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Material Structural Deficiencies of Road Bridges in the U.S.

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Abstract: This study analyzes the National Bridge Inventory in the U.S. to determine the relative structural deficiencies of bridge materials, comparing between the overall national values and each state, geographically. The analysis considers the most common bridge construction materials—concrete, steel, and prestressed/post-tensioned concrete. The results suggest need to reassess the efficacy of best performance practices for steel bridges and for states with structural deficiencies above the national average. Geographic consistency of structurally deficient bridge density with population density shows need to improve intervention strategies for regions with higher levels of service usage. The study also compares the relative operational lifespan of bridge materials in each state. The average structurally deficient bridge ages are lower than the 75-year life-cycle expectancy. Prestressed/post-tensioned concrete bridges reveal relatively lower lifespan. Over time, concrete and steel bridges show some gradual improvement with decreasing percentage of structural deficiency and increasing lifespan. Prestressed/post-tensioned concrete bridges reveal shifting earlier accumulation of structural deficiency for a particular age group. The study also reveals relative climate effects. Climate conditions correlate differently with the structural deficiency and life cycle of bridge materials in each state. Structurally deficient bridge densities show correlation with climate maps, especially under colder and moist conditions.

Keywords: bridges; bridge design; deterioration; life cycles; materials; construction materials; evaluation; structural behavior

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1. Introduction

The U.S. National Bridge Inventory (NBI) is compiled by the Federal Highway Administration (FHWA) as a unified database with information on road bridges from all states and territories [1,2]. A bridge is defined as having a span of more than 6.1 m (20 ft) [1]. Additionally, culverts may qualify to be considered bridge length and are included in the database. The recorded data items include technical and engineering categories. The structural status data include the evaluation of the deck, superstructure, and substructure of bridges for structural adequacy and safety. The evaluation is based on a rating scale from 9 (superior to present desirable criteria) down to 0 (bridge closed). A structural evaluation of 4 (meets minimum tolerable limits to be left in place as is) or lower qualifies a bridge as structurally deficient (SD) [3]. Structural deficiency is a diagnostic measure that results from separately rating the conditions of the structural components of a bridge [4–8]. The SD status of a bridge indicates the existence of one or more significant structural defect(s), often limiting its intended usage to ensure safety [6,8]. Overall, SD bridges impact the safety, mobility, and economy. Based on the NBI from 2016, there are 185 million daily crossings on nearly 56,000 SD bridges in the U.S. [9].

This study analyzes the NBI to determine the relative structural deficiencies of the most common bridge materials in each state, separately. The analysis includes the 50 states, Washington, D.C., and Puerto Rico. The NBI's construction material categories of concrete, steel, and prestressed/post-tensioned concrete (PC) are most common in the U.S. The comprehensive study compares the structural deficiencies of the national network-level with the individual state-level subsets of the different bridge materials. Comparison of the average age ranges of bridges reflects the relative potential of operational lifespan. The study also explores the extent of the correlation between the geographic distribution of the relative state-level structural deficiencies of each material with climate conditions. The results can help identify potential issues and improve the relative dependability and sustainability of bridge materials.

2. Inventory Distribution

Table 1 summarizes the counts of bridges in the NBI with a rated structural status at the end of the year 2015 by state [2], along with their designated alphabetic and numeric state codes [10]. The table details the counts of predominant kind of construction materials for bridge main span(s) of concrete, steel, and PC, based on the NBI's coded material categories. The sum of the counts of concrete, steel, and PC (C+S+P) bridges comprises 96.1% of all the bridges in the NBI. However, the percentages of each material and their sum in each state are different. Texas has the highest count with a total of 53,209 bridges, 29,237 concrete bridges, and 15,817 PC bridges. Ohio has the highest count of 11,844 steel bridges.

Figure 1 shows the overall percentage distribution of bridge counts in each state from the U.S. total. The map point on the top left shows the overall value for all of the U.S., followed by the maximum with the next highest and the minimum with the next lowest values. The next highest/lowest values provide a better outlook since some maxima/minima have extreme values. The value for Puerto Rico is shown on the bottom right as a map point, rather than a map shape, to discern relative color shades. The percentage concentration of all bridges is higher from Texas through the southern Midwest to the Mid-Atlantic, and California.

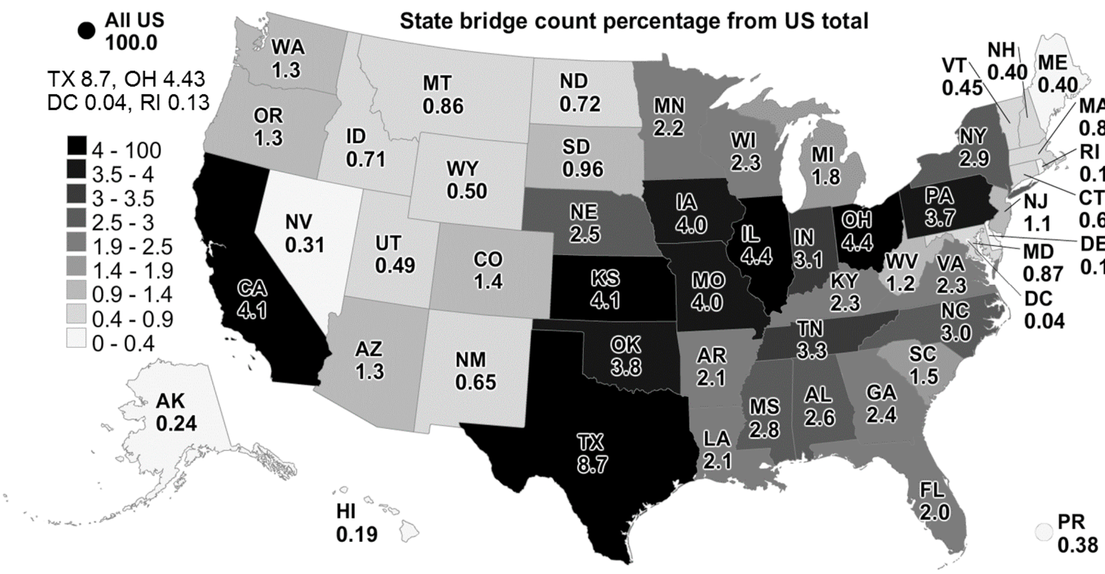


Figure 1. Percentage distribution of state bridge counts from U.S. total.

Table 1. Bridge Materials by State.

