NASHVILLE TORNADOES

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PRELIMINARY VIRTUAL RECONNAISSANCE REPORT (PVRR)

Virtual Assessment Structural Team (VAST) Lead:
David Roueche, Auburn University

Virtual Assessment Structural Team (VAST) Authors:
(in alphabetical order)
Kevin Ambrose, Auburn University
Tracy Kijewski-Correa, University of Notre Dame
Laura Micheli, The Catholic University of America
Hadiah Rawajfih, Auburn University
Madeline Rihner, Auburn University

Virtual Assessment Structural Team (VAST) Editors:
(in alphabetical order)
David O. Prevatt, University of Florida
Ian Robertson, University of Hawaii at Manoa

PREFACE

The National Science Foundation (NSF) awarded a 2-year EAGER grant (CMMI 1841667) to a consortium of universities to form the Structural Extreme Events Reconnaissance (StEER) Network (see https://www.steer.network for more details). *StEER builds societal resilience by generating new knowledge on the performance of the built environment through impactful post-disaster reconnaissance disseminated to affected communities.* StEER achieves this vision by: (1) deepening structural engineers' **capacity** for post-event reconnaissance by promoting community-driven standards, best practices, and training, as well as their understanding of the effect of natural hazards on society; (2) **coordination** leveraging its distributed network of members and partners for early, efficient and impactful responses to disasters; and (3) **collaboration** that broadly engages communities of research, practice and policy to accelerate learning from disasters. StEER works closely with other extreme event reconnaissance organizations and the Natural Hazards Engineering Research Infrastructure (NHERI) to foster greater potentials for truly impactful interdisciplinary reconnaissance after disasters.

Under the banner of NHERI's CONVERGE node, StEER works closely with the wider Extreme Events Reconnaissance consortium including the Geotechnical Extreme Events Reconnaissance (GEER) Association and the networks for Nearshore Extreme Event Reconnaissance (NEER), Interdisciplinary Science and Engineering Extreme Events Research (ISEEER) and Social Science Extreme Events Research (SSEER), as well as the NHERI RAPID equipment facility and NHERI DesignSafe CI, long-term home to all StEER data and reports. While the StEER network currently consists of the three primary nodes located at the University of Notre Dame (Coordinating Node), University of Florida (Atlantic/Gulf Regional Node), and University of California, Berkeley (Pacific Regional Node), StEER aspires to build a network of regional nodes worldwide to enable swift and high quality responses to major disasters globally.

StEER's founding organizational structure includes a governance layer comprised of core leadership with Associate Directors for each of the primary hazards as well as cross-cutting areas of Assessment Technologies and Data Standards, led by the following individuals:

- **Tracy Kijewski-Correa (PI),** University of Notre Dame, serves as StEER Director responsible for overseeing the design and operationalization of the network and representing StEER in the NHERI Converge Leadership Corps.
- **Khalid Mosalam (co-PI),** University of California, Berkeley, serves as StEER Associate Director for Seismic Hazards, leading StEER's Pacific Regional node and serving as primary liaison to the Earthquake Engineering community.
- **David O. Prevatt (co-PI),** University of Florida, serves as StEER Associate Director for Wind Hazards, leading StEER's Atlantic/Gulf Regional node and serving as primary liaison to the Wind Engineering community.
- **Ian Robertson (co-PI),** University of Hawai'i at Manoa, serves as StEER Associate Director for Coastal Hazards, serving as a primary liaison to the coastal engineering community and ensuring a robust capacity for multi-hazard assessments.
- **David Roueche (co-PI),** Auburn University, serves as StEER Associate Director for Data Standards, ensuring StEER processes deliver reliable and standardized reconnaissance data suitable for re-use by the community.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant No. CMMI 1841667. Any opinions, findings, and conclusions or recommendations expressed in this material are those of StEER and do not necessarily reflect the views of the National Science Foundation. All authors and editors listed on the cover page participate as volunteer professionals. Thus, any opinions, findings, and conclusions or recommendations expressed herein are those of the individual contributors and do not necessarily reflect the views of their employer or other institutions and organizations with which they affiliate.

Special thanks go to Frank Lombardo for some of early discussions of collapse mechanisms being observed in the preliminary photos being shared, Michael Vines for sharing some local insights on construction practices in the Nashville metro, and of course, the National Weather Service forecast offices personnel (Nashville and Memphis), the many social media users who shared early photos, videos and reports of the damage, and the many news reporters who provide important stories and insights from which we gleaned much of the content for this report,

The sharing of photos and damage reports via Slack by the entire NHERI community was tremendously helpful and much appreciated. StEER recognizes the efforts of the DesignSafe CI team who continuously supported and responded to StEER's emerging needs.

For a full listing of all StEER products (briefings, reports and datasets) please visit the StEER website: https://www.steer.network/products

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EXECUTIVE SUMMARY

In the early morning hours of March 3, 2020, a strong tornado struck the City of Nashville and the surrounding metropolitan region with estimated maximum wind speeds of 165 mph. The tornado passed through Nashville and continued east for 53 miles, impacting the communities of Donelson, Mt. Juliet and Lebanon before lifting. The same storm system then produced a second tornado that struck Cookeville, TN with estimated wind speeds of 175 mph. The Nashville tornado was the third tornado that passed through the Five Points area of Nashville, proving once again that tornadoes do indeed strike large urban areas, and they can and do impact the areas more than once, even though overall they are low probability events.

Damage was reported across a diverse cross-section of buildings spanning a number of communities: Camden, Germantown/North Nashville, East Nashville/Five Points, Donelson, Mt. Juliet, Lebanon and Cookeville. Exposure of an urban metro area to this series of tornadoes resulted in significant impacts to power infrastructure and building performance ranging from loss of roof cover and broken windows to complete destruction. Affected typologies and building classes include single and multi-family wood framed homes, commercial construction (ranging from big box stores down to smaller restaurants/retail shops), airport and industrial buildings, and a number of schools. More gravely, these nocturnal tornadoes claimed two dozen lives and injured hundreds more.

Given the loss of life and property in this event and the fact that the Nashville tornado sequence impacted an urban area with diverse building classes and typologies, this event offers an opportunity to advance our knowledge of structural resistance to strong winds, particularly given that new construction was among the inventory significantly damaged. The first product of StEER's effort to learn from the Nashville Tornadoes of 3 March 2020 is this Preliminary Virtual Reconnaissance Report (PVRR), which is intended to:

1. provide an overview of the tornado sequence, particularly relating to the impact of strong winds and wind-borne debris on the built environment,
2. overview the regulatory environment and construction practices in the affected area,
3. summarize the preliminary reports of damage to residential and commercial construction, as well as critical facilities such as schools, airports and power infrastructure,
4. establish current conditions in the affected area with respect to access and services,
5. outline recommendations to inform the continued study of this event by the engineering reconnaissance community, including interdisciplinary teams focusing on sheltering choices and decision making.

Ultimately, the tragic loss of life and property in the Nashville tornadoes reiterates the need to learn from the recommendations of past tornado investigations, but with a renewed commitment to address known vulnerabilities and accelerate this knowledge to affected populations.

1.0 Introduction

In the early morning hours of March 3, 2020, a strong tornado struck the City of Nashville and the surrounding metropolitan region with estimated maximum wind speeds of 165 mph. The tornado passed through Nashville and continued east for 53 miles, impacting the communities of Donelson, Mt. Juliet and Lebanon before lifting. The same storm system then produced a second tornado that struck Cookeville, TN with estimated wind speeds of 175 mph. The Nashville tornado was the third tornado that passed through the Five Points area of Nashville as shown in Figure 1.1, proving once again that tornadoes do indeed strike large urban areas, and they can and do impact the areas more than once, even though overall they are low probability events. The tornadoes occurred on the one year anniversary of the March 3, 2019 tornado that killed 23 in Beauregard, AL (Roueche et al., 2019a).

