20. FREQUENCY ANALYSIS OF EF-SCALE TORNADO DAMAGE INDICATORS

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ABSTRACT

The EF-Scale consists of 28 different damage indicators (DIs) with different degrees of damage (DOD) that are used to estimate tornado wind speeds and rate tornado EF scale intensities. In order to focus resources on improving the EF scale process and the estimated wind speeds, it is important to determine the most commonly used DIs.

To the author's knowledge, this paper presents the first analysis of DI frequency using data from the NWS Damage Assessment Toolkit (DAT). The data was first manually processed into a form that allowed the use of automated statistical analysis methods. The analysis results include: the frequency of events that contain each type of DI; the frequency of each DI across all tornado events; statistics on DIs with ratings equal to the tornado rating; the percentage of each DI within EF-Ratings; and the percentage of each DI used regionally. This analysis provides information to address the following questions: (1) how to focus resources on improving the EF scale; (2) what DIs are most commonly used to rate tornadoes for each EF scale intensity; (3) how many tornadoes are rated with wind speed-limited DIs; (4) how many DIs are rated the same as the tornado; and (5) how DI rating frequency changes with region.

1. INTRODUCTION

The Enhanced Fujita (EF) Scale (TTU, 2006) consists of 28 different damage indicators (DIs) with different degrees of damage (DOD) that are used to estimate wind speeds and rate tornado intensity. In order to focus resources when improving the EF scale process, it is important to develop and analyze the frequencies that individual DIs are used to estimate wind speeds. A quantitative analysis of the frequency of field-evaluated DIs has not been made since the EF scale was adopted by the NWS in 2007.

The NWS Damage Assessment Toolkit (DAT) (NOAA, 2016) is a GIS based framework that is used to collect and store geo-referenced tornado data. Tornado data is entered into the DAT during NWS damage surveys. The DAT interfaces with hand-held devices that allow surveyors to enter geo-tagged details for each DI, including, its location, DOD, EF rating, and damage photos. Contours of the damage intensity levels for the tornado path can also be drawn. The DAT has been beneficial in increasing the efficiency and accuracy of tornado damage surveys, as well as providing a central database for detailed tornado damage survey data. Data exists in the publicly available DAT database from 2008 to present, although the amount of data has largely increased in recent years as the DAT has developed and been adopted by more Weather Forecast Offices (WFOs). Figure 1 is a geographic plot of the DAT tornadoes from 2008 to 2015 that are analyzed in this paper. While not all WFOs may use the DAT, it is clearly being used by those offices in areas where tornadoes occur most frequently.

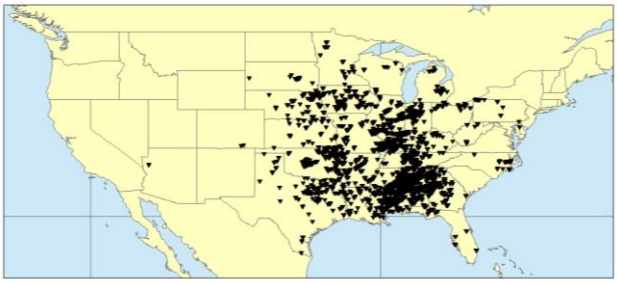

Figure 1. DAT Tornadoes (2008-2015)

A number of issues and uncertainties are involved in DI ratings and tornado damage surveys (see Twisdale et al. (2016) for a discussion of damage rating uncertainties and limitations). While these issues affect the data that is used herein, this paper does not discuss the issues and uncertainties involved in damage-based tornado wind speed ratings.

2. INITIAL PROCESSING OF DAT DATA

Each path line, DI, and contour exists within the DAT as a separate geometry entity. Examination of the DAT data found that many of the DIs, paths, and contours were not labeled with a unique event ID number. Each

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geometry object needs a unique ID number as well as an event ID number in order to automatically process and analyze the data. The event ID number allows a user to link together all of the geometries that exist for a single tornado, without displaying the data in a geographic interface, allowing the DIs to be processed by tornado. The DIs and tornado paths/contours were geographically plotted in ArcGIS. Based on location and date, the DI's, paths, and contours belonging to a single tornado were manually given a unique event ID number. It was sometimes difficult to distinguish which DIs belonged to the same tornado; hence, our matching may not be perfect.

