also design their tangents to resist some amount of longitudinal wire loads (Figure 2). These longitudinal wire loads can develop from differential ice loading or a broken wire condition. Tangent structures typically have a line angle of close to zero however some utilities do design tangents to resist line angles up to 5 degrees. If a tangent monopole structure were to fail, it is likely that the damage could be localized to just the few structures located adjacent to the failed tangent structure.

A heavy angle or dead-end structure is designed to resist the very large conductor tensions. If a heavy angle or dead-end structure failed, numerous structures in both the ahead and back spans could also be significantly damaged. For this reason, heavy angle or dead-end structures could be thought of as critical structures.

Transmission line structures can be designed with a variety of materials and structure types such as wood poles, steel poles, concrete poles, Fiber Reinforced Polymers poles, or lattice steel towers. Each of these pole materials can be framed or supported in different ways. Tangent structures can be monopole structures, or they could be two pole H-frame structures which exhibit different structural capacities in the transverse and longitudinal directions. There are also numerous turning structure types. Some turning structures make use of guywires to help support the large conductor loads. Other turning structures are referred to as “self-supporting” in that they support the conductor tension on their own without the use of guywires. For our analysis, we selected to model each of the seven different structure types as self-supporting monopole steel structures. In the future, we plan on modelling other structure types such as guyed structures or lattice towers.

One of the main reasons for selecting a self-supporting structure type was the ease to compare the base reactions. Specifically, the base moment reaction between the deterministic NESC Rule 250B with load factors from NESC Rule 253 and the base moment reactions from the 100-year MRI probabilistic load cases as recommended in ASCE No. 74 [6].

A way to compare base moment reactions from the deterministic loads and the probabilistic loads is by calculating a “moment ratio.” For example, the base moment reactions from a 45-degree angle structure can be compared. The base moment reaction from NESC Rule 250B with Load Factors ($M_{250B\ W/\ L.F.}$ = 4,556k-ft), and the base moment reaction from one of the probabilistic loads such as extreme ice and concurrent wind ($M_{EX\_ICE\ 100}$ = 3,309k-ft). The ratio between these two base reactions would be:

$$\frac{M_{250B\ with\ L.F.}}{M_{EX\_ICE_{100}}} = \frac{4{,}556\ k-ft}{3{,}309k-ft} = 1.38$$

This moment ratio is relative to the 100-year MRI extreme ice and concurrent wind loads. If the MRI for the probabilistic loads is reduced, the moment ratio will increase; if the MRI are increased, the moment ratio will decrease.

This ratio could also be interpreted as the load factor that would be needed to be applied to the probabilistic loads to achieve the same magnitude structural design loads as the deterministic NESC 250B structural design loads.

I. Conductor Types and Conductor Tension Limits Analysed

Two conductor types were selected to be analysed. A 795kcmil ACSS “Drake” and a 1272kcmil ACSR “Bittern” conductors. The properties of these two conductors can be seen in Table III.

TABLE III: MODELLED CONDUCTOR TYPES

Conductor Types Analysed				
[kcmil]	**Conductor Family**	**Name**	**Diameter**	**Rated Breaking Strength [lbs]**
795	ACSS	DRAKE	1.108	25,000
1272	ACSR	BITTERN	1.345	34,000

The NESC specifies a maximum limit on allowable conductor tensions. However, many utilities limit their conductors to tensions that are well below the NESC tension limits. Therefore “reduced” conductor tension limits were also analysed. In our analysis, the two conductor types were each modelled using these two different conductor tension limits. These two different tension limits can be seen in Table IV and Table V.

TABLE IV: NESC SPECIFIED TENSION LIMITS

Weather Case Description	Cable Condition	Allowable % of Ultimate
NESC Heavy/Medium/Light	Load	50
NESC District (Temperature)	Initial	35
NESC District (Temperature)	Creep	25

TABLE V: "REDUCED" TENSION LIMITS

Weather Case Description	Cable Conditions	Allowable % of Ultimate
NESC Heavy/Medium/Light	Load	50
NESC District (Temperature)	Initial	20
NESC District (Temperature)	Creep	18

NESC District (Temperature) is a weather case utilizing only the temperature of that specific district (heavy, medium, light). There is no ice or wind for this case. Refer to Table I for more information on the temperatures and weather cases. The case that controls our tension limits in this design is the NESC District (Temperature) under creep for NESC specified tensions and NESC District (Temperature) under initial for the “reduced” tension limits.