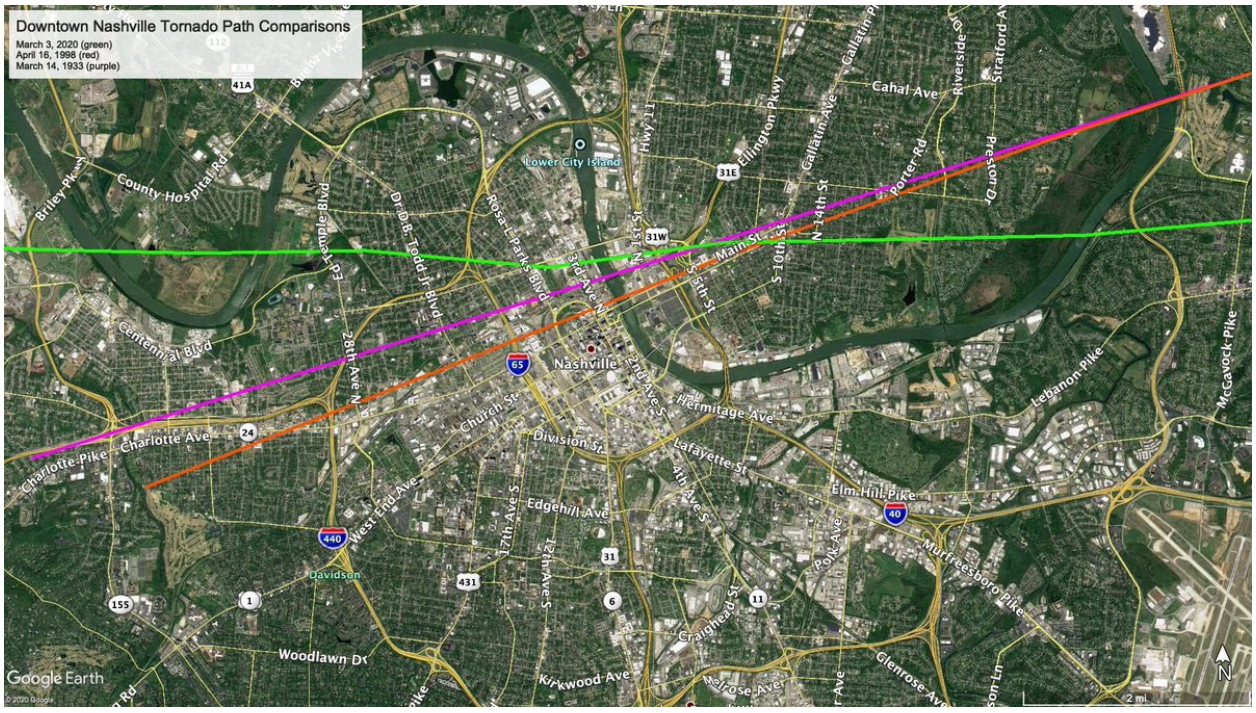

Figure 1.1. Preliminary path of the 2020 Nashville/Davidson County tornado (green) relative to an F3 tornado in 1998 (red) that killed one person and an estimated F3 tornado in 1933 (purple) that killed 15 persons (Grazulis, 1993). Source: Krissy Hurley, NWS Nashville

1.1 Societal Impact

The first tornado struck dense urban areas in Nashville and damaged potentially thousands of buildings (see Figure 2.3) as it passed through Nashville and eastward through Lebanon, TN. The area impacted consists of a mix of all building typologies, from historic buildings, to high-income housing, multi-family housing, schools, many commercial and industrial buildings, and even a regional airport. The estimated economic losses are not known as of yet, but will be

in the hundreds of millions if not billions due to the diversity of housing and industries impacted

1.2 Loss of Life and Injuries

The Tennessee Emergency Management Agency (TEMA) declared 24 storm-related fatalities on March 04: 18 fatalities in Putnam County, 3 fatalities in Wilson County, 2 fatalities in Davidson County and 1 fatality in Benton County. At the time of this report, only one fatality was confirmed in a mobile/manufactured home, the rest occurring in site-built commercial and residential buildings. The reported number of injuries is at least 300 (NWS Nashville), but the number is growing. These human impacts make the Nashville tornado one of the most deadly in recent years, matching the number of fatalities of the Moore, OK tornado in 2013. The fact that this was a nocturnal tornado sequence contributed to the amount of life loss and injury (Ashley et al. 2008, Bunker et al. 2019).

1.3 Official Response

Officials declared a State of Emergency in Tennessee soon after the tornadoes struck, activating an all-hands response from state emergency officials including activation of the State Emergency Operations Center (SEOC). The Red Cross has established six shelters in the area (4 in Nashville, 1 in Lebanon, and 1 in Cookeville). The Tennessee Emergency Management Agency (TEMA) and State of Tennessee AirBnB community partnered to provide no-cost accommodations to Tennessee tornado and storm survivors.

1.4 Report Scope

Given the loss of life and property in this event and the fact that the Nashville tornado sequence impacted an urban area with diverse building classes and typologies, this event offers an opportunity to advance our knowledge of structural resistance to strong winds. In particular, given that new construction was among the inventory significantly damaged, this is an important validation of modern codes and standards.

The first product of the StEER response to the Nashville Tornadoes of 3 March 2020 is this **Preliminary Virtual Reconnaissance Report (PVRR)**, which is intended to:

1. provide an overview of the tornado sequence, particularly relating to the impact of strong winds and wind-borne debris on the built environment,
2. overview the regulatory environment and construction practices in the affected area,
3. summarize the preliminary reports of damage to residential and commercial construction, as well as critical facilities such as schools, airports and power infrastructure,
4. establish current conditions in the affected area with respect to access and services,
5. outline recommendations to inform the continued study of this event by the engineering reconnaissance community.

2.0 Hazard Characteristics

The convective outlooks issued by the Storm Prediction Center recognized a slight risk for severe thunderstorms, including a few tornadoes overnight from March 2-3, 2020. The storms were expected near a frontal boundary progressing eastward across Tennessee, where a combination of ingredients (1000-1500 J/kg CAPE, effective bulk shear around 40 knots, and mid-level lapse rates upwards of 8 C/km) supported severe thunderstorms in the form of supercells. The first tornado warning of the event was issued at 11:02 PM CT near Camden, TN, about 75 miles west of Nashville. Almost an hour later, a second tornado warning was issued at 12:35 AM CT for the Nashville, TN area. At 12:36 AM CT, a debris ball was evident in radar products as the tornado entered Nashville, indicating a tornado had touched down. Warnings continued to be issued as the tornado progressed east, with a warning issued at 1:45 AM CT that included Cookeville, TN for the first time. The last tornado warning for the storm was issued at 2:12 AM CT. Figure 2.1 plots the tornado warnings along with key geographic regions that will be referred to elsewhere in this report.

As of March 5, 2020, the National Weather Service provided a summary of estimated intensities by geographic region, which are given in Table 2.1, along with the latest fatality counts from the TN Department of Emergency Management (TN EMA, 2019). These regions were affected by three separate tornadoes, which are summarized in Table 2.2. Preliminary paths are provided in Figure 2.2 and a summary of the housing density within the Nashville portion of the path is provided in Figure 2.3.

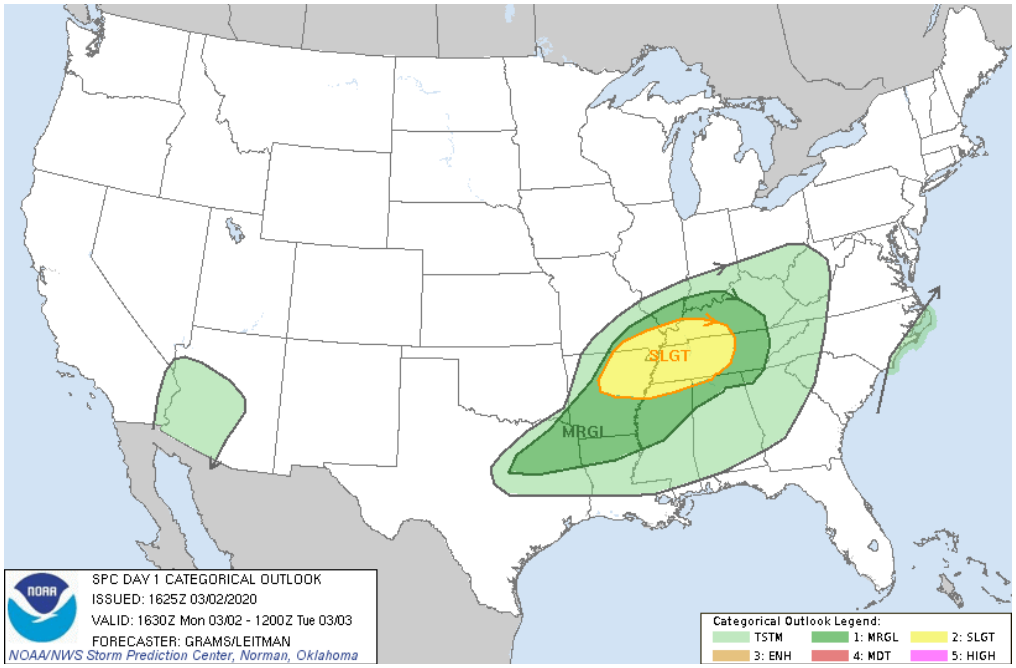

Figure 2.1. Convective outlook issued by SPC at 12:25 PM CT 3/2/2020 valid through 6:00 AM CT 3/3/2020.