State	#	ST	Bridge Counts	Concrete Bridge Counts	Steel Bridge Counts	PC Bridge Counts	C+S+P Bridge Counts
Alabama	01	AL	16,095	10,614	2922	1705	15,241
Alaska	02	AK	1493	31	760	416	1207
Arizona	04	AZ	8056	5416	829	1768	8013
Arkansas	05	AR	12,853	7435	4904	189	12,528
California	06	CA	25,318	15,851	2787	5938	24,576
Colorado	08	CO	8,624	2693	2977	2510	8180
Connecticut	09	CT	4225	1015	2252	860	4127
Delaware	10	DE	875	229	403	179	811
DC	11	DC	254	66	163	24	253
Florida	12	FL	12,198	4334	1374	6014	11,722
Georgia	13	GA	14,790	8320	3856	2437	14,613
Hawaii	15	HI	1142	678	111	318	1107
Idaho	16	ID	4369	1248	848	1746	3842
Illinois	17	IL	26,674	8668	7127	10,741	26,536
Indiana	18	IN	19,145	5573	5172	7328	18,073
Iowa	19	IA	24,242	9316	8108	4751	22,175
Kansas	20	KS	25,047	14,909	7790	1320	24,019
Kentucky	21	KY	14,261	5724	2586	5759	14,069
Louisiana	22	LA	13,012	8148	1711	1665	11,524
Maine	23	ME	2431	747	1403	179	2329
Maryland	24	MD	5313	1426	3197	424	5047
Massachusetts	25	MA	5166	850	2990	1097	4937
Michigan	26	MI	11,086	1705	4592	4092	10,389
Minnesota	27	MN	13,299	6403	2380	3202	11,985
Mississippi	28	MS	17,057	9802	1691	4695	16,188
Missouri	29	MO	24,398	8347	11,288	4581	24,216
Montana	30	MT	5243	552	1290	2151	3993
Nebraska	31	NE	15,341	5402	7390	1536	14,328
Nevada	32	NV	1919	1178	250	477	1905
New Hampshire	33	NH	2470	710	1405	180	2295
New Jersey	34	NJ	6686	1219	3578	1541	6338
New Mexico	35	NM	3960	2109	593	1053	3755
New York	36	NY	17,457	3335	10,552	2859	16,746
North Carolina	37	NC	18,124	3730	8450	5130	17,310
North Dakota	38	ND	4401	1452	1218	1281	3951
Ohio	39	OH	27,100	7104	11,844	7835	26,783
Oklahoma	40	OK	23,049	9974	8104	4484	22,562
Oregon	41	OR	8037	2273	1132	3974	7379
Pennsylvania	42	PA	22,783	6705	7031	8413	22,149
Rhode Island	44	RI	766	186	392	154	732
South Carolina	45	SC	9344	5485	1320	2442	9247
South Dakota	46	SD	5866	2877	1569	1146	5592
Tennessee	47	TN	20,106	12,146	2558	5227	19,931
Texas	48	TX	53,209	29,237	7297	15,817	52,351
Utah	49	UT	3019	979	854	1078	2911
Vermont	50	VT	2749	793	1697	162	2652
Virginia	51	VA	13,884	5186	7071	1504	13,761
Washington	53	WA	8157	3121	1084	3427	7632
West Virginia	54	WV	7215	1427	3366	2287	7080
Wisconsin	55	WI	14,134	5924	3538	4050	13,512
Wyoming	56	WY	3085	1284	1409	246	2939
Puerto Rico	72	PR	2306	1029	347	925	2301
United States		US	611,833	254,965	179,560	153,317	587,842

3. Structural Deficiency

Table 2 summarizes the counts of SD bridges for concrete, steel, PC and the total of all bridge materials. Figure 2 shows the percentage distribution of SD bridge counts in each state from the U.S. total. Most of the SD bridges are around the southern Midwest towards the northern Mid-Atlantic, scattered in the Southeast, and California. The SD percentage ranges from 0.02% in DC and 0.06% in Nevada to 8.1% in Pennsylvania and 8.5% in Iowa.

Table 2. Structural Deficiency of Bridge Materials by State.

State	SD Concrete Bridge Counts	SD Steel Bridge Counts	SD PC Bridge Counts	SD Bridge Counts	Land Area (10^6 m^2 = km^2)
Alabama	418	610	19	1353	131,171
Alaska	3	81	19	148	1,477,953
Arizona	101	95	38	246	294,207
Arkansas	180	518	3	845	134,771
California	1091	475	314	2009	403,466
Colorado	89	306	58	521	268,431
Connecticut	77	234	35	357	12,542
Delaware	2	38	3	48	5047
DC	4	6	0	10	158
Florida	100	69	34	251	138,887
Georgia	189	459	29	729	148,959
Hawaii	47	6	5	60	16,635
Idaho	61	138	89	385	214,045
Illinois	703	1094	421	2244	143,793
Indiana	566	673	416	1717	92,789
Iowa	915	2888	273	5025	144,669
Kansas	669	1240	33	2303	211,754
Kentucky	394	559	203	1183	102,269
Louisiana	696	232	79	1838	111,898
Maine	99	243	3	361	79,883
Maryland	81	169	17	306	25,142
Massachusetts	52	345	33	461	20,202
Michigan	192	788	228	1299	146,435
Minnesota	163	353	76	810	206,232
Mississippi	767	581	27	2184	121,531
Missouri	747	2387	41	3222	178,040
Montana	18	220	44	411	376,962
Nebraska	154	1622	26	2474	198,974
Nevada	13	17	2	35	284,332
New Hampshire	60	187	5	312	23,187
New Jersey	90	378	50	596	19,047
New Mexico	78	78	40	267	314,161
New York	231	1558	133	1990	122,057
North Carolina	177	1418	201	2085	125,920
North Dakota	65	406	47	692	178,711
Ohio	464	1189	167	1893	105,829
Oklahoma	1058	2186	133	3776	177,660
Oregon	105	113	96	417	248,608
Pennsylvania	1618	1934	981	4783	115,883
Rhode Island	37	101	25	178	2678
South Carolina	585	238	109	1004	77,857
South Dakota	316	611	96	1156	196,350
Tennessee	419	431	110	1026	106,798
Texas	242	510	32	1008	676,587
Utah	27	34	17	95	212,818
Vermont	32	134	0	190	23,871
Virginia	215	808	27	1063	102,279
Washington	165	97	56	385	172,119
West Virginia	338	606	119	1092	62,259
Wisconsin	354	678	178	1282	140,268
Wyoming	91	225	27	370	251,470
Puerto Rico	132	102	60	296	8868
United States	15,490	30,468	5277	58,791	9,156,461