J. Case Study Transmission Line and PLS-CADD Model

The 230kV transmission line was modelled in PLS-CADD, which is a finite element three-dimensional modelling software used throughout the transmission industry. This software can model structures and wires in a 3D spatial environment that can have varying terrain. For the model in this study, the ground elevation remained constant. Additionally, each structure analysed are identical with span lengths of 700 feet to create consistent and commensurable results. All structures modelled maintained appropriate heights and phase spacing to satisfy 230kV NESC required clearances.

In addition to the 3D modelling, the program allows numerous weather cases to be modelled. This allowed us to model the incremental wind speeds and incremental ice thicknesses to determine adjusted wind speeds and adjusted ice thickness that would create equivalent base moment reactions.

Our transmission line was modelled assuming an exposure Category C. Wind pressures and ice thicknesses were adjusted using the wind pressure exposure coefficient (K_z), gust response factors (G) for conductors, shield wires and structures, as well as adjusting the nominal ice thickness for height above ground (t_z). Equations for (K_z) and (t_z) can be seen below. There are different equations for (G) for wires or for structures and both are quite a bit more complex. Details on the calculations of the gust response factor can be found in Section 2.1.5 of ASCE No. 74 [6].

$$K_z = 2.01\left(\frac{z_h}{z_g}\right)^{\frac{2}{\alpha}} \quad (4)$$

Where:

$$\alpha = Power\ law\ coefficient\ (9.5\ for\ exposure\ C)$$
$$z_h = Effective\ Height$$
$$z_g = (275\ meters\ for\ exposure\ C)$$

$$t_z = t_{MRI}\left(\frac{z}{10\ meters}\right)^{0.10}$$

Where:

$$t_z = Design\ ice\ thickness\ at\ height\ z$$
$$t_{MRI} = Nominal\ ice\ thickness\ for\ specific\ MRI$$
$$z = Hight\ above\ ground\ in\ meters$$

Values of (K_z) and (G) were applied to both the extreme wind speeds, <u>as well as the concurrent wind speeds</u>. Applying these adjustment factors to the concurrent wind speeds is not common practice in the United States and for our transmission line it had the effect of slightly reducing the concurrent wind pressures. We chose to adjust the concurrent wind pressures because the ASCE No. 74 allows these adjustments, and it is common practice in Canada.

III. RESULTS

The results displayed highly varying ranges of both equivalent MRIs, moment ratios, and probability of load exceedance. These values varied depending on different locations, structure types, conductor types and different conductor tension limits. Result tables, like the one shown in Table VI, were created for the following conductor sizes and tension limits:

- 1272kcmil ACSR “Bittern” conductor
  - NESC conductor tension limits
  - “Reduced” conductor tension limits.
- 795kcmil ACSS “Drake” conductor
  - NESC conductor tension limits
  - “Reduced” conductor tension limits

Table VI displays the results for the 33 cities, for all seven 230kV structure types for 1272kcmil ACSR conductor under NESC conductor tension limits. Instead of providing full tables for each conductor and tension limit, we chose to provide a result summary table for the above conductors and tension limit conditions. These summary tables can be seen in Table VII and provide minimum, median, and maximum values of Equivalent MRI of NESC Rule 250B, moment ratio, and probability of load exceedance for each of the seven structure types.

The results of equivalent MRI, moment ratio, and probability of load exceedance are related in the following way: as the equivalent MRIs increase, so does the moment ratio, and the probability of load exceedance goes down. The trends stated below refer only to equivalent MRI but the trends for moment ratio and probability of load exceedance follow the relationships stated above. It is also important to note there are cities and structure types that display NESC 250B equivalent MRIs less than the probabilistic MRIs. For these cities and structures, the probabilistic loads would control the design of the structure with a 100-year MRI.

TABLE VI. EQUIVALENT MRIs, MOMENT RATIOS, AND PROBABILITY OF EXCEEDANCE FOR 1272 KCMIL UNDER NESC CONDUCTOR TENSION LIMITS

EQUIVALENT MRIs, MOMENT RATIOS, AND PROBABILITY OF EXCEEDANCE FOR 1272kcmil ACSR "BITTERN" CONDUCTOR WITH NESC CONDUCTOR TENSION LIMITS