The DAT data processing resulted in a dataset of 1,074 tornadoes, linked to their associated DIs, contours, and path lines. Table 1 gives the number and percentage of these tornadoes by EF scale. We note that there are only two EF5's in the dataset. Because most of the tornado data consists of groupings of rated DIs and not necessarily an overall rating, we set the tornado rating equal to the maximum rated DI in each tornado. We evaluated this method by randomly selecting 10 DAT tornadoes and matching them to their corresponding tornadoes in the SPC database. The maximum DI rating for each event was compared to the tornado's SPC rating. All 10 cases agreed, which tends to confirm the method used to determine the DAT tornado ratings.

Table 1. Number and Percentage of Tornadoes by EF-Scale in the Processed DAT Dataset

Rating	EF0	EF1	EF2	EF3	EF4	EF5	All
No. Tors.	267	525	187	69	24	2	1,074
% Tors.	24.9	48.9	17.4	6.4	2.2	0.2	100

Table 2 gives the number of tornadoes contained in the processed data by year. As mentioned above, the number of tornadoes with DAT data has increased with time as the toolkit has continued to be adopted and developed, which is apparent in Table 2. Note that the small number of tornadoes in year 2015 is because the data was downloaded in March 2015 and only contains information through February 2015.

Table 2. Number and Percentage of Tornadoes by Year in the Processed DAT Dataset

Year	'08	'09	'10	'11	'12	'13	'14	'15	'08-'15
No. Tors.	5	3	18	194	141	357	332	24	1074
% Tors.	0.5	0.3	1.7	18.0	13.0	33.0	31.0	2.2	100

3. DI FREQUENCY ANALYSIS

The number and percentage of each DI and of the tornadoes that include each DI are given in Table 3. The DI descriptions in Column 2 of Table 3 correspond to the Texas Tech abbreviations (TTU, 2006). Column 3 provides the number of tornadoes that contain each DI, and Column 4 gives the frequency of tornadoes that contain each DI (Column 3 ÷ 1,074 tornadoes). Column 5 gives the total number of each DI, and Column 6 contains the percent of each DI out of all DIs (Column 5 ÷ 17,397 DIs).

Table 3. Numbers and Percentages of Each DI and Tornadoes that Include Each DI

Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6
DI No.	DI Description	No. Tors. that Used the DI	Freq. of Tors. that Used the DI	Total No. of DI in All Tors.	% of DI in All Tors.
1	SBO	515	47.95	1,842	10.59
2	FR12	572	53.26	5,362	30.82
3	MHSW	211	19.65	744	4.28
4	MHDW	99	9.22	356	2.05
5	ACT	36	3.35	163	0.94
6	M	9	0.84	11	0.06
7	MAM	11	1.02	17	0.10
8	SRB	51	4.75	103	0.59
9	SPB	50	4.66	101	0.58
10	SM	22	2.05	42	0.24
11	LSM	1	0.09	1	0.01
12	LIRB	15	1.40	28	0.16
13	ASR	5	0.47	5	0.03
14	ASB	17	1.58	20	0.11
15	ES	26	2.42	34	0.20
16	JHSH	12	1.12	14	0.08
17	LRB	24	2.23	47	0.27
18	MRB	4	0.37	5	0.03
19	HRB	1	0.09	2	0.01
20	IB	17	1.58	32	0.18
21	MBS	139	12.94	364	2.09
22	SSC	24	2.23	28	0.16
23	WHB	45	4.19	77	0.44
24	ETL	140	13.04	370	2.13
25	FST	13	1.21	15	0.09
26	FSP	57	5.31	93	0.53
27	TH	767	71.42	4,547	26.14
28	TS	552	51.40	2,974	17.09
Total				**17,397**	**100**

The percent of each DI out of DIs in all tornadoes (Column 6) is given in Figure 2, and the frequency of tornadoes that include each DI (Column 4) is given in Figure 3. Both Figure 2 and Figure 3 show that trees and single family houses dominate the DIs and tornado events. Other highly used DIs are barns, manufactured

homes, electrical transmission lines, and metal buildings.