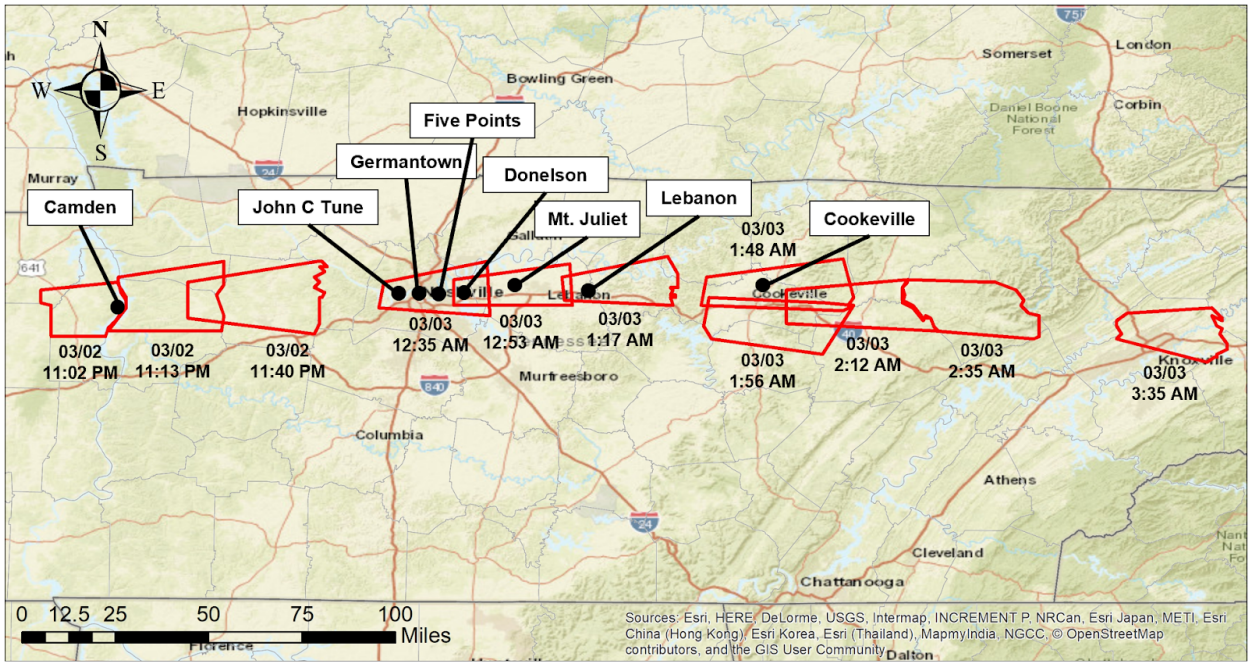

Figure 2.2. Tornado warnings issued in TN near Nashville by the National Weather Service overnight between March 3-4, 2020. Times given are in CT and represent the time the warning was issued.

Table 2.1. Major regions affected by the March 3, 2020 tornadoes in TN

Region	County	EF Rating	Estimated Wind Speed (mph)	Fatalities
Camden	Benton	2	125	1
John C Tune Airport	Davidson	2	130	0
Germantown/North Nashville	Davidson	2	125	0
East Nashville/Five Points	Davidson	3	140	2
Donelson	Davidson	3	165	0
Mt. Juliet	Wilson	3	160	3
Lebanon	Wilson	1	n/a	0
Cookeville	Putnam	4	175	18

Table 2.2. Summary of individual tornadoes in TN and primary regions affected

Tornado	Primary Regions Affected	Max Intensity	Length	Max Width	Injuries
Gibson County	Rural areas of Gibson County	95 mph (EF-1)	7 miles	100 yards	0
Carroll County	Rural areas of Carroll County	125 mph (EF-2)	14 miles	100 yards	0
Benton County	Camden and rural areas of Benton County	125 mph (EF2)	6 miles	150 yards	1 fatality / 2 injured
Davidson County	JC Tune Airport, Nashville, Germantown, Five Points, Donelson, Mt. Juliet, Lebanon, rural areas	165 mph (EF-3)	60.1 miles	800 yards	5 fatalities / 220 injuries
Putnam County	Baxter, Cookeville, rural areas of Putnam County	175 mph (EF-4)	8.21 miles	500 yards	18 fatalities / 88 injuries

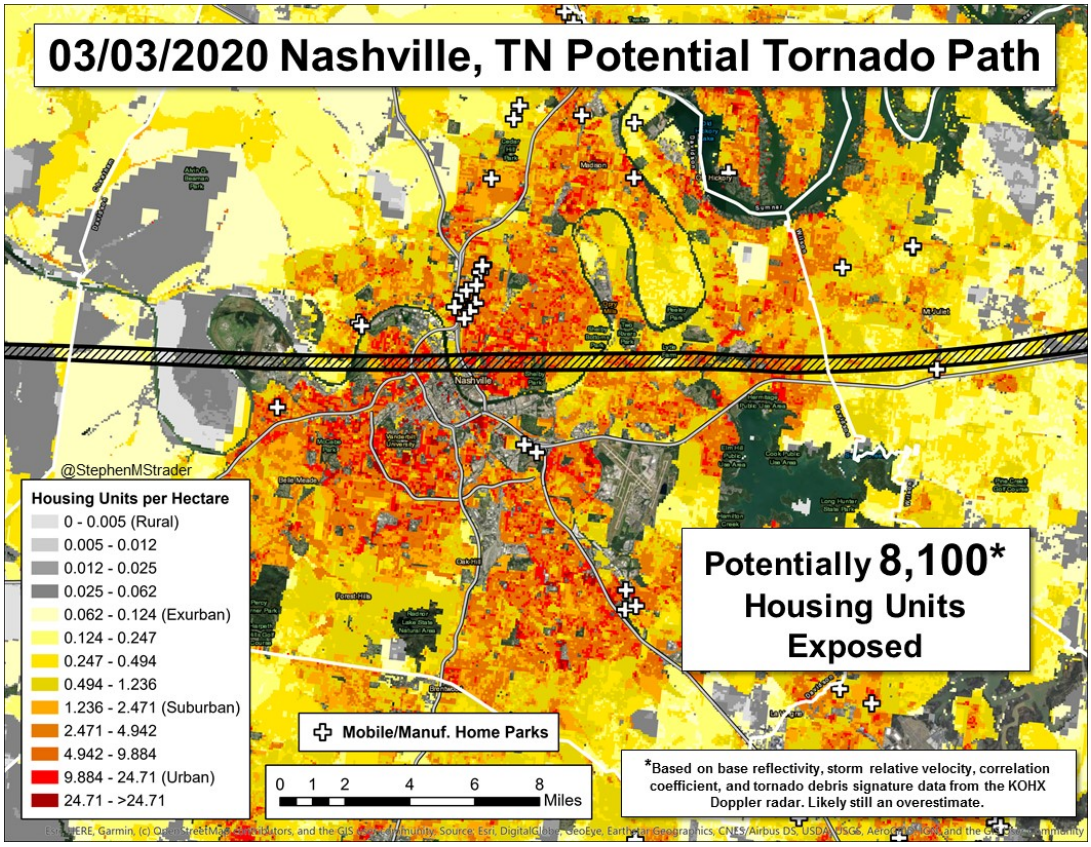

Figure 2.3. Housing density in the Nashville tornado with an estimated number of units affected based on preliminary path estimates (Source: Stephen Strader, University of Villanova).

3.0 Local Codes and Construction Practices

Table 3.1 provides a history of the adopted building codes in Tennessee. However, per the TN Department of Commerce and Insurance, jurisdictions can apply for an exemption to the minimum statewide standards under T.C.A. 68-120-101. Forty-one jurisdictions (four of which are counties) have authorized exemptions, including Nashville/Davidson County, Lebanon, Mt. Juliet, and Cookeville, all of which were affected by the March 3rd tornado(es)[1]. Rule 0780-02-02-.05 prohibits any jurisdiction without an exemption from adopting or enforcing any ordinance less stringent than those adopted by the state of Tennessee. Any jurisdiction that has adopted an edition of a building construction code within seven years of the most current

[1] https://www.tn.gov/content/dam/tn/commerce/documents/fire_prevention/posts/FirePlansExemptJurisdictions.pdf

published edition is deemed in compliance[2]. Additional information on the building inventory in this area, by year of construction, is available at: https://factfinder.census.gov/bkmk/table/1.0/en/ACS/17_5YR/DP04/0500000US47037.

Table 3.1. Tennessee code adoption history

	Edition											
Effective Date	**NEC**	**IBC**	**IFC**	**IECC**	**IMC**	**IPC**	**IFGC**	**IEBC**	**IPMC**	**IRC**	**SBC**	**NFPA LSC**
3/19/2018	2017	-	-	-	-	-	-	-	-	-	-	-
2/2/2017	-	-	-	2009*** Res.	-	-	-	-	-	-	-	-
8/4/2016	-	2012	2012	2012** Com.	2012	2012	2012	2012	2012	-	-	2012*
6/27/2010	-	-		2006	-	-	-	-	-	2009	-	-
12/16/2008	-	-	2006	-	-	-	-	-	-	-	-	2006*
9/1/2008	-	2006		-	2006	-	-	-	-	-	-	-
6/2/2004	-	-	-	-	-	-	-	-	-	-	-	2003
8/26/2001	-	-	-	-	-	-	-	-	-	-	1999	2000
12/28/1997	-	-	-	-	-	-	-	-	-	-	1997	1997
5/27/1996	-	-	-	-	-	-	-	-	-	-	1994	1994
8/23/1990	-	-	-	-	-	-	-	-	-	-	1988	1988
11/10/1985	-	-	-	-	-	-	-	-	-	-	1985	1985
8/26/1982	-	-	-	-	-	-	-	-	-	-	1982	1982

3.1 Davidson County and Nashville, TN

The City of Nashville and Davidson County have adopted the 2012 IBC/IRC with a basic wind speed (i.e., 50 year return period, 3-second gust) of 90 mph[3]. The ordinance enacting the adoption went into effect on August 18, 2015. The first edition of the IBC/IRC adopted by the Nashville metro was the 2006 edition, which was enacted in 2007 per Ordinance BL2007-1373. Prior to 2007, the metro used the Standard Building Code. Communications with a local engineer indicated that hurricane ties (Simpson StrongTie H2.5 or similar) were required at roof-to-wall connections in new construction.