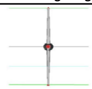
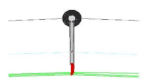
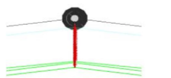
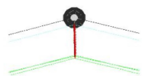
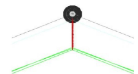
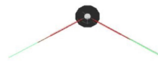
					ASCE 74 - 4th Edition (100YR MRI)	ASCE 74 - 4th Edition Extreme Ice (100-YR MRI) and Concurrent Wind		230kV I-String Tangent (W = Adjusted Ext. Wind) or (I = Adjusted Ext. Ice w/ Conc. Wind)				230kV 5° Running Angle (W = Adjusted Ext. Wind) or (I = Adjusted Ext. Ice w/ Conc. Wind)			
Ref. Number	Country	NESC District	City	State / Province	Extreme Wind Speed (mph)	Radial Ice Thickness (in)	Concurrent Wind Speed (mph)	Controlling NESC 250B Equiv. MRI [Years]	Moment Ratio	Probability of Load Exceedance [PE_{50YR}]		Controlling NESC 250B Equiv. MRI [Years]	Moment Ratio	Probability of Load Exceedance [PE_{50YR}]	
9		Light	Miami	FL	139	0.00	30	14	0.56	97%	W	23	0.69	89%	W
8		Light	New Orleans	LA	118	0.00	30	40	0.77	72%	W	72	0.90	50%	W
7		Light	Bluffton	SC	105	0.50	30	74	0.97	49%	W	125	1.08	33%	W
4		Light	Alexandria	LA	92	0.50	30	366	1.25	13%	W	929	1.33	5%	W
6		Light	Baton Rouge	LA	102	0.25	30	118	1.02	35%	W	246	1.13	18%	W
5		Light	Troy	AL	96	0.25	30	194	1.15	23%	W	444	1.24	11%	W
2		Light	El Paso	TX	90	0.25	30	565	1.30	8%	W	1,676	1.37	3%	W
1		Light	San Francisco	CA	78	0.00	30	3,806	1.71	1%	W	12,511	1.67	0%	W
3		Light	Las Vegas	NV	85	0.00	30	1,296	1.45	4%	W	4,031	1.49	1%	W
15		Medium	Vancouver	WA	82	1.50	30	82	0.99	46%	W	51	0.91	63%	I
12		Medium	Andrews	TX	91	0.75	30	24	0.81	88%	W	236	1.10	19%	W
11		Medium	Durham	NC	95	0.75	30	22	0.74	90%	W	126	1.03	33%	W
10		Medium	Annapolis	MD	95	0.50	40	22	0.74	90%	W	133	1.03	31%	W
13		Medium	Farmington	NM	90	0.25	40	26	0.83	86%	W	284	1.12	16%	W
14		Medium	Salt Lake City	UT	89	0.25	40	31	0.84	81%	W	305	1.14	15%	W
15.1_CA		Medium	Abbotsford	BC	94	1.02	40	18	0.76	94%	W	55	1.05	60%	I
15.2_CA		Medium	Lethbridge	AB	104	0.44	50	6	0.63	100%	W	44	0.89	68%	W
19		Heavy	Massena	NY	90	1.50	50	36	0.83	76%	I	36	0.81	76%	I
21		Heavy	McAlester	OK	91	1.00	30	120	1.04	34%	W	491	1.36	10%	I
24		Heavy	Dallas	TX	90	1.00	30	143	1.06	30%	W	491	1.38	10%	I
23		Heavy	St. Louis	MO	93	1.00	40	115	1.00	35%	W	583	1.32	8%	I
26		Heavy	Queens	NY	97	0.75	50	64	0.92	55%	W	592	1.23	8%	I
18		Heavy	Toledo	OH	91	1.00	40	118	1.04	35%	W	857	1.36	6%	I
25		Heavy	Wichita	KS	95	1.00	40	77	0.96	48%	W	1,333	1.27	4%	I
22		Heavy	Pierre	SD	97	0.50	60	61	0.92	56%	W	4,777	1.23	1%	I
16		Heavy	Williston	ND	95	0.25	60	78	0.96	48%	W	16,802	1.27	0%	W
17		Heavy	Wausau	WI	90	0.75	50	139	1.06	30%	W	37,304	1.38	0%	W
20		Heavy	Berlin	NH	90	0.75	50	134	1.06	31%	W	25,546	1.38	0%	W
29_CA		Heavy	Windsor	ON	94	1.11	40	91	0.97	43%	W	669	1.29	7%	I
31_CA		Heavy	Fredericton	NB	88	1.11	40	212	1.11	21%	W	669	1.29	7%	I
27_CA		Heavy	Estevan	SK	103	0.44	50	31	0.82	81%	W	7,425	1.12	1%	W
30_CA		Heavy	Sherbrooke	QC	76	0.89	30	1,725	1.47	3%	W	19,422	1.77	0%	I
28_CA		Heavy	Winnipeg	MB	94	0.71	40	92	0.97	42%	W	38,868	1.29	0%	W