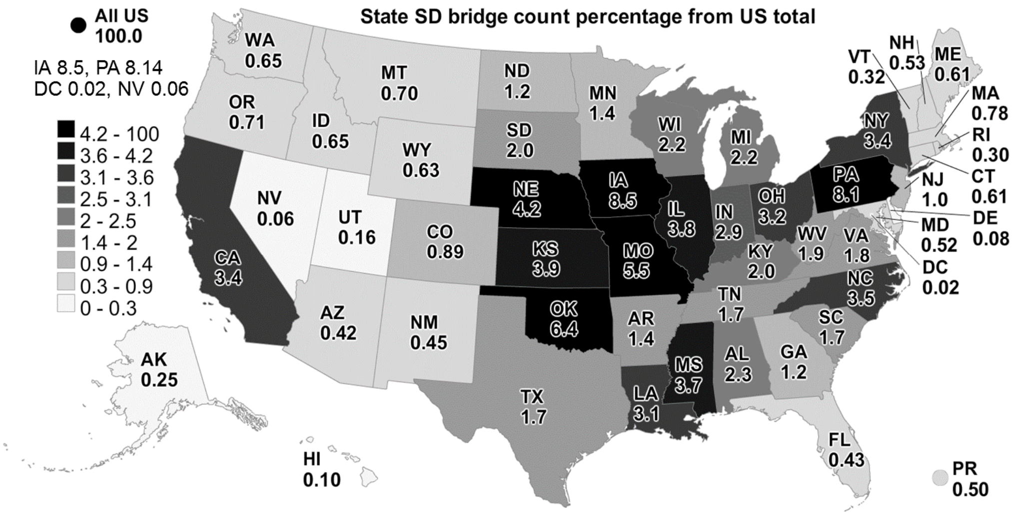


Figure 2. Percentage distribution of state structurally deficient bridge counts from U.S. total.

Figure 3 shows the respective SD bridge count percentages for concrete, steel, PC and all the bridges within each state, comparing between states and the overall national value. SD concrete bridge percentages are higher from around the Midwest through the Mid-Atlantic to the Northeast and scattered in the Southeast with a national average of 6.1%. SD steel bridge percentages are higher scattered around the Midwest, Southeast, Mid-Atlantic, and Northeast with a relatively higher national average of 17.0%. SD PC bridge percentages are higher scattered in the North, East, Southeast, California, and Alaska with a relatively lower national average of 3.4%. The overall SD bridge percentages are higher from around the Midwest to the western Southeast and from the south Mid-Atlantic to the Northeast, ranging from 1.8% in Nevada and 1.9% in Texas to 21% in Pennsylvania and 23.2% in Rhode Island with a national average of 9.6%. These results suggest the need to reassess the relative efficacy of best performance practices for steel bridges and for states with structural deficiencies above the national average.

Figure 4 shows the density (count/10^8 m^2 = count/100 km^2) of SD bridge counts per the land area in each state (Table 2) [11]. SD concrete bridge density is higher around the southern Midwest and scattered in the Southeast, Mid-Atlantic, and Northeast with a national average of 0.17. SD steel bridge density is higher around the southern Midwest, northern Southeast, Mid-Atlantic, and southern Northeast with a national average of 0.33. SD PC bridge density is higher around the eastern Midwest, northern Mid-Atlantic, and southern Northeast with a national average of 0.06. The overall SD bridge density is higher from around the Midwest through the central Mid-Atlantic to the southern Northeast, ranging from 0.01 in Alaska and Nevada to 6.3 in DC and 6.6 in Rhode Island with a national average of 0.64 bridges per 10^8 m^2. Overall, the SD bridge density of all bridges generally correlates with the population density map [12]. While concrete and steel bridges mostly match this correlation, PC bridges have some regional exceptions with lower SD density. The general geographic consistency of SD bridge density with population density suggests need to improve intervention strategies for regions with higher levels of service usage. Structural deficiency maps do not reveal any significant correlation with seismic hazard maps [13]. Regional comparisons show the relative awareness of local transportation agencies based on accumulated experiences.