2 https://www.tn.gov/content/dam/tn/commerce/documents/fire_prevention/posts/0780-02-02_2018_Codes-and-Standards.pdf

3 https://library.municode.com/tn/metro_government_of_nashville_and_davidson_county/codes/code_of_ordinances?nodeId=CD_TIT16BUCO_CH16.08BUCO_16.08.014AMINRECOOMIDW

3.2 Putnam County and Cookeville, TN

Cookeville, TN adopted the 2012 IBC and IRC effective January 1, 2015. The specified design criteria for wind is a basic wind speed of 90 mph[4]. The building code department requires inspections for sill plates and anchor bolts. Putnam County (in which Cookeville, TN is located) also currently enforces the 2012 IBC/IRC but adoption date and history is unknown[5].

4.0 Damage to Buildings

4.1 Single-Family Residential Buildings

Representative damage from the EF2 tornado in Benton County northeast of Camden, TN is shown in Figure 4.1. A site-built and a mobile/manufactured (MH) home were destroyed, while other homes in the area sustained more minor damage. The destroyed site-built home shown in Figure 4.1(a) exemplifies the lack of a continuous vertical load path common in many homes in non-hurricane prone regions, with the wood-frame structure built atop unreinforced masonry stem walls and piers.

(a) Home near Bradford, TN partially lifted off of foundation (GPS: 36.045426, -88.743747). Source: Stephanie Amador / The Jackson Sun

(b) Destroyed site-built home (GPS: 36.095, -88.057). Source: Brandon Shields.

Figure 4.1. Severe damage in Gibson County near Bradford, TN (a) and Benton County near Camden, TN (b). Both homes exhibit the lack of foundation anchorage common to many homes in non-hurricane prone regions.

[4] https://www.cookeville-tn.gov/163/Adopted-Codes
[5] https://putnamcountytn.gov/building-codes

In East Nashville, the path tracked through a region of mostly small, 1930-1950s wood-frame homes constructed on stem walls with crawl spaces underneath the home, according to property records. Homes from this era tend to be heavier, using larger structural members, than more modern homes (see Prevatt and Roueche, 2015). Roofs are typically the most vulnerable as the roof-to-wall connections are minimal (toe-nails), as illustrated in Figure 4.2. Some examples of damage in Donelson are shown in Figure 4.3. Roof structure damage was common, with subsequent wall collapse also noted in several images.

Figure 4.2. Roof structure damage to (left) a single-family house located in Underwood St. (Source: Brett Carlsen/Getty Images); (right) roof damage to a single-family house located on Russell St. in East Nashville (GPS: 36.176342 -86.750374; Source: Ruth Ann Cox).

Figure 4.3. (Left) Collapsed walls in a 1960's single-family house on Edgemont drive in Donelson, TN. Source: WTMJ-TV. (right) roof structure damage to single-family homes near Donelson Christian Academy (GPS: 36.184046, -86.648980). Source: NewsChannel5 Nashville.

An aerial view of damage to single-family homes in Mt. Juliet is provided in Figure 4.4. The most severe damage here primarily consists of complete roof failure and partial wall collapse based on the available imagery thus far. The damage path was approximately 1500 ft wide at this point based on available imagery.

Figure 4.4. Before and after aerial view (looking east) of the tornado path through Mt. Juliet, TN near West Wilson Middle School. Structural damage for residential buildings primarily consists of complete roof failure and partial wall collapse.

Residential damage in Putnam County in Cookeville, TN is documented in Figure 4.5. Figures 4.6 and 4.7 show before and after aerial views of damage in modern subdivisions in the Plunk Whitson Rd area in Putnam County, near Cookeville, but outside the city limits. Damage here was catastrophic but within a relatively narrow path with a sharp damage gradient. Property records indicate the homes in these areas were all constructed on continuous footings, but foundation anchorage details are unknown. Other residential damage in the Cookeville area is documented in Figure 4.7.

Figure 4.5. Single-family home damaged by the tornado in Cookeville, TN (House Cookeville)

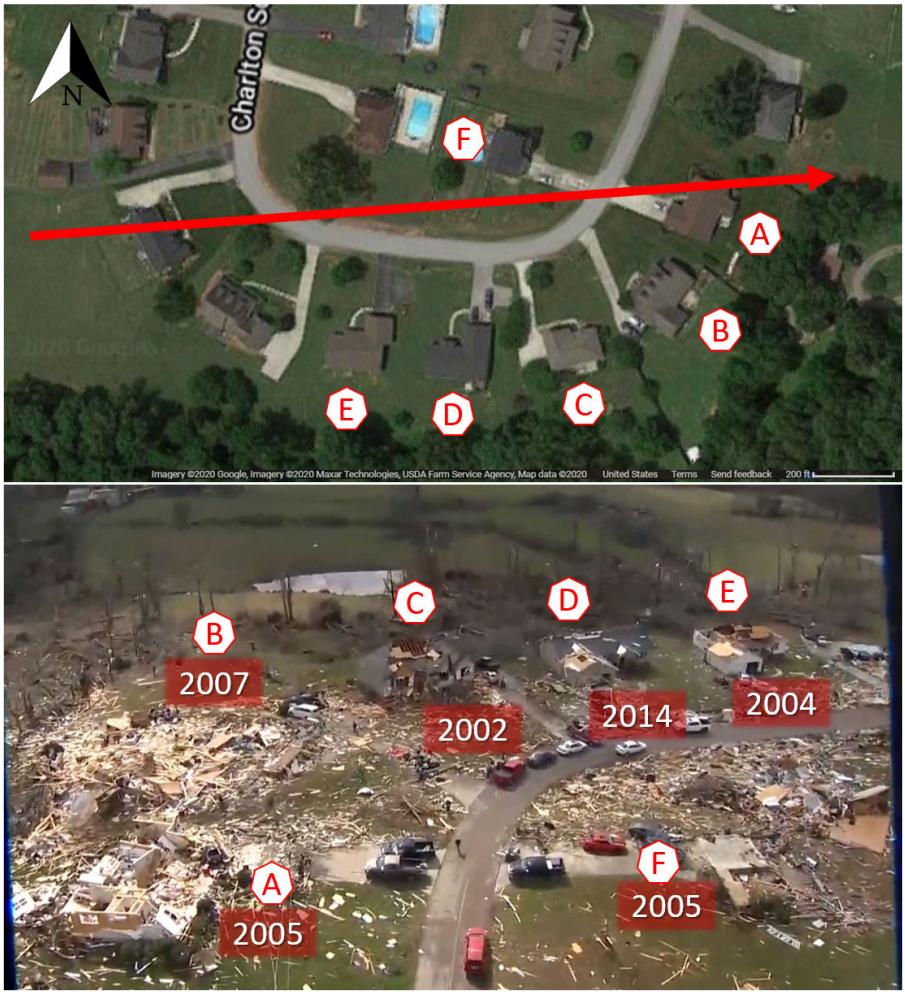

Figure 4.6. Before and after views of destroyed single-family homes in Putnam County, TN near Cookeville, TN (GPS for Home A: 36.176940, -85.589230). Red arrow indicates approximate tornado path. Some homes here were completely levelled to the foundation while adjacent homes sometimes suffered only loss of roof decking. Source: News Channel 5 Nashville.