	230kV 15° Running Angle (W = Adjusted Ext. Wind) or (I = Adjusted Ext. Ice w/ Conc. Wind)				230kV 30° Running Angle (W = Adjusted Ext. Wind) or (I = Adjusted Ext. Ice w/ Conc. Wind)				230kV 45° Running Angle (W = Adjusted Ext. Wind) or (I = Adjusted Ext. Ice w/ Conc. Wind)			
Ref. Number	Controlling NESC 250B Equiv. MRI [Years]	Moment Ratio	Probability of Load Exceedance [PE_{50YR}]		Controlling NESC 250B Equiv. MRI [Years]	Moment Ratio	Probability of Load Exceedance [PE_{50YR}]		Controlling NESC 250B Equiv. MRI [Years]	Moment Ratio	Probability of Load Exceedance [PE_{50YR}]	
9	63	0.89	55%	W	114	0.99	36%	W	164	1.05	26%	W
8	255	1.11	18%	W	535	1.20	9%	W	835	1.25	6%	W
7	383	1.29	12%	W	740	1.37	7%	W	1,099	1.41	4%	W
4	3,961	1.50	1%	I	2,576	1.55	2%	I	2,218	1.52	2%	I
6	1,165	1.33	4%	W	2,910	1.41	2%	W	5,041	1.44	1%	W
5	2,577	1.43	2%	W	7,250	1.49	1%	W	13,484	1.52	0%	W
2	16,861	1.53	0%	W	65,564	1.58	0%	W	100,000	1.60	0%	I
1	100,000	1.76	0%	I	100,000	1.76	0%	I	100,000	1.77	0%	I
3	44,912	1.62	0%	W	100,000	1.66	0%	I	100,000	1.67	0%	I
15	63	0.99	55%	I	59	0.98	57%	I	59	0.97	57%	I
12	711	1.48	7%	I	645	1.42	7%	I	645	1.40	7%	I
11	2,375	1.41	2%	W	10,884	1.42	0%	W	28,961	1.40	0%	W
10	2,833	1.41	2%	W	13,827	1.54	0%	W	38,311	1.55	0%	W
13	16,284	1.50	0%	W	100,000	1.62	0%	I	100,000	1.69	0%	I
14	14,675	1.52	0%	W	100,000	1.64	0%	I	100,000	1.71	0%	I
15.1_CA	102	1.21	39%	I	83	1.21	45%	I	83	1.20	45%	I
15.2_CA	744	1.27	7%	I	744	1.40	7%	I	744	1.48	7%	I
19	63	0.99	55%	I	76	1.02	48%	I	76	1.03	48%	I
21	640	1.52	8%	I	640	1.45	8%	I	587	1.42	8%	I
24	640	1.52	8%	I	640	1.45	8%	I	587	1.42	8%	I
23	1,066	1.41	5%	I	1,230	1.39	4%	I	1,066	1.38	5%	I
26	1,134	1.49	4%	I	1,432	1.50	3%	I	1,432	1.51	3%	I
18	1,549	1.41	3%	I	1,780	1.39	3%	I	1,549	1.38	3%	I
25	2,649	1.41	2%	I	3,120	1.39	2%	I	2,649	1.38	2%	I
22	13,230	1.56	0%	W	26,478	1.61	0%	I	31,063	1.63	0%	I
16	16,802	1.67	0%	W	100,000	1.82	0%	I	100,000	1.90	0%	I
17	37,304	1.49	0%	W	100,000	1.50	0%	I	100,000	1.51	0%	I
20	25,546	1.49	0%	W	100,000	1.50	0%	I	100,000	1.51	0%	I
29_CA	2,026	1.36	2%	I	2,673	1.34	2%	I	2,026	1.33	2%	I
31_CA	2,026	1.36	2%	I	2,673	1.34	2%	I	2,026	1.33	2%	I
27_CA	7,425	1.51	1%	W	46,314	1.67	0%	W	100,000	1.76	0%	I
30_CA	54,767	1.67	0%	I	54,767	1.59	0%	I	38,765	1.56	0%	I
28_CA	38,868	1.69	0%	W	100,000	1.69	0%	I	100,000	1.68	0%	I