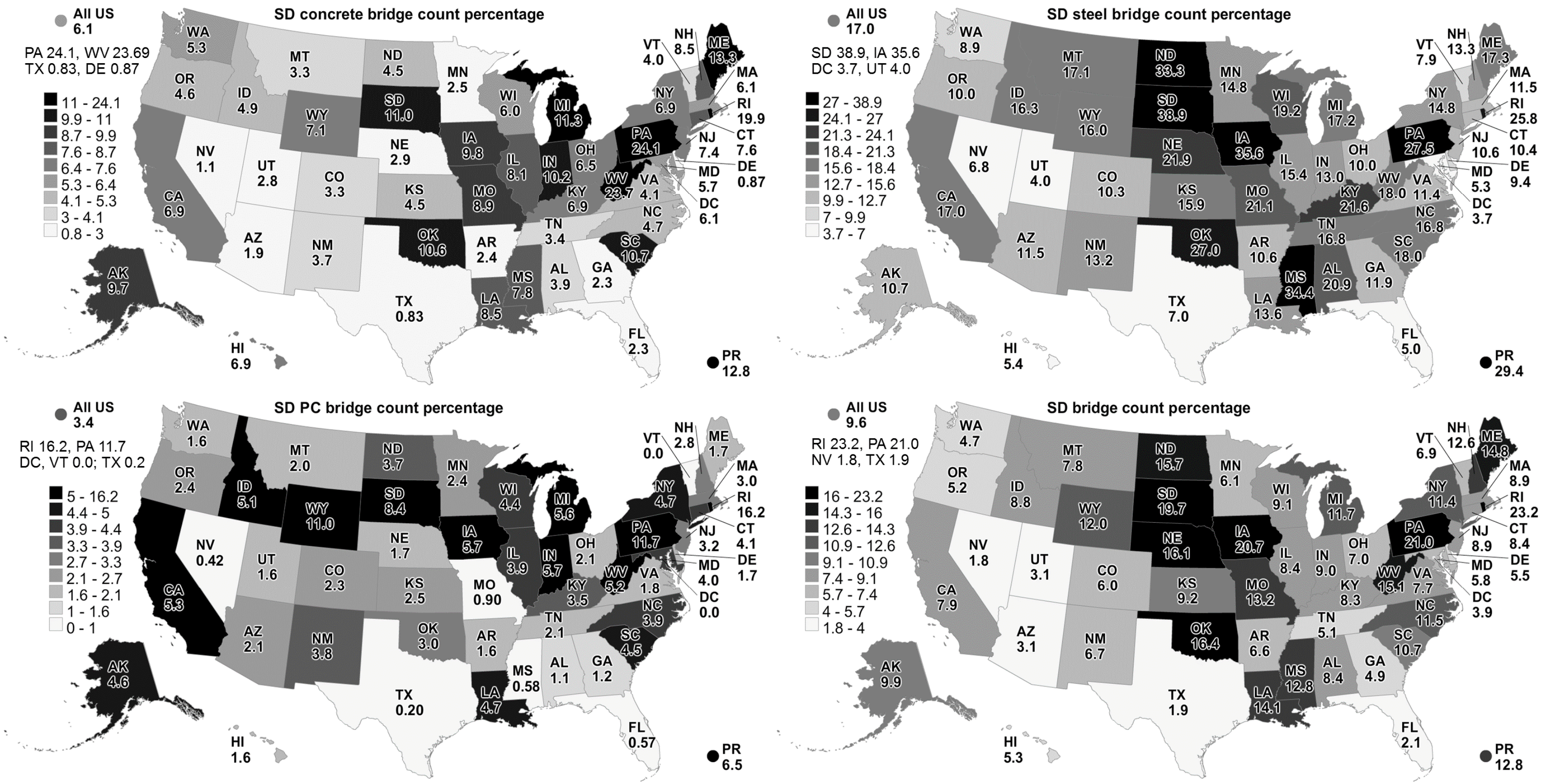


Figure 3. Structurally deficient bridge count percentage from state total.

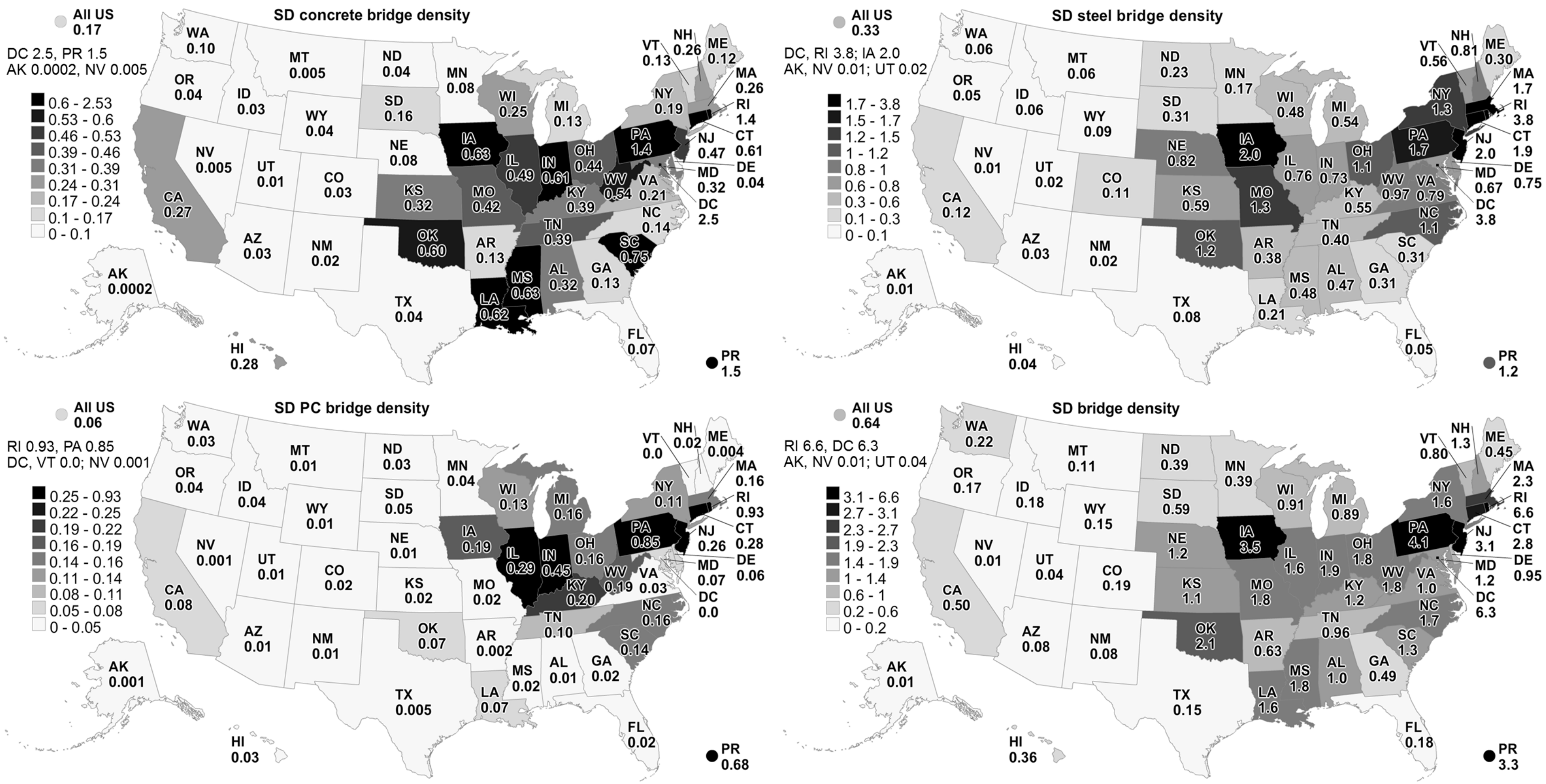
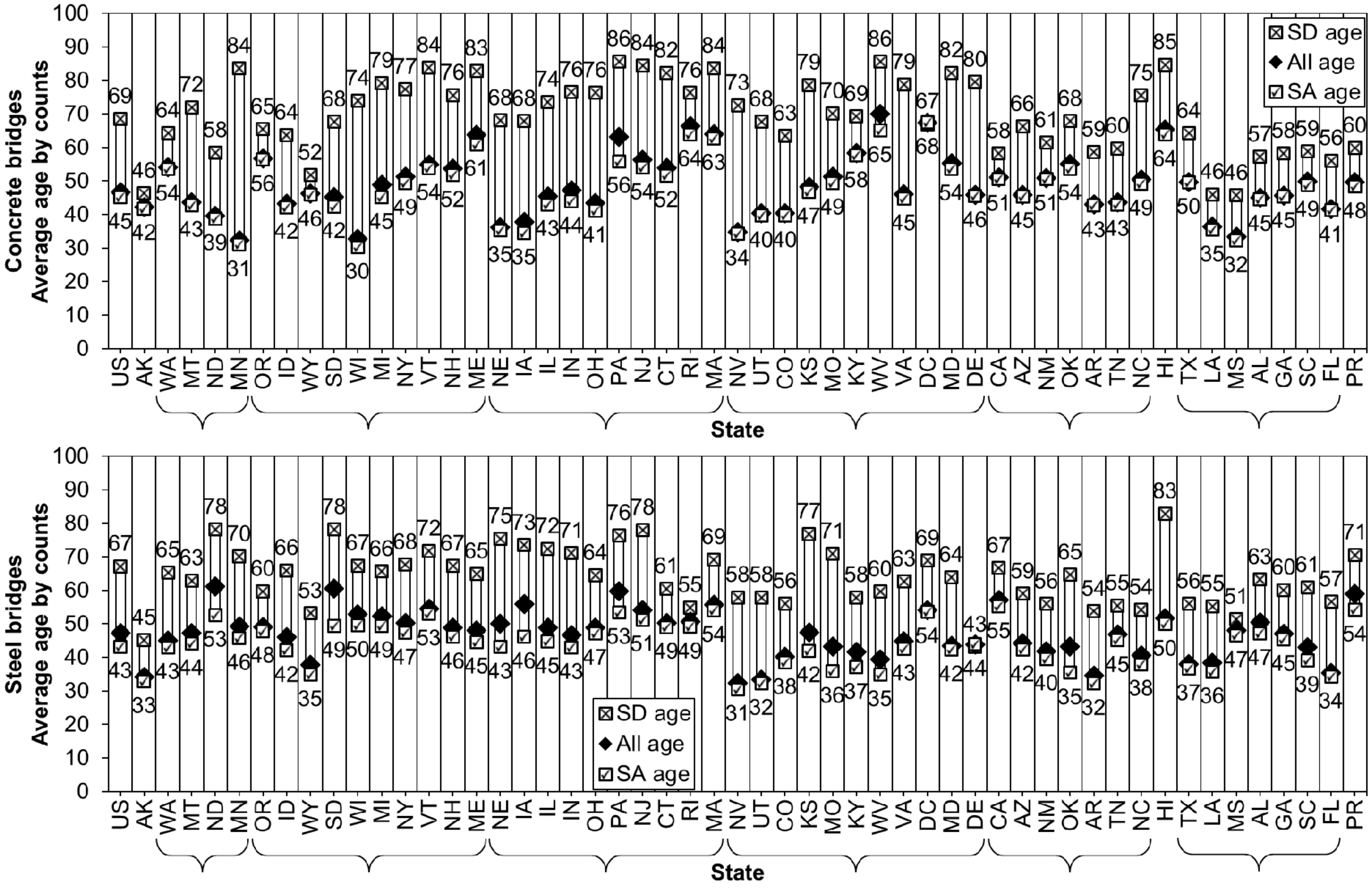