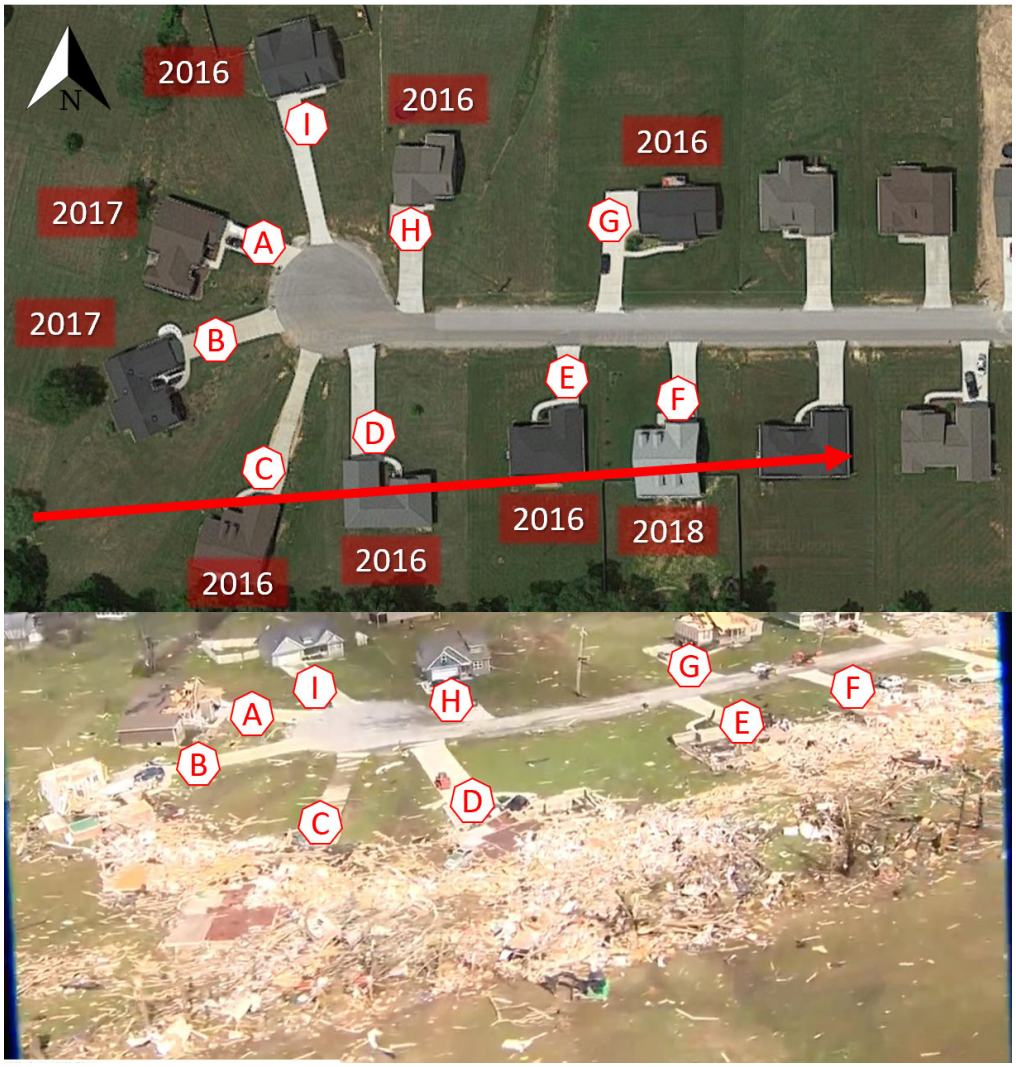

Figure 4.7. Before and after views of destroyed single-family homes in Putnam County, TN near Cookeville, TN (GPS for Home A: 36.177339, -85.584119). Red arrow indicates approximate tornado path. Source: News Channel 5 Nashville.

4.2 Multi-Family Residential Buildings

The tornado severely damaged a number of apartments throughout Nashville and other regions. Exact locations of damaged apartments could not always be determined, but preliminary imagery shows damage ranging from partial collapse to windows breached and complete blow through of the buildings. Figure 4.8 and 4.9 show samples of the damage in Nashville. A high density of apartments appear to be within the path limits particularly in Donelson, but details of the performance are not known as of yet. Damage to multi-family residences in Germantown (Fig. 4.10) and Cookeville (Fig. 4.11) was also reported.

Figure 4.8. Margaret Robinson Apartments before and after the tornado (GPS 36.178388 -86.597882; source: tmj4).

Figure 4.9. A sampling of damage to apartments in the Nashville metro. Exact location unknown. Source: Twitter user @melaninsings.

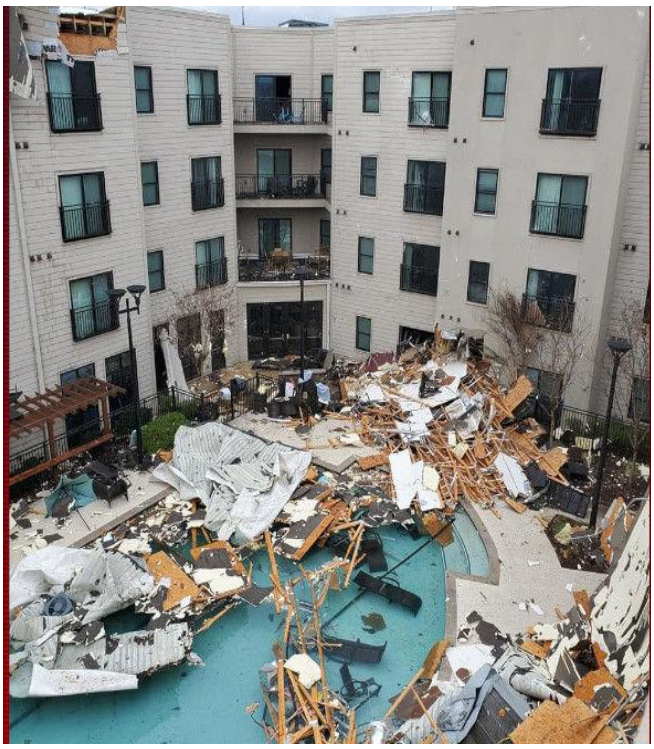

Figure 4.10. Damage to The Vista Apartments in Germantown (GPS: 36.174459 -86.788849). Source:The Vista Apartments in Germantown.

Figure 4.11. Damage to multiple duplex residential buildings near Broad St. (Cookeville, TN) (GPS: 36.170992 -85.537113): before and after the tornado (source: wkrn news), looking North.

4.3 Commercial Buildings

A variety of commercial buildings were damaged/destroyed by the tornado. A sample is shown in Figures 4.12-4.15, which includes historic restaurants in downtown Nashville, restaurants in more modern parts of the metro area, and industrial facilities in Mount Juliet.

Figure 4.12. Damage to restaurants caused by the tornado: (left) Geist restaurant (Nashville) (Alex Carlson via AP); (right) Burger up (Source: @LuluLady).

Figure 4.13. Damage to buildings caused by the tornado in downtown Nashville: (left) commercial buildings in Nashville (Parlor Nashville); (right) live music venue "Basement East" (Basement East).

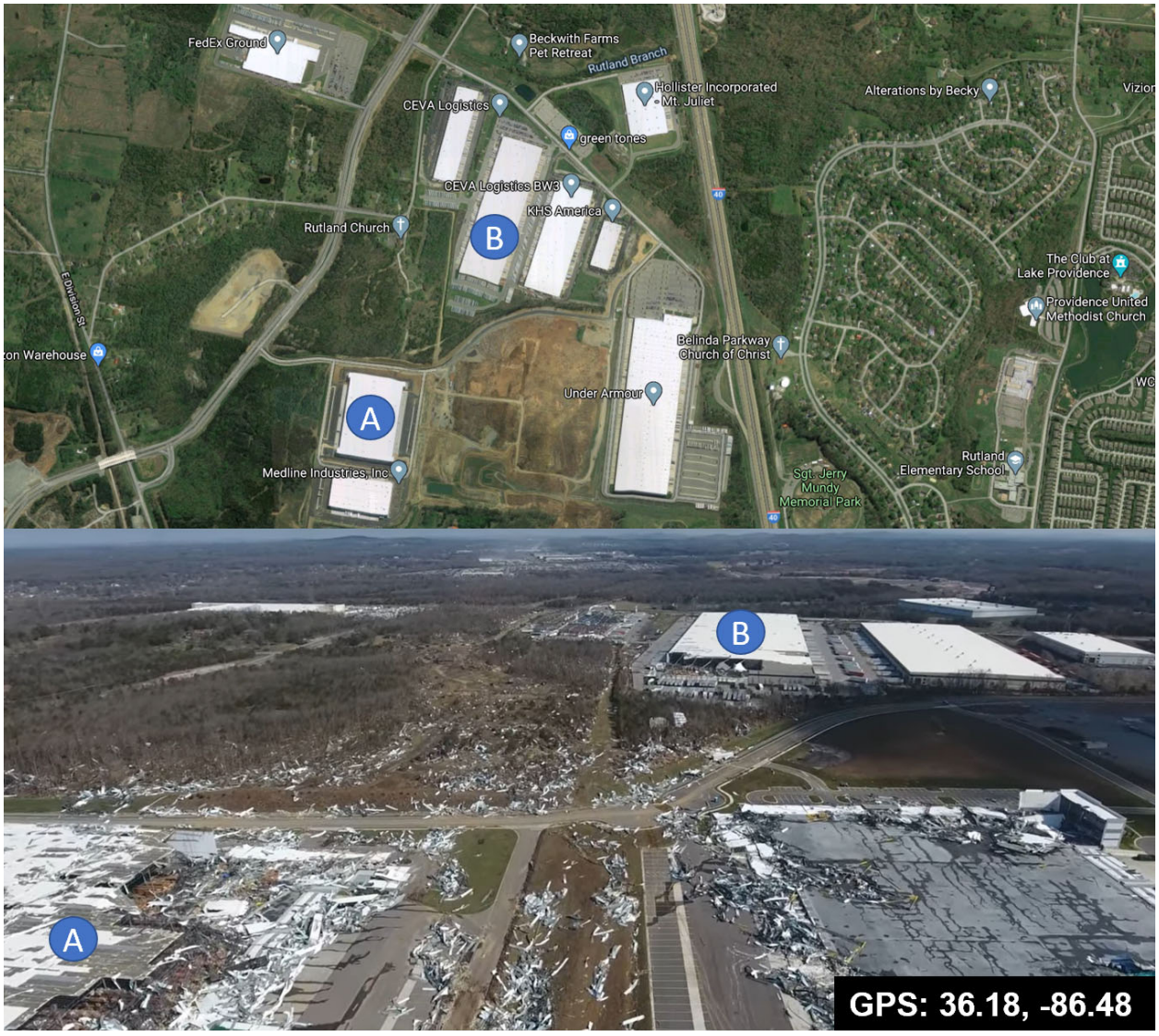

Figure 4.14. Before and after aerial views of damage to an industrial complex in Mount Juliet, TN that contained distribution/manufacturing centers for a variety of retailers. Post-tornado imagery was captured by Brady Turner.