	230kV 60° Dead-End (W = Adjusted Ext. Wind) or (I = Adjusted Ext. Ice w/ Conc. Wind)				230kV 90° Dead-End (W = Adjusted Ext. Wind) or (I = Adjusted Ext. Ice w/ Conc. Wind)			
Ref. Number	Controlling NESC 250B Equiv. MRI [Years]	Moment Ratio	Probability of Load Exceedance [PE_{50YR}]		Controlling NESC 250B Equiv. MRI [Years]	Moment Ratio	Probability of Load Exceedance [PE_{50YR}]	
9	154	1.03	28%	W	234	1.09	19%	W
8	775	1.24	6%	W	1,302	1.29	4%	W
7	1,029	1.39	5%	W	1,630	1.43	3%	W
4	2,218	1.52	2%	I	1,903	1.46	3%	I
6	4,600	1.43	1%	W	8,733	1.47	1%	W
5	12,159	1.51	0%	W	25,079	1.54	0%	W
2	100,000	1.59	0%	I	100,000	1.62	0%	I
1	100,000	1.75	0%	I	100,000	1.76	0%	I
3	100,000	1.66	0%	I	100,000	1.68	0%	I
15	59	0.98	57%	I	55	0.97	60%	I
12	645	1.40	7%	I	583	1.38	8%	I
11	23,300	1.40	0%	W	69,122	1.38	0%	W
10	30,547	1.55	0%	W	94,784	1.53	0%	W
13	100,000	1.67	0%	I	100,000	1.74	0%	I
14	100,000	1.68	0%	I	100,000	1.74	0%	I
15.1_CA	83	1.22	45%	I	67	1.21	53%	I
15.2_CA	1,005	1.46	5%	I	1,005	1.54	5%	I
19	83	1.05	45%	I	83	1.05	45%	I
21	587	1.42	8%	I	587	1.40	8%	I
24	587	1.42	8%	I	587	1.40	8%	I
23	1,230	1.38	4%	I	1,230	1.37	4%	I
26	1,602	1.51	3%	I	1,602	1.51	3%	I
18	1,780	1.38	3%	I	1,780	1.37	3%	I
25	3,120	1.38	2%	I	3,120	1.37	2%	I
22	36,269	1.63	0%	I	42,158	1.65	0%	I
16	100,000	1.87	0%	I	100,000	1.90	0%	I
17	100,000	1.51	0%	I	100,000	1.51	0%	I
20	100,000	1.51	0%	I	100,000	1.51	0%	I
29_CA	2,673	1.34	2%	I	2,673	1.33	2%	I
31_CA	2,673	1.34	2%	I	2,673	1.33	2%	I
27_CA	100,000	1.72	0%	I	100,000	1.82	0%	I
30_CA	38,765	1.55	0%	I	38,765	1.53	0%	I
28_CA	100,000	1.67	0%	I	100,000	1.66	0%	I