The data in Table 3 and Figure 2 and 3 do not distinguish by EF scale. Table 4 gives the percentage of each DI within each EF scale. For example, from Table 4 we see that 9.3% of DIs rated EF0 are barns. Ratings greater than a DI's maximum potential rating are colored grey. The rank is given in the last column for the most commonly used DIs.

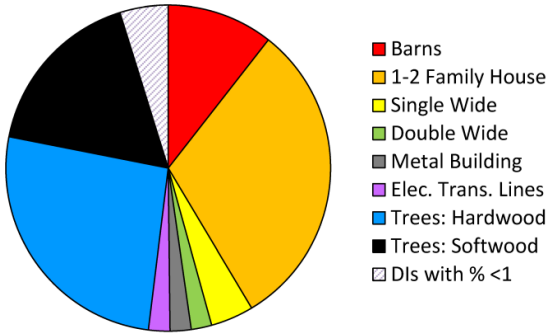

Figure 2. Fraction of DI in All Tornadoes

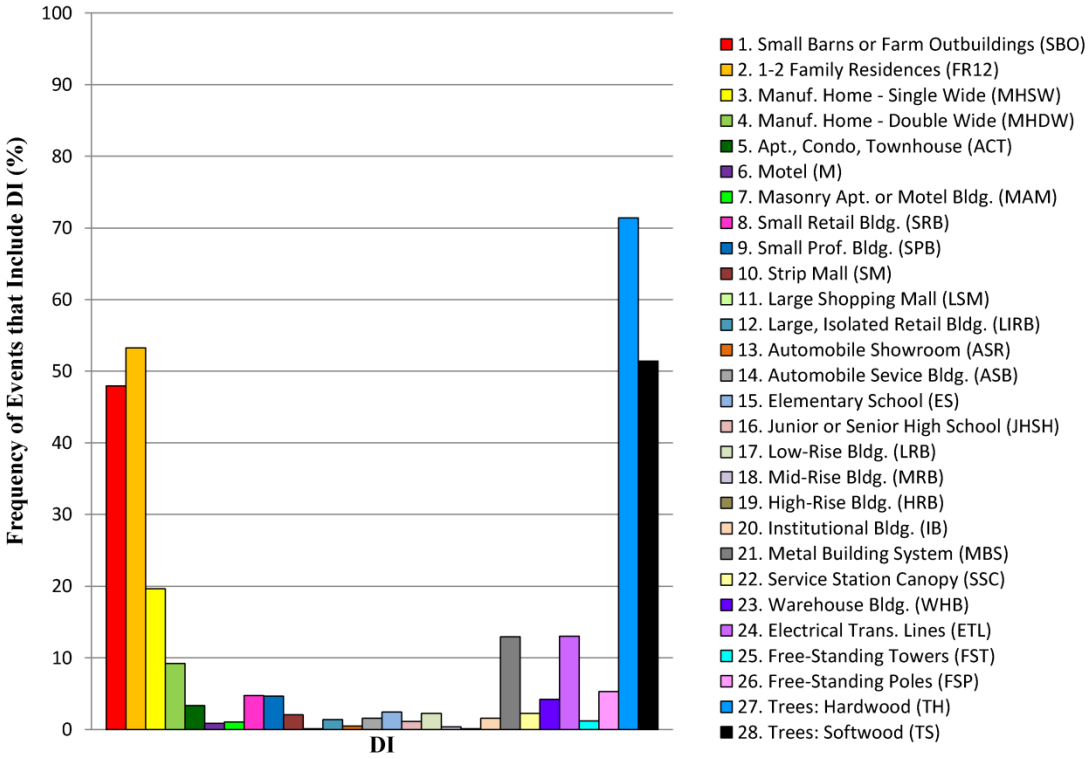

Figure 3. Percentage of Events that Used DI

Table 4. Frequency of Each DI within Each EF-Scale Rating

DI No.	DI Description	Percent of DIs within EF-Rating						Avg. Freq.	Rank Order
		EF0	EF1	EF2	EF3	EF4	EF5		
1	SBO	9.3	12.4	14.7				6.1	4
2	FR12	32.9	19.0	39.5	64.9	86.6	100.0	57.1	1
3	MHSW	2.8	3.6	11.9	2.8			3.5	5
4	MHDW	1.4	1.4	6.3	2.1			1.9	7
5	ACT	1.4	0.6	1.2	0.1	1.1	0.0	0.7	
6	M	0.0	0.1	0.2	0.0	0.0	0.0	0.1	
7	MAM	0.1	0.0	0.4	0.1	0.3	0.0	0.1	
8	SRB	0.6	0.4	0.5	1.1	3.0		0.9	9
9	SPB	0.6	0.5	0.5	1.4	0.0		0.5	
10	SM	0.2	0.3	0.2	0.2	0.5		0.2	
11	LSM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
12	LIRB	0.1	0.2	0.2	0.6	0.0	0.0	0.2	
13	ASR	0.0	0.0	0.0	0.1	0.0		0.0	
14	ASB	0.1	0.2	0.1	0.2	0.0		0.1	
15	ES	0.1	0.1	0.5	0.0	0.8	0.0	0.3	
16	JHSH	0.0	0.1	0.2	0.3	0.0	0.0	0.1	
17	LRB	0.1	0.1	0.8	0.9	0.3	0.0	0.4	
18	MRB	0.0	0.1	0.0	0.0	0.0	0.0	0.0	
19	HRB	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
20	IB	0.1	0.2	0.4	0.2	0.3	0.0	0.2	
21	MBS	1.1	1.9	2.8	8.6	1.6		2.7	6
22	SSC	0.1	0.2	0.2	0.0			0.1	
23	WHB	0.3	0.3	0.8	0.9	3.0		0.9	10
24	ETL	0.5	2.8	4.9	2.1			1.7	8
25	FST	0.0	0.1	0.3	0.2			0.1	
26	FSP	0.3	0.6	1.2	0.1			0.4	
27	TH	26.8	34.9	6.7	11.0	2.5		13.6	2
28	TS	21.1	19.9	5.5	2.1			8.1	3
Total %		100	100	100	100	100	100	100	