Figure 4.15. Precast tilt-up concrete building with approximately 50% of the building footprint collapsed. Photos indicated the facility caught on fire during/after the tornado. (Source: Mark Humphrey / AP Photos). GPS: 36.187, -86.434.

4.4 Healthcare/Medical Facilities

Several hospitals were close to the tornado path but appear to have avoided any significant damage. Nashville General Hospital reported it was operating as normal as of March 4th. Summit Medical Center in Hermitage, TN (just east of Nashville and within the metro area) also did not report any damage. In Lebanon, Summit Convenient Care was also near the tornado path but does not appear to have suffered any damage. Nashville.gov reported the following on March 4, 2020: “All Metro Public Health Department locations, including Metro Animal Care and Control (MACC), are operating today during regular business hours. Our East Health Center, located at 1015 East Trinity Lane, did not sustain building damage. The East Health Center is serving customers but currently is without telephone service.”

4.5 Schools

At least six schools suffered significant damage due to the tornadoes. Near Nashville, the Tennessee State University campus reported some roof cover damage and other minor damage to some main campus buildings. The most severe damage occurred to buildings in the agricultural research farm, where a horse barn and greenhouse were severely damaged, but did

not collapse (Fig. 4.16). Further east, the tornado damaged the Meigs Middle Magnet School (Fig. 4.17) and Robert Churchwell Museum Magnet Elementary School (Fig. 4.18) in Nashville, destroyed portions of Donelson Christian Academy in Donelson (Fig. 4.19), and collapsed portions of Stoner Creek Elementary School (Fig. 4.2) and West Wilson Middle School (Fig. 4.21) in Mt. Juliet. Other schools may have been affected but could not be confirmed at the time of this report was authored.

Figure 4.16. (Left) building damage (exact building unknown) on Tennessee State University campus. Source: Tennessee State University; (right) damaged greenhouses at the Tennessee Sate University Agricultural Research Farm (Source: TSU Ag. Extension).

Figure 4.17. Meigs Middle Magnet School Damage (GPS: 36.176388, -86.760729). Source: Nashville Metro Schools.

Figure 4.18. Robert Churchwell Museum Magnet Elementary School Damage (GPS: 36.175469, -86.810060). Source: Nashville Metro Schools.

Figure 4.19. Donelson Christian Academy Google Street View of School Before the Tornado Impact and damage after the impact (GPS: 36.184433, -86.650141). Source: Eric Hilt NewsChannel 5.

Figure 4.20. Building and Roof Damage to Stoner Creek Elementary School in Mt. Juliet (GPS: 36.184852, -86.502176).Source: Stoner Creek Elementary School.

Figure 4.21. Damage to the West Wilson Middle School in Mt. Juliet (GPS: 36.184785, -86.510193). Source: West Wilson Middle School.

4.6 Government Facilities

No reported damage to government buildings was noted in the reporting available to the authors.

4.7 Mobile/Manufactured Homes

Per preliminary analysis by Stephen Strader, the tornado paths avoided any mobile/manufactured home parks. Isolated MH damage is likely, but no specifics are available at this time outside of a fatality that occurred in a single-wide mobile home in Camden, TN during the EF2 Benton County tornado.

4.8 Religious Institutions

Damage to historic churches in Germantown (Fig. 4.22), near Nashville, and East Nashville (Fig. 4.23) was reported. It is unknown whether other religious buildings may have been affected by the tornadoes.

Figure 4.22. Damaged churches in Germantown. (Left) Assumption of the Blessed Virgin Mary Church, which suffered collapse of a wall and damage to the roof. The church was built in 1859. (Source: The Catholic World Report); (right) damage to historic Hopewell Missionary Baptist Church.

Figure 4.23. Heavy damage to the East End United Methodist Church at 1212 Holly in East Nashville (Source: George Walker IV / Tennessean.com).

4.9 Historical Buildings

The Tennessee Department of Corrections (TDOC) Tennessee State Prison in Nashville (Fig. 4.25) was closed in 1992. It has been mothballed as a historic building ever since, and was not occupied at the time of the tornados.

Figure 4.22. Tennessee Department of Corrections Historical State Prison. (GPS: 36.177011, -86.865586). Source: TN DOC.

5.0 Damage to Infrastructure

5.1 Power and Telecommunications Infrastructure

According to the Tennessee Valley Authority (TVA), thirty transmission structures were knocked down, and five damaged. According to NewsChannel5 - Tennessee 70 poles were knocked down by the tornado in Lebanon city, resulting in loss of power to 12,000 customers. NES (Nashville Electric NES via twitter) estimated the number of customers without power as 38,000. Middle Tennessee Electric Membership Cooperative reported over 7,400 customers without power and 60+ broken poles (WKRN). Crews started to assess and repair damage, but many

operations are impeded by the extensive damage and difficulties in reaching the impacted areas. Some examples of damage to power infrastructure are provided in Figures 5.1 and 5.2.

(a) (b)

Figure 5.1. (a) Power pole damaged by the tornado in Nashville (Source: wlfi.com via WTVF-TV, CBS News). (b) Damage to utility poles in Underwood St. (Nashville) (Source: Yahoo News).

Figure 5.2. Transmission tower damage on Riverside Drive in Nashville, TN (Source: TMJ4); (right) Transmission tower damaged near the Cumberland River (Source: Tennessee Valley Authority).

5.2 Airports

The John C. Tune airport was located near the beginning of the Nashville tornado path and was severely damaged by the tornado (Figs. 5.3 and 5.4). The Class E airport is owned by the Metropolitan Nashville Airport Authority and averages 230 aircraft operations per day[6], primarily serving corporate and private aircraft needs. It underwent extensive renovations in 2015, mostly to the runway and taxiways. The airport contains 134 different hangar buildings.

Figure 5.3. Damage to John C. Tune Airport, Nashville International's sister airport in West Nashville (Source: Fox News)

6 https://www.flynashville.com/john-c-tune/Documents/John%20C%20Tune%20Fact%20Sheet_June%202018.pdf

Figure 5.4. An aerial view of John C. Tune Airport showing collapsed hangars and other buildings and damaged aircraft (Source: George Walker IV / Tennessean.com).

6.0 Fatalities and Injuries

As of March 5, 2020, the official fatality count for the tornadoes stood at 24, which included the following per the Tennessee EMA[7]:

- One fatality in Benton county from the EF2 tornado there
- Two fatalities in Davidson County (Five Points area of Nashville)
- Three fatalities in Wilson County (at least two in Mt. Juliet)
- Eighteen fatalities in Putnam County, many if not all in site-built homes.

Details are still forthcoming about locations and circumstances of the fatalities, so analysis will be postponed until details can be confirmed. Early evidence suggests that the majority of victims were not killed in mobile/manufactured homes.

7.0 Current Conditions and Access

7.1 Power Outages

NES (Nashville Electric NES via twitter) estimated the number of customers without power as 38,000. Middle Tennessee Electric Membership Cooperative reported over 7,400 customers without power and 60+ broken poles (WKRN). As of 6:17 pm 3/4/2020, the TN EMA still

[7] https://www.tn.gov/tema/news/2020/3/4/tema-flash-report--7---tornado-and-severe-weather-event.html

reported 38,800 without power due to the storms per TEMA Flash Report #7. In the TEMA Flash Report #8, these numbers were updated as follows: Davidson County has 18,350 without power; Wilson County has 2,200; and Putnam and Jackson counties have a total of 3,000 without power.

7.2 Water and Sanitation Disruption

No known reports of water and sanitation disruption.

7.3 Cellular Outages

There were several reports that communication networks went down for areas in the path of tornado due to damage caused by the tornado, e.g., this tweet by Aubrey Urbanowicz. The status of the networks is not known at this time.

7.4 Road Closures

At the time of this report there are still a number of road closures in the Nashville metro area and in Cookeville (Fig. 7.1). Figure 7.2 shows road closures via Google Maps in the Hermitage area (east of Donelson, TN). Figure 7.3 shows road closures via Google Maps in Lebanon. No road closures are currently shown for Cookeville and surrounding areas, but it is likely that access is restricted to areas with the heaviest damage (Charlton Square Road and McBroom Chapel Rd area).