TABLE VII: RESULT SUMMARY TABLES FOR ALL CONDITIONS OF CONDUCTOR SIZES AND CONDUCTOR TENSION LIMITS

EQUIVALENT MRI FOR NESC RULE 250B - RESULT SUMMARY TABLE

	Structure Type	230kV I-String Tangent			230kV 5° Running Angle			230kV 15° Running Angle			230kV 30° Running Angle			230kV 45° Running Angle			230kV 60° Dead-End			230kV 90° Dead-End		
	Structure Plan View																					
Conductor Size and Conductor Tension Limits	(Min, Median and Max Results)	Controlling NESC 250B Equiv. MRI [Years]	Probability of Load Exceedance for Corresponding MRI [PE_{50YR}]	Moment Ratio $\frac{M_{250B\ W/L.F.}}{M_{PROB\_100\text{-}YR}}$	Controlling NESC 250B Equiv. MRI [Years]	Probability of Load Exceedance for Corresponding MRI [PE_{50YR}]	Moment Ratio $\frac{M_{250B\ W/L.F.}}{M_{PROB\_100\text{-}YR}}$	Controlling NESC 250B Equiv. MRI [Years]	Probability of Load Exceedance for Corresponding MRI [PE_{50YR}]	Moment Ratio $\frac{M_{250B\ W/L.F.}}{M_{PROB\_100\text{-}YR}}$	Controlling NESC 250B Equiv. MRI [Years]	Probability of Load Exceedance for Corresponding MRI [PE_{50YR}]	Moment Ratio $\frac{M_{250B\ W/L.F.}}{M_{PROB\_100\text{-}YR}}$	Controlling NESC 250B Equiv. MRI [Years]	Probability of Load Exceedance for Corresponding MRI [PE_{50YR}]	Moment Ratio $\frac{M_{250B\ W/L.F.}}{M_{PROB\_100\text{-}YR}}$	Controlling NESC 250B Equiv. MRI [Years]	Probability of Load Exceedance for Corresponding MRI [PE_{50YR}]	Moment Ratio $\frac{M_{250B\ W/L.F.}}{M_{PROB\_100\text{-}YR}}$	Controlling NESC 250B Equiv. MRI [Years]	Probability of Load Exceedance for Corresponding MRI [PE_{50YR}]	Moment Ratio $\frac{M_{250B\ W/L.F.}}{M_{PROB\_100\text{-}YR}}$
1272kcmil ACSR w/ NESC Limits	Min =	6	>99%	0.56	23	89%	0.69	63	55%	0.89	59	57%	0.98	59	57%	0.97	59	57%	0.98	55	60%	0.97
	U.S. Median =	80	47%	0.98	491	10%	1.24	2,476	2%	1.49	3,015	2%	1.47	3,845	1%	1.47	3,860	1%	1.47	5,927	1%	1.47
	CAN. Median =	91	43%	0.97	669	7%	1.29	2,026	2%	1.36	2,673	2%	1.40	2,026	2%	1.48	2,673	2%	1.46	2,673	2%	1.53
	Max =	3,806	1%	1.71	38,868	<1%	1.77	100,000	<1%	1.76	100,000	<1%	1.82	100,000	<1%	1.90	100,000	<1%	1.87	100,000	<1%	1.90
1272kcmil ACSR w/ Reduced Limits	Min =	7	>99%	0.56	18	94%	0.64	29	83%	0.74	37	75%	0.80	34	78%	0.79	34	78%	0.80	31	81%	0.78
	U.S. Median =	86	44%	0.98	448	11%	1.19	753	6%	1.37	992	5%	1.37	945	5%	1.31	999	5%	1.31	1,041	5%	1.30
	CAN. Median =	91	43%	0.98	507	9%	1.26	669	7%	1.27	1,163	4%	1.28	2,128	2%	1.34	1,671	3%	1.31	4,875	1%	1.42
	Max =	3,806	1%	1.72	13,747	<1%	1.76	22,681	<1%	1.67	61,853	<1%	1.78	100,000	<1%	1.89	100,000	<1%	1.83	100,000	<1%	1.98
795kcmil ACSS w/ NESC Limits	Min =	7	>99%	0.56	18	94%	0.64	26	86%	0.72	33	79%	0.78	39	73%	0.82	43	69%	0.89	43	69%	0.87
	U.S. Median =	91	42%	0.99	448	11%	1.19	899	5%	1.38	1,001	5%	1.40	1,065	5%	1.38	1,383	4%	1.38	1,804	3%	1.39
	CAN. Median =	104	38%	1.01	507	9%	1.25	1,164	4%	1.30	1,481	3%	1.28	4,394	1%	1.36	2,710	2%	1.32	9,075	1%	1.41
	Max =	3,806	1%	1.70	15,638	<1%	1.74	27,439	<1%	1.67	86,988	<1%	1.71	100,000	<1%	1.79	100,000	<1%	1.73	100,000	<1%	1.83
795kcmil ACSS w/ Reduced Limits	Min =	7	>99%	0.56	18	94%	0.58	27	84%	0.74	37	75%	0.80	44	68%	0.81	39	73%	0.81	51	63%	0.80
	U.S. Median =	91	42%	0.99	433	11%	1.16	643	7%	1.35	1,004	5%	1.38	945	5%	1.35	999	5%	1.34	999	5%	1.33
	CAN Median =	104	38%	1.01	384	12%	1.24	881	6%	1.26	3,834	1%	1.23	6,887	1%	1.31	6,546	1%	1.26	3,451	1%	1.36
	Max =	3,806	1%	1.70	13,747	<1%	1.75	19,547	<1%	1.68	50,841	<1%	1.72	100,000	<1%	1.81	78,595	<1%	1.74	100,000	<1%	1.85

Consistent trends that occurred for all the different modelled conditions are as follows:

1) *There was a significant variation in equivalent MRIs for the selected cities that were analysed:* The variable of location created the highest amount of variation in equivalent MRIs. This high variation in equivalent MRIs shows that the Deterministic NESC Rule 250B simplified loading districts, provides inconsistent and less accurate design loads as compared to the probabilistic design loads. Some locations may underestimate the design loads while others may significantly overestimate design loads.

2) *In general, as the supported line angle increases, the equivalent MRIs increase:* As the line angle increases, more of the total transverse load applied to the structure comes from the tensioned conductors and the NESC Rule 253 requires a load factor of 1.65 applied to the wire tension from NESC Rule 250B. This load factor on transverse wire tensions creates higher design loads for heavy angle and dead-end structures than for tangent and light angle structures. Therefore, the equivalent MRIs generally increase as the supported line angle increases. However, the increase in equivalent MRIs level off for the structures that support a line angle of 30 degrees or more.