4. FREQUENCY OF DI'S USED TO RATE INTENSITY

Section 3 presented data on the frequency of DIs without consideration of what DI(s) were used in rating the tornado intensity. In this section, the analysis focuses exclusively on the frequency analysis of DIs used in tornado ratings.

Table 5 presents the frequency of tornadoes, by EF Scale and DI, where the DI was used to determine the tornado rating. If a DI has the same rating as the tornado, then we say that the DI was "used to determine the tornado rating." For example, from Table 5 we see that 39.6% of EF1 tornadoes contain at least one barn DI that is rated EF1. Ratings greater than a DI's maximum potential rating are colored grey. The average frequency by DI for all EF Scales and the rank order of the top 10 average frequencies are given in the last 2 columns of the table. On average, across all EF scales, the top DIs used to rate tornadoes are houses; trees; barns; metal building systems; single wide manufactured homes; electric transmission lines; double wide manufactured homes; apartments, condos, and townhomes; and warehouse buildings. Figure 4 plots the non-zero frequencies for each EF Scale from Table 5. We see that the most commonly used DIs to determine ratings are trees, barns, and houses for EF0-EF1; barns, houses, and manufactured homes for EF2; and houses for EF3-EF5.

We note that some DIs that were in the dataset had ratings greater than their maximum allowed rating (e.g., a barn rated EF3, since its maximum potential rating in the EF-Scale is EF2). This erroneous data was most likely data that accidentally made it through the quality control process, and these DI's (37 in total (0.2% of the DIs)) were neglected from this analysis.