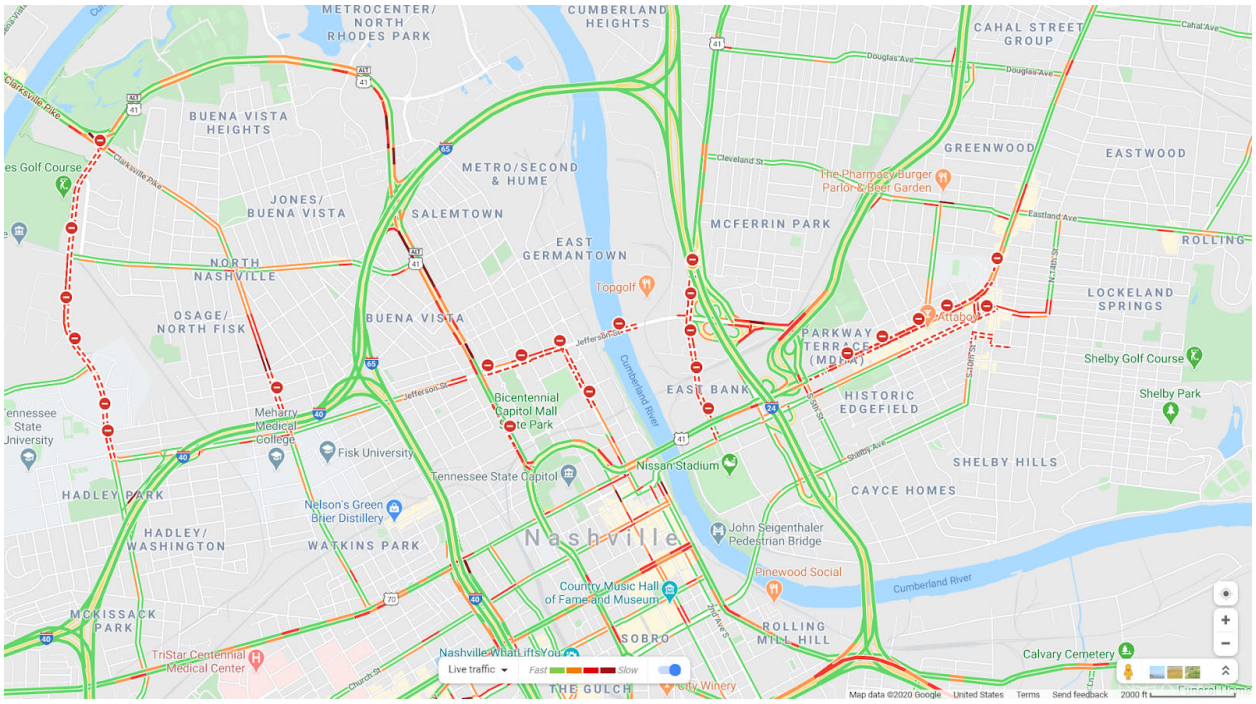

Figure 7.1. Road closures in downtown Nashville due to the tornado. Image from Google Maps.

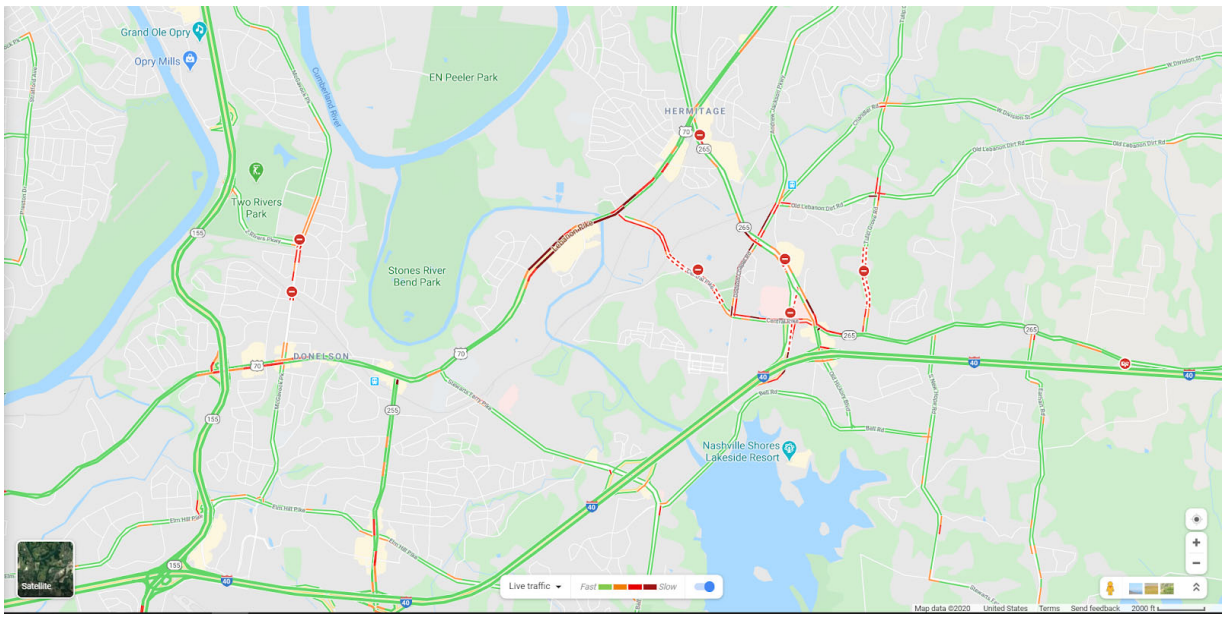

Figure 7.2. Road closures due to the tornado in the Hermitage region east of Nashville and Donelson, TN. Image from Google Maps.

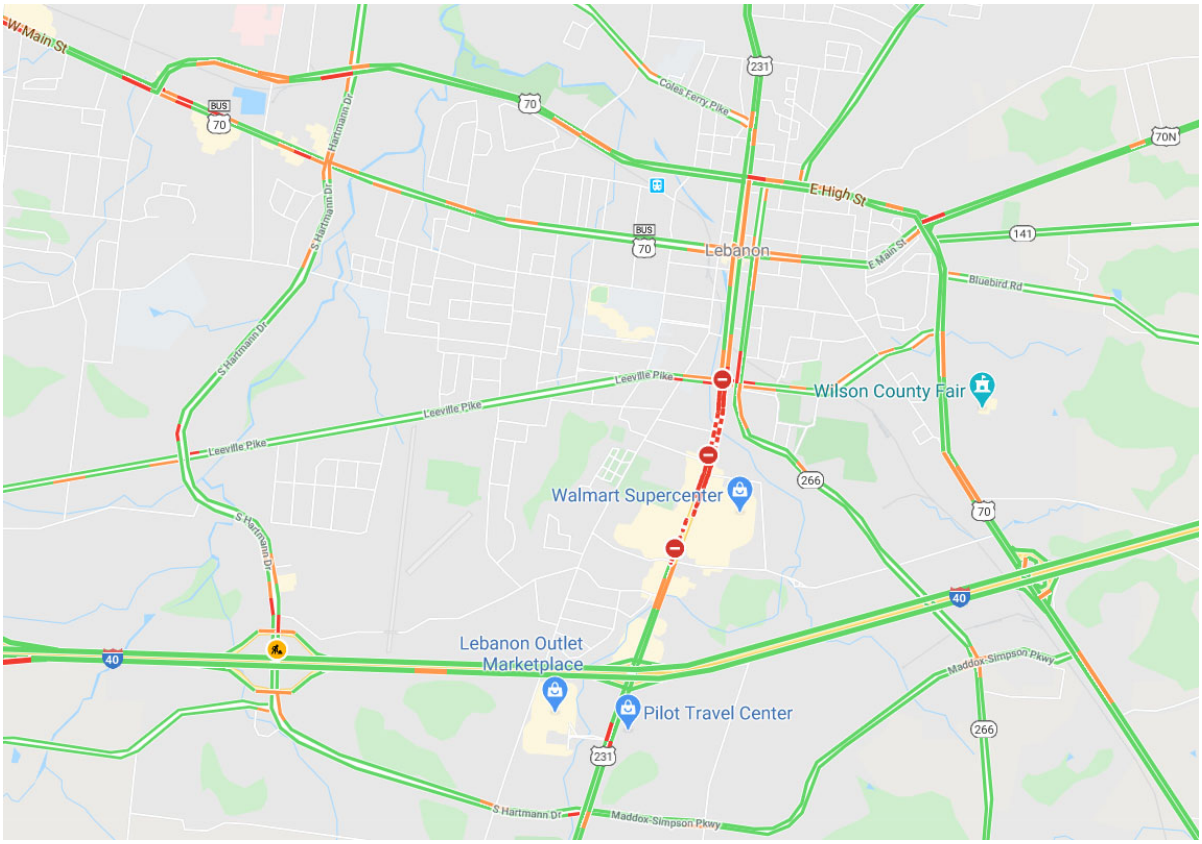

Figure 7.3. Road closures in Lebanon, TN due to the tornado. Image from Google Maps.