Figure 4. Density (count/10^8 m^2) of structurally deficient bridges by state.

4. Life Cycle

To observe relative service life-cycle dependability, Figure 5 summarizes side-by-side the average age ranges of all, structurally adequate (SA—not structurally deficient), and SD bridges for concrete, steel, PC, and all bridges in each state. States are arrayed in west-to-east strips (shown within horizontal braces) and sequenced north-to-south corresponding with their approximate geographic location. The national (US) average is set first for comparison. The overall position of the up-down bars and the ranges between the SD, all, and SA ages indicate relative potential of operational lifespan. The SA to SD age range reveals the average durability of SA bridges before they become SD. The centroid position of all age between SA and SD ages reveals the ratio of SA and SD bridges and how relatively older or newer they are. The west-to-east strips (within the horizontal braces) show a slight upward shift within each strip, showing that bridges are relatively older towards the east, more noticeably for concrete bridges. The average SD bridge ages are 69 for concrete, 67 for steel, 48 for PC, and 65 for all the bridges in the NBI. Overall, the average SD bridge ages are lower than the 75-year life-cycle expectancy before structural deficiency [14], showing need to improve service life-cycle. PC bridges reveal relatively lower operational lifespan with even younger SD bridges.



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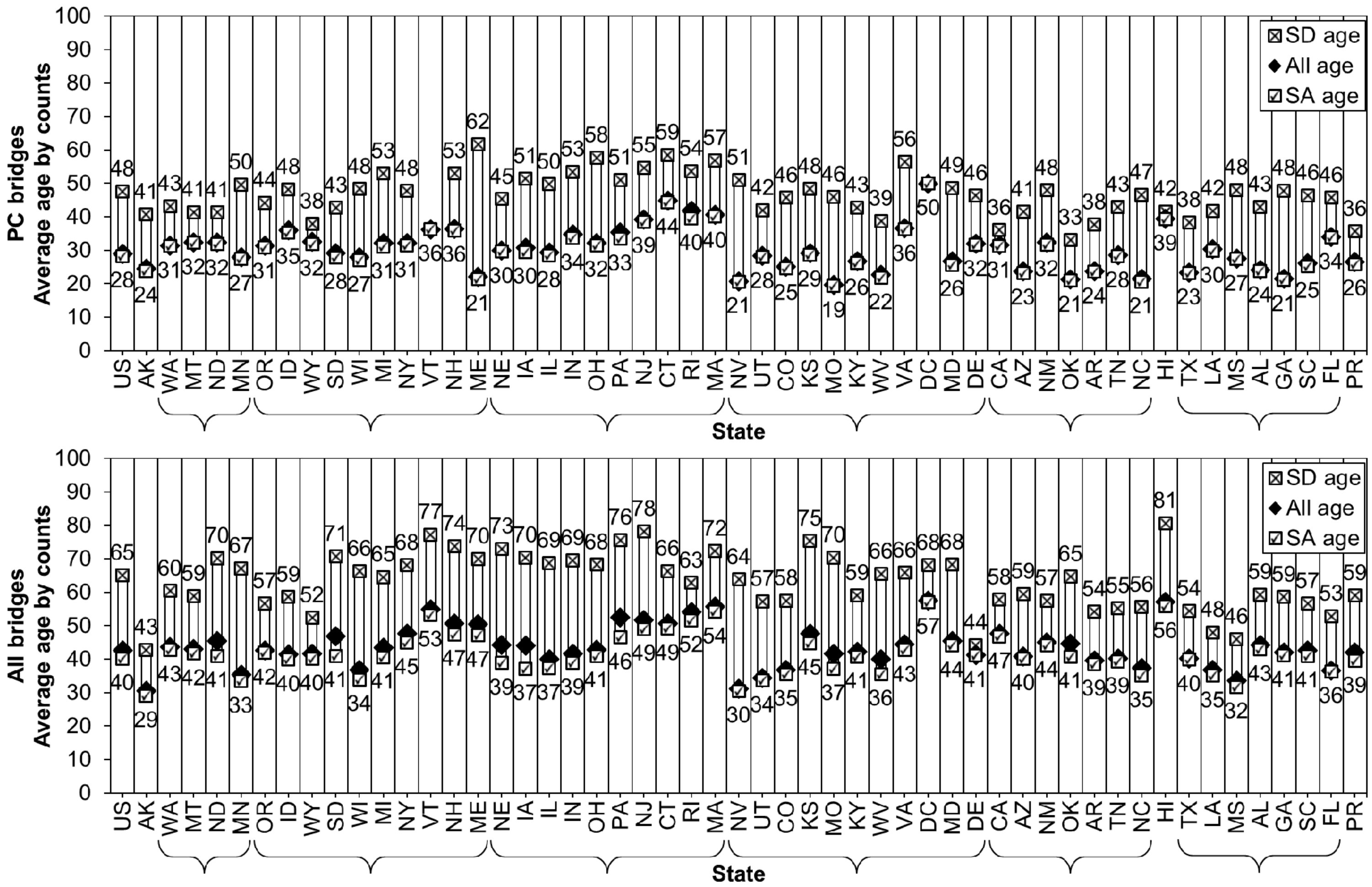