As shown in Figure 3, barns are one of the most frequently used DI's. This result is not surprising, as the

majority of land area in the US contains rural land. Due to the typical construction features and quality of barns, the maximum EF-Scale rating that a barn can receive is EF2. This brings up the question of how many strong tornadoes were limited to a maximum rating of EF2 because they occurred in rural areas where barns were struck. This is also an issue for other highly used DIs with maximum potential ratings less than EF5, such as manufactured homes and trees.

Figure 4 shows higher percentages of barn DIs with ratings equal to the tornado rating for EF0 through EF2 tornadoes, with no barns in the plots for higher EF scales due to their upper limits. A similar trend is also observed with trees, which dominate in the lower rated tornadoes but drop off in the more intense tornadoes. It is also apparent in Figure 4 that one-two family residences are significant in the lower rated tornadoes and dominate the higher EF scale ratings. This result suggests that tornadoes that pass through areas of higher population density likely have higher ratings than tornadoes that pass through rural areas.

We also investigated the number of DI types and DIs with the same rating as the tornado. On average across all EF Scales, 2.1 different DI types are rated the same as the tornado. For EF0 to EF5 tornadoes, an average of 1.9, 2.3 1.8, 1.8, 1.6 and 1.0 DI types, respectively, are rated the same as the tornado. The slightly higher averages for lower EF scales may occur because more of the commonly used DIs are capable of rating less intense tornadoes. In addition, we analyzed the number of DIs that were rated the same as the tornado. We found that 100%, 60%, 21%, 11%, 6%, and 2% of DIs were rated the same as the tornado for EF0-EF5 tornadoes, respectively.

Table 5. Frequency of Tornadoes where DI Rating = Tornado Rating

DI No.	DI Description	Frequency of Tornadoes where DI Rating = Tornado Rating							
		EF0	EF1	EF2	EF3	EF4	EF5	Avg. Freq.	Rank Order
1	SBO	25.8	39.6	24.1				8.6	4
2	FR12	28.5	34.1	56.1	76.8	95.8	100	37.6	1
3	MHSW	6	11.8	17.1	13			4.6	6
4	MHDW	1.5	4.4	7.5	8.7			2.1	8
5	ACT	0	1.7	4.3	0	12.5	0	1.8	9
6	M	0.4	0.6	1.1	0	0	0	0.2	
7	MAM	0.4	0	2.1	1.4	4.2	0	0.8	
8	SRB	1.9	2.1	2.1	2.9	4.2		1.2	
9	SPB	3	1.3	1.6	4.3	0		1.0	
10	SM	0.7	1	0.5	0	4.2		0.6	
11	LSM	0	0	0	0	0	0	0.0	
12	LIRB	0	0.6	0.5	2.9	0	0	0.4	
13	ASR	0	0.2	0.5	0	0		0.1	
14	ASB	1.1	1	0.5	1.4	0		0.4	
15	ES	1.1	0.6	2.1	0	0	0	0.4	
16	JHSH	0	0.2	2.1	0	0	0	0.2	
17	LRB	1.5	0.6	2.7	4.3	4.2	0	1.2	
18	MRB	0	0.2	0	0	0	0	0.0	
19	HRB	0	0	0	0	0	0	0.0	
20	IB	1.1	0.8	1.1	1.4	0	0	0.4	
21	MBS	3.7	7.2	11.2	21.7	12.5		5.4	5
22	SSC	1.1	1.1	0.5	0			0.3	
23	WHB	2.2	1.7	3.2	4.3	4.2		1.5	10
24	ETL	1.1	8.2	13.9	15.9			3.8	7
25	FST	0.4	0.2	1.1	1.4			0.3	
26	FSP	1.5	3.4	3.7	1.4			1.0	
27	TH	61	63.6	17.6	14.5	16.7		16.6	2
28	TS	46.8	41.7	5.9	4.3			9.5	3
Total		190.8	227.9	183.1	180.6	158.5	100	100	