7.5 Curfews/Restricted Access

Table 7.1 provides a summary of known curfews in place. Additionally, Putnam County has a temporary FAA flight restriction in place until 10 AM Friday, March 6, 2020.

Table 7.1. Known curfews in place at the time of this report

County	Davidson	Wilson	Smith	Putnam
Curfew Time	none	6pm-6am	none	7pm-8am

8.0 Recommended Response Strategy

The tragic loss of life and property in the Nashville tornadoes reiterates the need to learn from the observations and recommendations following past tornadoes (Coulbourne et al. 2015, Prevatt et al. 2012a,b, Prevatt et al. 2016, Roueche et al. 2019a-c), and with a greater commitment to address known vulnerabilities. The acceleration of this knowledge not just to practitioners but to the affected populations will be critical as rebuilding unfolds. Based on the information gathered by this Preliminary Virtual Reconnaissance Report (PVRR), StEER offers the following recommendations for future study, which expand upon and regrettably revisit some of the vulnerabilities documented in past tornadoes. These recommendations will be refined based on the findings of subsequent FAST observations.

Topic 1 - Residential Construction Performance

1. *Survivability in Modern Residential Construction*
   Early reports indicate that the eighteen fatalities in Putnam County, just outside Cookeville, TN, occurred within an approximately 2-mile portion of the tornado path that consisted primarily of modern (post-IBC) construction, including some destroyed homes built as recently as 2016 and 2017. The high number of fatalities in a region characterized by modern construction is highly concerning, even within the context of a nighttime tornado. Details of the complete structural load path need to be ascertained to assess the contributions of structural vulnerability to the high fatality rate. Circumstances of the fatalities should be documented, including structural characteristics of the buildings in which the fatalities occurred.
2. *Foundation Anchorage in Non-Hurricane Prone Regions*
   Related to Topic 1.1, the VAST observed that the majority of collapsed structures for which early data was available were constructed on unreinforced masonry stem wall foundations. Unreinforced masonry piers are highly vulnerable weak points in the structural load paths of residential structures and are well-documented as contributors to failures in previous tornadoes (Tuscaloosa, AL and Joplin, MO in 2011). Documentation of the vulnerability of these foundations in this event should be used as an opportunity to emphasize the vulnerability of this foundation class relative to other elements of the structural load path, and more importantly to highlight the importance of reinforcing foundation load paths in existing construction potentially subjected to high wind events.

Topic 2 - School Performance

A number of schools were severely damaged in the Nashville tornado. While thankfully the tornado occurred outside of school hours, their vulnerability to an EF3 tornado indicates there may be little residual capacity to protect life safety in similar or stronger events.

1. *Viability of Sheltering in Schools*

The status of shelters and designated places of refuge in these facilities should be documented, as well as the best available place of refuge given the damage state from post-storm analysis if possible.

2. *Variability of School Performance*
   The disparity in damage between different schools should be examined to ascertain whether the differences were due to changes in hazard (e.g., proximity to path centerline) or varying structural capacity.

Topic 3 - Commercial Building Performance

A number of low-rise, large-volume industrial buildings were severely damaged by the tornado, as well as numerous restaurants and retail stores that should be studied further.

1. *Commercial Buildings as Baseline for Engineered Construction Performance*
   The performance of the smaller, more regularly-shaped commercial buildings should be documented to contrast the performance of engineered buildings relative to surrounding residential buildings.
2. *Performance of Big Box Construction Across High-Wind Events*
   High-fidelity captures (e.g., lidar, SfM) of the performance of big box buildings, particularly the large industrial buildings in Mt. Juliet. These are of similar size to buildings damaged in Hurricane Michael. The contrast or similarities between the failures under hurricane and tornado-induced loads could improve our understanding of tornado-induced wind loads.

Topic 4 - Power Infrastructure Performance

The Tennessee Valley Authority reported the tornado in Putnam County blew down a transmission tower along with four substations, hampering response and recovery efforts. The performance of power infrastructure relative to their proximity to the tornado centerline should be examined.

Topic 5 - Sheltering Choices and Decision Making

Strong nighttime tornadoes impacting a major metropolitan region are relatively rare and will happen again. StEER recognizes an opportunity for the social science and structural engineering communities to come together to study warning reception and sheltering choices within the context of the structure in which occupants are sheltering. The uniqueness of nighttime tornadoes is that a higher proportion of people are in homes and likely have to shelter in-home depending on the timing of the issuance and reception of the early warning system.

Given the magnitude of the Nashville and Cookesville tornadoes, the impacts documented in this PVRR, and recommendations for further study articulated above, StEER anticipates deploying up to two Field Assessment Structural Teams (FAST), with FAST 1 deploying the week of March 9th, and FAST 2 deploying the following week, if warranted. The FASTs will include Level 3 and 4 StEER members with expertise in wind engineering and high-fidelity data

capture and at least one Level 2 member as a FAST Trainee for this event. StEER's approach to this event will enable a more systematic documentation of damage across transects, coupling in-depth damage assessments with more rapid assessment technologies to capture perishable data along the tornado path and support subsequent hypothesis-driven research such as the systematic validation of evolving tornado design provisions. StEER is coordinating with other organizations responding to this event to further develop its FAST strategy.

References

Ashley, W. S., Krmenec, A. J., & Schwantes, R. (2008). Vulnerability due to nocturnal tornadoes. *Weather and forecasting,* 23(5), 795-807.

Bunker, Ryan C.; Cohen, Ariel E.; Hart, John A.; Gerard, Alan E.; Klockow-Mcclain, Kim E.; Nowicki, David P. (2019) *"Examination of the predictability of nocturnal tornado events in the southeastern United States* Source: Weather and Forecasting, v 34, n 2, p 467-479.

Coulbourne, W.L., Prevatt, D.O., Stafford, T.E., Ramseyer, C.C. and Joyce, J.M., (2015) *Moore, Oklahoma, Tornado of 2013: Performance of Schools and Critical Facilities,* American Society of Civil Engineers.

Grazulis, Thomas (1993), *Significant Tornadoes 1680-1991: A Chronology and Analysis of Events*, St. Johnsbury, Vermont: Environmental Films, ISBN 1-879362-03-1

Prevatt, D.O., Coulbourne, W., Graettinger, A.J., Pei, S., Gupta, R. and Grau, D., (2012a) *Joplin, Missouri, Tornado of May 22, 2011. Structural Damage Survey and Case for Tornado-Resilient Building Codes.* American Society of Civil Engineers.

Prevatt, D.O., Roueche, D.B., Van De Lindt, J.W., Pei, S., Dao, T., Coulbourne, W., Graettinger, A.J., Gupta, R. and Grau, D., (2012b). Building damage observations and EF classifications from the Tuscaloosa, AL and Joplin, MO tornadoes. Structures Congress 2012 - Proceedings of the 2012 Structures Congress, 999-1010.

Prevatt, D.O. and Roueche, D.B. "A Tale of Two Houses: Investigation of Disproportionate Damage in 2011 Tuscaloosa, AL Tornado." *Wood Design Focus*, V. 25, N. 1, Spring 2015.

Prevatt, D.O., Roueche, D.B. and Chen, A., (2016) Preliminary Analysis of Post-Tornado Damage Survey Data from the 2015 Christmas Tornado in Garland, Texas. University of Florida, Gainesville, FL.

Roueche, D., Cleary, J., Barnes, R., Davis, B., Marshall, J., Rittelmeyer, B., Smallegan, S., Guo, Y., Hodges, C., Kijewski-Correa, T., Salman, A., Turner, K., Merschman, E., mulchandani, H., Prevatt, D., Robertson, I., Mosalam, K., (2019a) "StEER - 3 March 2019 Tornadoes in the Southeastern US: Field Assessment Structural Team (FAST) Early Access Reconnaissance Report (EARR)." DesignSafe-CI. (DOI: https://doi.org/10.17603/ds2-qav0-t570).

Roueche, David; Davis, Brett; Hodges, Courtney; Rittelmeyer, Brandon; Turner, Kelly; Kijewski-Correa, Tracy; Prevatt, David; Robertson, Ian; Mosalam, Khalid, (2019b), "StEER - 19 JANUARY 2019 TORNADOES IN THE SOUTHEASTERN US: FIELD ASSESSMENT TEAM EARLY ACCESS RECONNAISSANCE REPORT (EARR)" , DesignSafe-CI [publisher], Dataset, doi:10.17603/ds2-eb6e-tr31 (DOI: https://doi.org/10.17603/ds2-eb6e-tr31)

Roueche, David; Robertson, Ian; Prevatt, David; Kijewski-Correa, Tracy; Mosalam, Khalid (2019c) "StEER - 10.20.2019 Dallas, TX EF-3 Tornado: Event Briefing." DesignSafe-CI. (DOI: https://doi.org/10.17603/ds2-14zk-v983).