3) *In general, the tangent and small angle structures equivalent MRIs are controlled from the adjusted wind speeds, and the heavy angle structures equivalent MRIs are controlled from adjusted ice thicknesses:* The transverse loads from wire tensions on tangents and light angle structure are relatively low due to the small line angles. Most of the applied load for tangents and light angle structures comes from transverse wind pressure applied to the projected area of the conductors and pole. As the line angle increases so too does the transverse component of the wire tensions. At a line angle of 30 degrees, approximately two-thirds of the equivalent MRIs are controlled from the adjusted ice thicknesses.

4) *Conductors with higher rated breaking strength (RBS) on average exhibited slightly higher equivalent MRIs, and transmission lines with higher conductor tension limits exhibited slightly higher MRIs.* Structures supporting conductors with higher tension will exhibit higher equivalent MRIs. NESC Rule 253 requires a load factor of 1.65 to be applied to the transverse wire tensions from NESC Rule 250B. Conductor tensions are set as a percentage of the conductor RBS. The higher the RBS or the higher the conductor tension limit, the higher the conductor tension. When applying this 1.65 factor the magnitude of increased tension is larger for high tension conductors loads than for low tension conductor loads. Therefore, the adjusted wind speeds or adjusted ice thickness must be larger for the highly tensioned conductors, and this results in higher equivalent MRIs for the structures that support conductors with high tensions.

5) *The Canadian cities exhibited similar trends when the loads from NESC 250B were applied in Canada.* The same trends that were observed for locations in the United States would be observed for Canada if NESC were to be a legislated code. However, the legislated code in Canada is CSA C22.3 No. 1-18 (Overhead Systems). Clause 7 of CSA C22.3 specifies a deterministic load case that is very similar to the NESC 250B deterministic load case, however, the CSA deterministic load case is only applicable to voltages up to 45 kV. For voltages higher than 45 kV, CSA C22.3 No. 60826:19 (Design Criteria of Overhead Transmission Lines) provides requirements for reliability-based design for a baseline MRI of 50 years. However, load factors are provided to adjust the climatic loads (i.e., wind and ice) to MRI of 150 or 500 years. These higher MRI are recommended for critical structures or lines.

IV. DISCUSSION

A. Future Loading Standards for Transmission Line Design in the United States

Currently, the NESC is the primary legislative code that is specified in 45 of 50 states in the United States. California specifies its own overhead line design specification called General Order 95, and the states of Georgia, Louisiana, Massachusetts, and South Dakota do not specify legislative loads. However, for the states that do specify the NESC, it is important to recognize that it is not a structural design code. It is a safety code.

The ASCE has been tasked with creating a loading standard for the structural design of overhead utility lines. This loading standard committee started meeting in the fall of 2021 and it is likely the standard will not be completed until the end of 2026. This standard is promoting RBD methodology and specifies probabilistic load cases for the structural design. It also will specify many different loading conditions that are not specified in the NESC.

One major question for the industry is what MRI is appropriate for the structural design loads of transmission lines. As shown in Table VI, some locations in the United States have designs that are controlled by probabilistic loads with 50 or 100-year MRIs and the structural reliability of the transmission lines in these cities has proven to be adequate. Have cities that have high equivalent 250B MRIs been designing with conservative design loads? Or is the relative reliability between different cities not as dramatic as the varying equivalent MRIs due to different structural design criteria used by different utilities in different cities?

It is our hope that this research can help advise the ASCE committee to specify loads with appropriate MRI and appropriate load factors. Many of the arguments against specifying design loads with higher MRIs state that it will create a more conservative design which will cost more money to construct. This research shows that many of the cities analysed, for structures that support a line angle of 30 degrees or more are already designed to resist loads that have an equivalent MRI that is significantly higher than the 50-year MRIs specified in the NESC, or the 100-year MRIs recommended in ASCE No. 74.

V. CONCLUSION/RECOMMENDATIONS

The equivalent MRIs and moment ratios exhibit a large amount of variation across the country. The equivalent MRIs and moment ratios vary significantly due to location and structure type, conductor type and the tension limits. In general structures with larger line angles have higher equivalent MRIs and moment ratios. Tangent structures have the lowest equivalent MRI, and, on the average, the equivalent MRIs are close to the 100-year MRI of the probabilistic extreme wind load case.