Figure 5. Average age ranges of bridges by state.

5. Distribution and Accumulation of Structural Deficiency

The distribution of the proportion of SD bridges relative to the respective total counts versus service life enables analysis of the deterioration [15]. Figure 6 shows the distribution of the SD percentages of concrete, steel, PC, and all bridges versus year built for the year 2015. The deterioration accumulates backwards as bridges age and wanes with decommissioning of older bridges. Intermittent interventions, lack of resources for periodic inspections, and inconsistent, inaccurate, and/or outdated status recording/reporting are analytically known reasons that create the annual uneven variances of structural deficiency. Thus, considering the context of time in applied statistics, a sixth-order polynomial trendline averages the distribution [16,17].

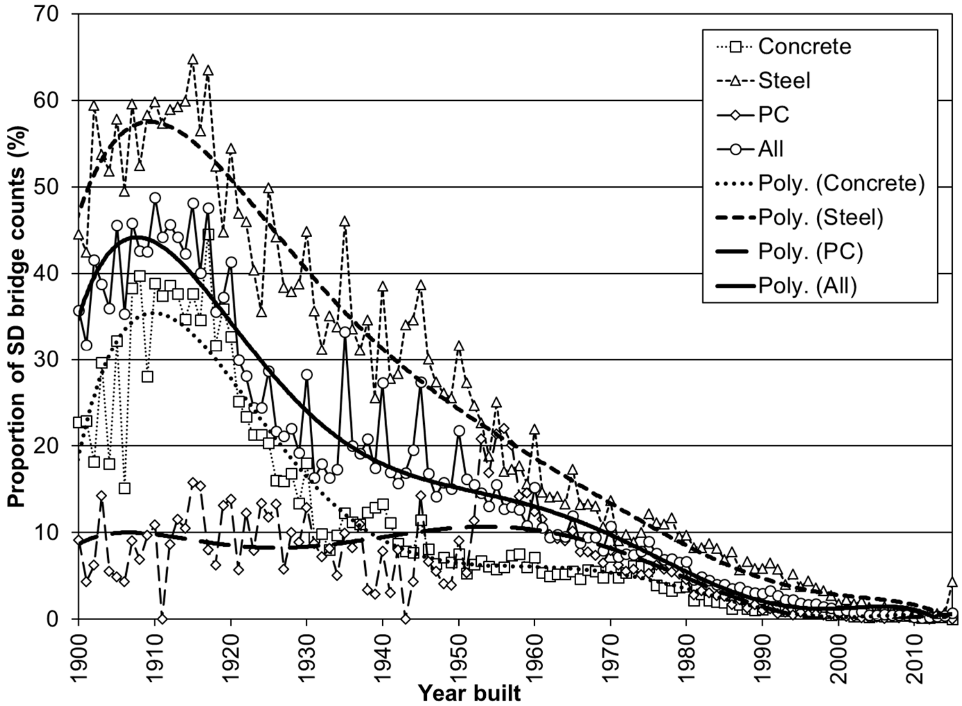

Figure 6. Distribution of the proportion of structurally deficient bridges.

Observation of the backwards accumulation outlines the relative deterioration over time, considering the maximum percentage of structural deficiency versus the lifespan it is reached for the different materials. The maximum average accumulation of structural deficiency is 35.43% at 105.15 years for concrete, 57.51% at 105.65 years for steel, 10.69% at 61.26 years for PC, and 44.17% at 107.30 years for all bridges. Steel bridges accumulate more structural deficiency than concrete bridges at comparable years. PC bridges accumulate significantly less structural deficiency while the trendline is nearly comparable to all the bridges backwards to the late 1970s. This shows that PC bridges older than the late 1970s have better performance with less accumulation of structural deficiency.

Observation of the distributions in Figure 6 enables to detect relatively earlier accumulation of structural deficiency caused by groups of bridges built during certain periods before the maximum. These critical accumulations can be associated with particular practices and technologies of construction and intervention during these periods, helping identify the etiologies of earlier deterioration. The proportional distributions of structural deficiency of each material in individual states can show such higher relative accumulation of deterioration in different time periods.

To observe the changes in deterioration over time, Figure 7 summarizes the maximum average accumulation of structural deficiency in percentage (thick line, left axis) along with the time span it was reached (thin line, right axis) for concrete, steel, PC, and all bridges for the years 2006, 2013, and 2015 [15,18]. Overall, concrete and steel bridges show some improvement—the maximum SD percentage is gradually decreasing while the time span is gradually increasing. The time span of PC bridges slightly declined from 2013 to 2015.