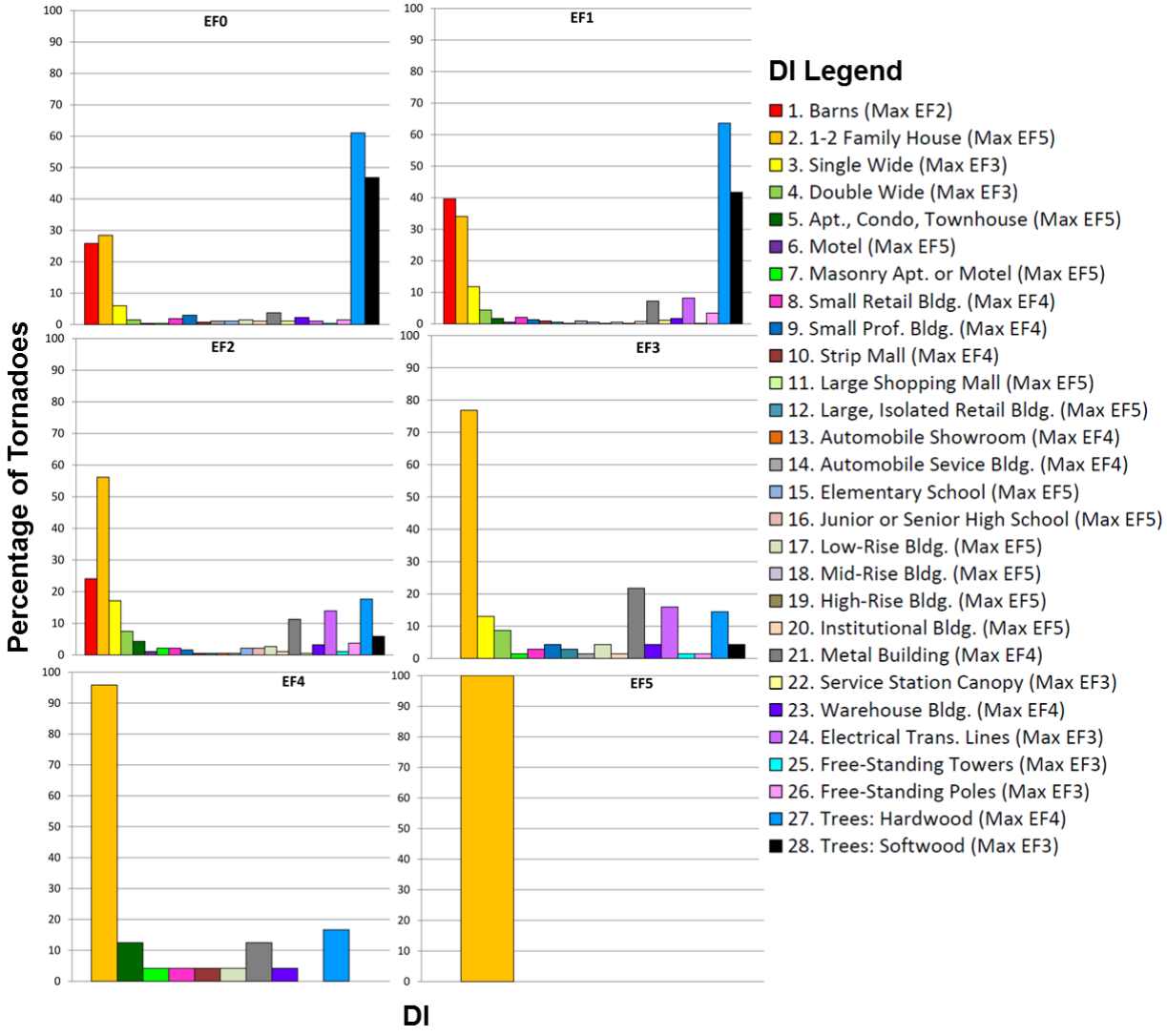

Figure 4. Frequency of Tornadoes, by DI, with at Least 1 DI Equal to the Tornado EF Rating

5. EXPLORATORY REGIONAL DI FREQUENCY ANALYSIS

DI frequency was examined by the regions shown in Figure 5. The regions consist of a Midwestern region (Region 1), a Greatlakes region (Region 2), and a Southeastern region (Region 3)[1].