As was discussed previously, significantly more damage could be caused to a transmission line if a heavy angle or dead-end structure failed as compared to a failure of a tangent structure. For this reason, structures with large line angles or dead-end structures could be considered "Critical Structures." The effect of the NESC Rule 253 load factor of 1.65 that is applied to transverse wire loads and dead-ends, causes these critical structures to have much higher equivalent MRIs. However, the NESC Rule 250B equivalent MRIs are not consistent across the country. This could potentially lead to highly varying levels of reliability in different parts of the country. Using the probabilistic load cases to design transmission line structures would create consistent MRIs across the nation. The ASCE No. 74 recommends using 100-year MRIs, but our analysis shows that in most locations for structures with line angles greater than 30 degrees, the structural equivalent MRI from NESC Rule 250B with Load Factors are more than 300 years. We have also discussed how structures that support large line angles could be considered more critical to the overall performance of the transmission line than tangent structures. Perhaps specifying probabilistic design loads with higher MRI is appropriate for these structure that support large line angles. There are potentially two ways that this could be done:

The first way would be to design these critical structures using probabilistic loads with a higher MRI, for example, a 300-year MRI. This would be the more accurate and precise way of specifying loads for reliability-based design. However, it could be more difficult to implement because every structure is connected with conductors or wires. For the tangent structures that are adjacent to dead-end, would half the tangent span have a 300-year MRI applied loads and the other half the span have 100-year MRI applied loads? There are likely many ways to implement this correctly and accurately but if the process is difficult to understand or difficult implement it will be challenging for a typical transmission line engineer to adopt this process.

The second way would be applying a 100-year MRI design loads as a base load to all structures. Then for the critical structures, apply a load factor to the 100-year MRI design loads. This way, the increases in design loads could be isolated to just the critical structure types. This method would be simple to implement and would be easier to adopt. Unfortunately, applying a load factor to the 100-year MRI probabilistic loads can create different equivalent MRIs depending on location and which probabilistic load case controls the design.

As discussed above, the primary program used to design transmission lines is called PLS-CADD. To specify different wind speeds or different load factors applied to different structure types would also require changes to the design software.

Acknowledgment

This research would not be possible without the help of several people. Dr. Jerry Wong and Dr. Leon Kempner who have spent much of their careers promoting reliability-based design methodology and provided valuable advice on the proposed methodology of calculating equivalent MRI for NESC Rule 250B as well as providing critical contact information.

The authors would also like to thank Austin Baughman, who created 12 different PLS-CADD models and extracted thousands of base moment reactions that were needed to analyse the adjusted wind speeds and adjusted ice thicknesses. The authors thank Austin for the many hours of his own time that were spent to model and gather this data.

The authors also thank RonaMay Chilton who provided technical editing and formatting assistance to adequately display the figures and tables. Her assistance was critical.

The lead author would also like to thank his company, Ulteig, for giving him the freedom and flexibility to pursue this research topic. Many otherwise "billable hours" were spent processing this data and writing this paper and many other consulting engineering companies would not allow their employees to invest so much time on a non-billable research project.

References

[1] Insitute of Electrical and Electronics Engineers, Inc. (IEEE), National Electrical Safety Code, New York: IEEE, 2017.

[2] A. H. Peyrot and H. J. Dagher, "Reliability-Based Design of Transmission Lines," *Journal of Structural Engineering,* vol. 110, no. 11, pp. 2758 - 2777, 1984.

[3] G. C. Parent, B. Hubbard and J. Ratliff, "The History and Accuracy of NESC Rule 250B," in *Transmission and Substation Design and Operation Symposium*, Frisco, Texas, 2019.

[4] D. Scholes, Fundamental Considerations Governing the Design of Transmission-Line Structures, Atlantic City: A.I.E.E., 1908.

[5] T. Worcester, Some Mechanical Considerations of Transmission Systems, Schenectady: A.I.E.E., 1912.

[6] American Society of Civil Engineers, Guidelines for Electrical Transmission Line Structural Loading, Reston: ASCE, 2020.

[7] American Society of Civil Engineering, Reliability-Based Design of Utility Pole Structures, Reston: ASCE, 2006.

[8] American Society of Civil Engineers, (ASCE/SEI 7-22), Minimum Design Load and Associated Criteria for Buildings and Other Structures, Reston: ASCE, 2022.

[9] C. S. Association, CSA C22.3 No. 60826:19 Overhead Transmission Lines - Design Criteria, Toronto: CSA Group, 2019.

[10] J. Hosking and J. Wallis, Regional Frequency Analysis, New York: Cambridge University Press, 1997.

[11] F. Lombardo, A. Pintar, P. Vickery, E. Simiu and M. Levitan, Developements of New Wind Speed Maps for ASCE 7-16, NIST Special Publications, 2016.