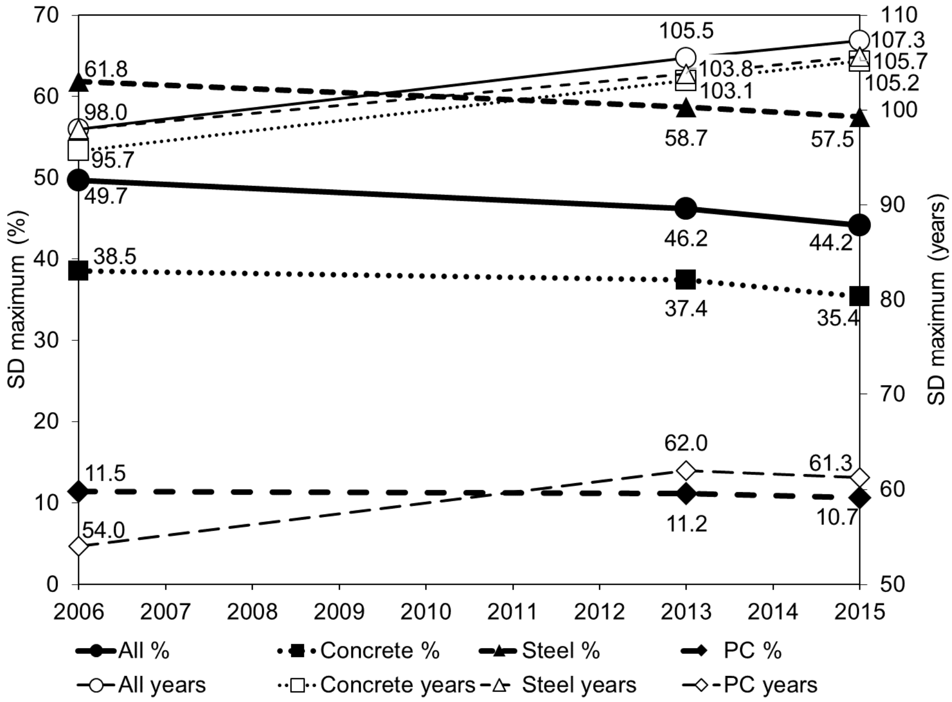

Figure 7. Maximum average accumulation of structural deficiency.

Analysis of PC bridges for the years 2006 and 2013 identified earlier accumulation of structural deficiency for a particular age (year built) group around the 1950s [15,18]. In 2013, this accumulation slightly widened, confirming the slight decrease in the time span. Comparison with the proportional distribution of SD PC bridges reveals a minor improvement, confirming the slight increase in 2015, but also a slight shift of this accumulation from the 1950s to the early 1960s.

6. Climate Conditions

Climate effects and associated issues affect bridge materials during preparation, manufacturing, construction, and service exposure. Climate also impacts the behavior of the bridge components and their interactions as a system. Furthermore, climate variables require the use of road treatment and deicing chemicals that accelerate bridge material deterioration. Over time, climate conditions have accumulating consequences on the structural condition and life cycle of bridges. The progression, climate effects, and outcome of bridge deterioration are essentially different for the various kinds of materials. Based on perceived experiences with the regional climate, bridge officials devise local best practices attempting to overcome climate-related issues on the various materials. To enable the development of data-driven decision-making tools at the level of individual states, it is necessary to provide national- and state-level analysis of bridge behavior [19] correlating materials to climate.

Climatic and related factors designate typical map regions: Frost Belt (Northeastern and northcentral cold states), Salt Belt (Northeast and Midwest states with extensive chemical deicing in winter), Snowbelt (Northeast and northern Midwest states with lake-effect snow around the Great Lakes), and Sun Belt (Southern, hot-weather states). Map zones of the freezing severity of winter and frost depth consider the magnitude and duration of below freezing air temperature based on a 100-year return period (Figure 8) [20]. In comparison, climate zones map of the severity and frequency of extreme weather conditions consider distinct hygrothermal conditions (Figure 9) [21].

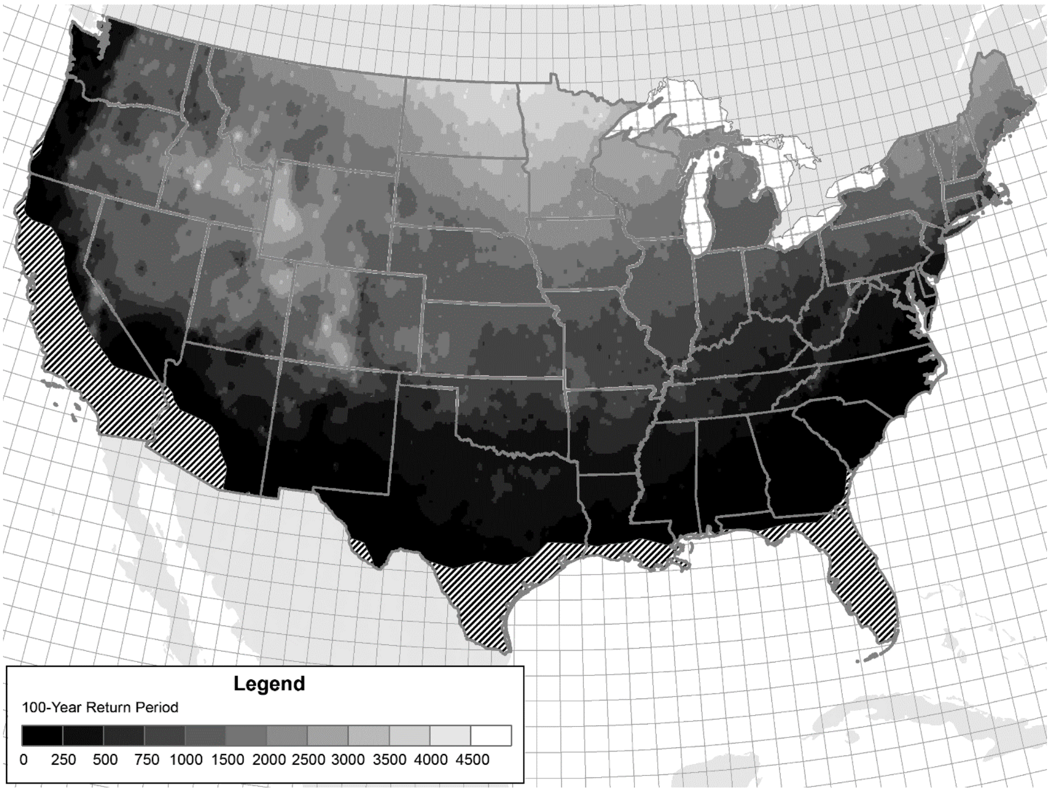

Figure 8. Freezing severity of winter and frost depth [20]. (Excerpt reprinted with permission).