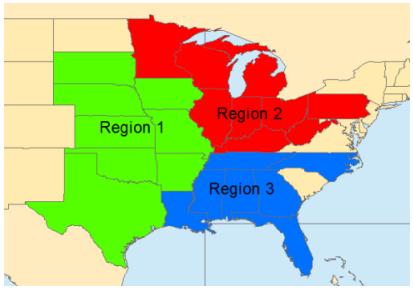

Figure 5. Regions Used for Exploratory Regional DI Frequency Analysis

The percentages of each DI out of all tornadoes, by region, are given in Table 6 and plotted in Figure 6. The largest portion of houses by region is within Region 1, which also contains the smallest portion of trees, consistent with the plains in the Midwest. Region 2 contains the largest portion of barns, and Region 3 contains the largest portion of trees. Additionally, a higher portion of Region 3 DIs is made up of manufactured homes, which are most common throughout the South (U.S. Census Bureau, 1980-2013). While there are some regional differences, the most commonly used DIs are consistent across regions. We also regionally compared the DIs frequently used to rate tornadoes (DI rating = tornado rating). Similar to the comparison discussed above, some regional differences were observed, although the top DIs used to rate tornadoes were consistent between the three regions. This preliminary analysis shows that the DIs used in tornado ratings can differ by region, although the most commonly used DIs are consistent between regions.

Table 6. Percentage of Each DI within Region 1, 2, and 3

DI No.	DI Description	Percentage of Each DI within Region		
		Region 1	Region 2	Region 3
1	SBO	10.4	18.8	8.0
2	FR12	44.0	22.0	18.6
3	MHSW	3.9	2.7	5.3
4	MHDW	2.7	1.5	1.5
5	ACT	1.5	0.3	0.5
6	M	0.1	0.0	0.1
7	MAM	0.1	0.2	0.1
8	SRB	0.3	0.4	0.9
9	SPB	0.4	0.5	0.8
10	SM	0.2	0.2	0.3
11	LSM	0.0	0.0	0.0
12	LIRB	0.3	0.2	0.1
13	ASR	0.1	0.0	0.0
14	ASB	0.1	0.1	0.2
15	ES	0.2	0.3	0.2
16	JHSH	0.1	0.1	0.0
17	LRB	0.2	0.2	0.3
18	MRB	0.0	0.0	0.0
19	HRB	0.0	0.0	0.0
20	IB	0.1	0.2	0.3
21	MBS	2.5	1.1	2.0
22	SSC	0.1	0.1	0.2
23	WHB	0.4	0.8	0.4
24	ETL	2.7	2.8	1.2
25	FST	0.0	0.1	0.1
26	FSP	0.4	0.7	0.5
27	TH	22.6	34.4	27.2
28	TS	6.6	12.3	31.2
Total		100	100	100

[1] There was no data in South Carolina and Virginia

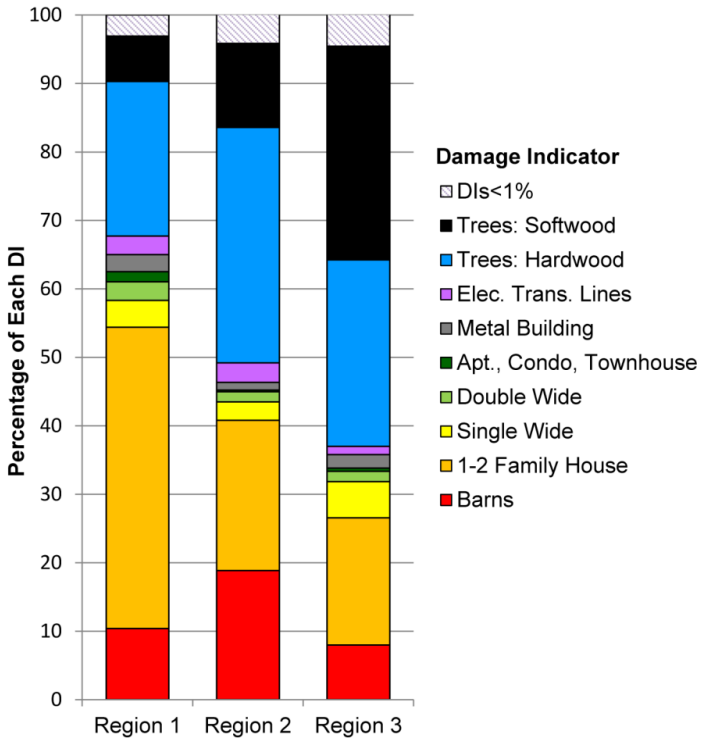

Figure 6. Percentage of Each DI within Region 1, 2, and 3

6. CONCLUSIONS & RECOMMENDATIONS

The DAT database has been analyzed to determine summary statistics relating to DI frequency. It is important to remember that this dataset is preliminary and does not contain data for all tornadoes that have been surveyed, and may only contain partial data for some tornadoes. Also, due to NWS time constraints, some of the tornadoes in the database may have been rated through more detailed surveys than others. This analysis took an initial look at the frequency of DIs that are used in rating tornadoes based on the initial 7 years of DAT data.

Table 7 shows the analysis results of the most commonly used DIs to rate damage of each EF-Scale. Houses are frequently used for all EF-Scales, and trees are often used to rate damage through EF4. Barns are frequently used through EF2, where they reach their upper limit. Manufactured homes are numerous within EF0-EF3 DIs, and EF5 DIs are entirely made up of houses in this analysis. Other top DIs used are metal building systems, warehouse buildings, apartments, condos, and townhomes, electrical transmission lines, and small retail buildings.

Table 7. Top 10 DIs within each EF Scale

DI Rank	Top DIs Used to Rate Damage					
	EF0	EF1	EF2	EF3	EF4	EF5
1	FR12	TH	FR12	FR12	FR12	FR12
2	TH	TS	SBO	TH	SRB, WHB	
3	TS	FR12	MHSW	MBS	TH	
4	SBO	SBO	TH	MHSW	MBS	
5	MHSW	MHSW	MHDW	MHDW, ETL, TS	ACT	
6	MHDW	ETL	TS	SPB	ES	
7	ACT	MBS	ETL	SRB	SM	
8	MBS	MHDW	MBS	LRB	MAM, LRB, IB	
9	SPB	ACT, FSP	ACT, FSP	WHB		
10	SRB	SPB	LRB	LIRB		

Trees and barns are often indicators of tornadoes occurring in rural areas. Unfortunately, tree ratings max out at the upper end of EF3 and lower end of EF4 ratings, and barns can only have a maximum rating of EF2, preventing their use in rating higher intensity tornadoes. Due to these upper limits of trees and barns, we hypothesize that tornadoes are often under rated in events where the tornado mostly only came into contact with these DIs. Houses are the most prominently used DI throughout all tornado intensities. Improvements made to the one-two family residences DI would have a

significant impact on the accuracy of tornado ratings. A preliminary study of DI frequency by region showed that the DI frequency results are dependent in part on location within the US.

More DIs are needed for one-two family residences to cover single family houses separately. As indicated by Twisdale et al (2016), the wind speed estimation for houses varies significantly with house characteristics and connection strength. DIs for other buildings need to be based on structural frame type and building size/height. Many of the DIs in the EF scale are based on usage instead of the structural type.

The implementation of the DAT has been very useful in increasing the amount of detailed tornado data that is available. In order for the public to be able to use the DAT to a fuller potential, we make the following suggestions: provide a unique tornado ID number to every geometry entity added for a tornado; add information on as many DIs as time allows; make all of the data collected in a survey available to the public; signify if a DI experienced its maximum DOD and hence is a lower limit of damage; enter all rated DIs into the DAT; and enter structures without damage as undamaged DIs.

7. ACKNOWLEDGMENTS

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