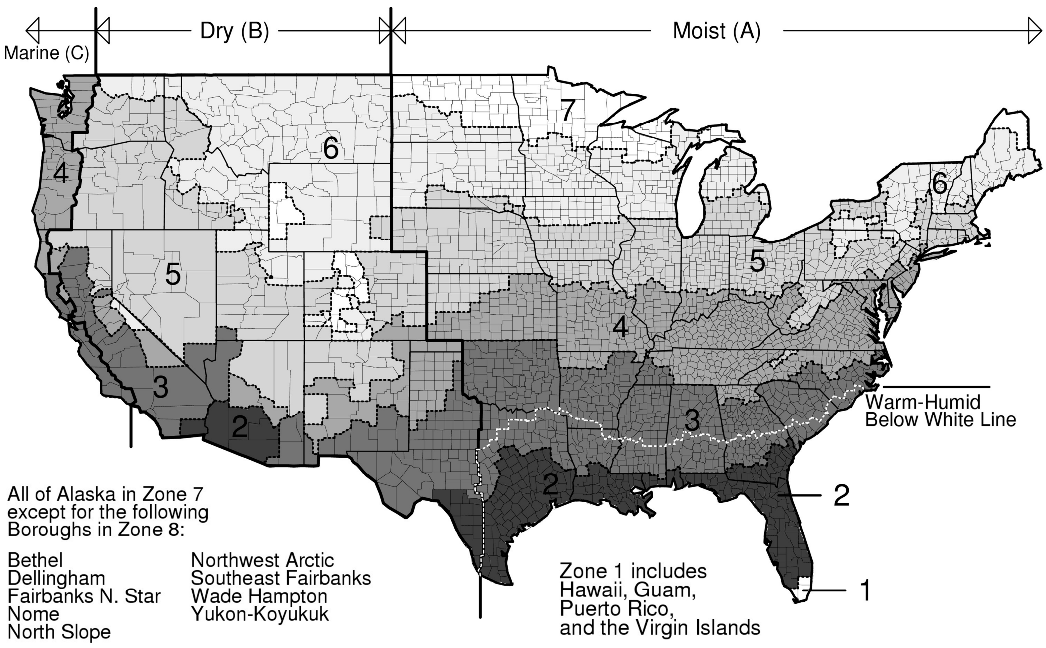

Figure 9. Severity and frequency of extreme weather conditions [21]. (Climate Zone Map, excerpted from the 2015 International Energy Conservation Code; Copyright © 2014 International Code Council, Inc., www.iccsafe.org. All rights reserved. Excerpt reprinted with permission).

Maps of bridge material structural deficiency by state (Figure 3) correlate in certain regions with the different climate zone variations showing the potential effect of climate. SD concrete bridge percentages are higher scattered around the Salt Belt. SD steel bridge percentages are higher scattered around the East and North. SD PC bridge percentages are higher scattered around northern states.

Maps of SD bridge material density by state (Figure 4) also show some correlation with climate maps. SD concrete bridge density shows scattered correlation around the southern Salt Belt, and the Southeast. SD steel bridge density shows scattered correlation around the eastern and western Salt Belt. SD PC bridge density shows scattered correlation around the Snowbelt. Overall, SD bridge densities reveal correlation with climate effects, especially under colder and moist climate conditions.

7. Discussion

Mapping the structural deficiencies of the various bridge materials by geographic location enables comparative analysis helps identify relative issues, and leads to improvement of sustainability. The comprehensive study by states highlights the need for even further efforts to achieve county-level comparative analysis. Regional correlations of structural deficiencies, service life cycle (age ranges), higher service usage, and climate conditions further enable comparative funding priorities for improved bridge management.

The approach of the proportional distribution of structural deficiency detects critical deterioration instances of age groups within a material category relative to its own general trend of proportional distribution of structural deficiency. In addition, it enables comparison relative to other materials and the overall deterioration trend. These comparative analyses can be implemented on various subsets of local/regional, category, and diverse bridge inventories. The perspective helps focus on the relative need for improvement of the life-cycle dependability of bridge age groups within material categories. In addition, it supports efficient prioritizing of applicable intervention resources to improve the management of the deteriorating bridge groups.

The SD status of bridges in the NBI simply states the presence of the restricting structural defect(s), and thus it is dichotomous (yes or no). It does not indicate further details, measure, and/or percentage on the nature, location, level, and value of severity of the structural defect(s). Recording and reporting of a prioritized and weighted percentage of structural deficiency for each bridge will increase the level of efficacy in bridge management.

Novel and automated methods associated with nondestructive testing and structural health monitoring reflect the ongoing trends in bridge management [22]. Besides, new structural codes are implementing advanced performance evaluation methods to assess structural state of existing buildings. Likewise, reliability based methods have become more and more popular in this field [23,24]. Latest examples combine experimental and theoretical methods developing hybrid bridge condition assessment techniques [25]. Therefore, it is indispensable to adopt quantitative and objective methods into the forthcoming bridge deficiency assessment applications.

8. Conclusions

This comprehensive national- and state-level comparative study analyzes the NBI to determine the relative structural deficiencies of the most common bridge construction materials—concrete, steel, and PC. The geographic distribution of the relative state-level structural deficiencies of each material enables regional and climatic correlations.

The SD bridge count percentage is 6.1% for concrete, 3.4% for PC, 17% for steel, and 9.6% for all the bridges in the NBI. SD bridge percentage maps show materials and states with structural deficiencies higher than the national average. SD density maps show that some states have structural deficiencies substantially above the national average, requiring intervention for improvement of their status. The corresponding cross-correlation between SD bridge density and population density requires to reassess intervention strategies for regions with higher usage levels, to improve satisfactory operational performance.

Comparing age ranges of bridge materials indicates the relative potential of operational lifespan. The average SD bridge ages are 69 for concrete, 67 for steel, 48 for PC, and 65 for all the bridges in the

NBI. These are lower than the 75-year life-cycle expectancy. The geographic distribution of materials and states with lower SD bridge ages shows the particular need for improvement of their operational lifespan before structural deficiency.

The distribution of structural deficiency versus service life shows higher relative accumulation of deterioration for steel bridges, requiring to reassess the efficacy of practices to improve their status. From 2006 to 2015, the deterioration rate of concrete and steel bridges show some improvement. PC bridges improved less, while their life cycle also declined from 2013 to 2015. The earlier accumulation of deterioration of PC bridge age subsets shifting from the 1950s to the 1960s requires observation of performance to examine intervention options for relative improvement.

Climate conditions show different effects on the various bridge materials. The state distributions of bridge structural deficiencies of the individual materials reveal correlation with climate effects and associated issues, especially under colder and moist climate conditions. This enables identifying regions and materials with critical issues to improve their structural condition.

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