The Stability of Passenger Vehicles at Tornado Wind Intensities of the (Enhanced) Fujita Scale

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(Manuscript received 21 August 2015, in final form 9 November 2015)

ABSTRACT

Two independent datasets (total $n = 959$) of tornado-stricken passenger vehicles collected from 12 tornado events over a 15-yr time span are combined and tested to determine whether vehicle movement and/or upset are consistent at various wind speed intensities. Impacted vehicles are classified into three categories of upset motions (no movement, lateral shifting, rolling and lofting motions) for each wind intensity category of the Fujita and Enhanced Fujita scales. Vehicles observed by Schmidlin exposed to F1 and F2 winds are statistically assessed to determine if upset distribution values are consistent with those assessed by Marshall at these respective wind speeds; this same approach is subsequently conducted for vehicles at F3/EF3 and F4/EF4 winds. No statistical differences are found between the two sets of field survey data, which are therefore considered to be of the same population. Passenger vehicles are currently not utilized as damage indicators for rating tornado wind intensities, although the results of this study suggest that only 10% of vehicles are typically shifted at EF0 wind speeds, 36% are displaced at EF1 and EF2 winds (5% are rolled or lofted), 63% are displaced at EF3 and EF4 winds (15% are rolled and lofted), and all vehicles exhibit some form of movement or upset at the EF5 wind speed. The results of this study may potentially serve as a basis for providing better tornado safety protocols, designing safer vehicles and infrastructure, and estimating tornado wind speeds where few EF-scale damage indicators are available.

1. Introduction

Since 1985, approximately 9% of all tornado fatalities in the United States have been persons in motor vehicles (SPC 2015a,b). Up until May 2009, the National Weather Service (NWS) had recommended that persons abandon motor vehicles and lie down in outdoor ditches if no indoor shelters or basements are available during tornado events (NOAA 1992; Schmidlin et al. 2002; NOAA 2009). Schmidlin and King (1996) and Schmidlin et al. (2002) later questioned whether such actions would increase the risk to injury and death. Studies by Carter et al. (1989) and Duclos and Ing (1989), for instance, reveal cases of persons in outdoor locations being at greater risk of sustaining tornado-induced injuries than those remaining inside their vehicles. Schmidlin et al. (2002) also note multiple instances of passenger vehicles remaining upright in tornado damage paths where adjacent mobile homes are demolished.

Between 1994 and 1999, Schmidlin et al. (2002) collected data for 291 tornado-stricken passenger vehicles and determined the ratios of vehicles moved (>1 m) or tipped over at various Fujita scale wind speeds [the Fujita scale (F scale) was used until the Enhanced Fujita (EF scale) was introduced in 2007]; see Table 1. Timothy Marshall and colleagues collected a larger set of similar data to determine whether vehicles were moved or tipped at various EF wind speed thresholds (Marshall et al. 2008a,b, hereafter MAR2008a,b; Marshall 2010, hereafter MAR2010). This research reports on the combined data from Schmidlin et al. (2002), MAR2008a,b, and...
2. Literature review

Prior to 2009, motor vehicle safety guidelines from the NWS and American Red Cross were based, in part, on the assumption that passenger vehicles may be rolled or lofted at low wind speeds (e.g., the F1 threshold of the F scale); the risk of injury or death for occupants was therefore also assumed to be high at these lower wind thresholds (NOAA 1992; Hammer and Schmidlin 2002; SPC 2015c). A series of field surveys and wind tunnel tests conducted by Schmidlin et al. (2002), however, suggest that passenger vehicles are not as easily displaced by lower tornado wind speeds as originally described by the F scale (Schmidlin et al. 2002; SPC 2015c). Furthermore, there are documented instances of mobile home residents safely fleeing incoming tornadoes in automobiles to seek sturdier shelters (Schmidlin and King 1997); such actions are believed to have saved lives and reduced injuries, despite running counter to NWS public safety protocols (NOAA 1992; Schmidlin and King 1997). In 2009, the NWS and American Red Cross modified their safety protocols; persons in mobile homes are now encouraged to abandon them, and persons outdoors are urged to seek shelter in vehicles only if no sturdy buildings are available nearby (NOAA 2009; Simmons and Sutter 2012).

Some in the meteorology field have observed that tornado-induced risk to motor vehicle occupants cannot be truly assessed without examining the issue of debris penetration, as fatalities have resulted from such circumstances in the past (Golden 2002; Blair and Lunde 2010). Damage surveys conducted in the aftermaths of multiple tornado events (Schmidlin et al. 1998a; MAR2008a,b; MAR2010) support this assertion, as tornado-impacted vehicles have been regularly found to be penetrated by debris and broken glass. Moreover, tornadoes of similar magnitudes can produce widely differing outcomes of debris-induced damage to passenger vehicles, and the risk of serious injury for vehicle occupants (requiring hospital care) may therefore also vary (Schmidlin et al. 1998a,b; King et al. 1999).

The research findings reinforce some of the motor vehicle dangers associated with tornado events, but also raise questions as to the true extent of these dangers. Further studies of vehicles exposed to tornadoes can therefore 1) provide better guidance for tornado safety recommendations, 2) contribute to the discussion of evacuation from tornado paths, and 3) provide guidance for the inclusion of vehicles as an EF-scale damage indicator.

3. Methods

This study combines independent survey findings by Thomas Schmidlin and Timothy Marshall to determine whether tornado-induced vehicle displacement patterns are statistically consistent among the datasets. Surveys conducted by Schmidlin et al. (2002) were undertaken during a period when the original F scale was still being utilized, whereas surveys by MAR2008a,b and MAR2010 were all conducted following the 2007 implementation of the EF scale (SPC 2007). The EF-scale wind categories and degree of damage (DOD) indicators were developed with the approach of maintaining damage outcome consistencies relative to the intensity categories of the F scale (Wind Science and Engineering Center 2004; SPC 2007, 2014); this was undertaken through linear regression techniques that had established statistical relationships between EF-scale and F-scale winds (Wind Science and Engineering Center 2004; SPC 2007, 2014); this was undertaken through linear regression techniques that had established statistical relationships between EF-scale and F-scale winds (Wind Science and Engineering Center 2004; SPC 2007, 2014). This study therefore assumes that structural damage patterns previously witnessed in F2 intensity swaths, for instance, are expected to be similar to those found within EF2 intensity swaths. Motor vehicle damage ratings are ultimately based on damages sustained to homes (this is discussed further below).

Altogether, this study incorporates 12 field surveys for 959 passenger vehicles struck by tornadoes between 1994 and 2008. Schmidlin et al. (2002) assessed 291
vehicles over the course of nine surveys (1994–99), and 668 vehicles were assessed by MAR2008a,b and MAR2010 (Fig. 1) over three surveys (2007–08). All impacted vehicles were assessed within 10 days following each tornado event. Vehicles surveyed by Schmidlin et al. (2002) consisted of sedans, pickup trucks, vans, and sport utility vehicles while excluding larger and heavier vehicles (e.g., box trucks, semis, buses, and recreational and commercial vehicles). Surveys conducted by MAR2008a,b and MAR2010 similarly consisted of evaluating only “automobiles” and “light trucks.”

Determinations of whether vehicles were displaced by tornadic winds were based on interviews conducted with homeowners familiar with the circumstances of each vehicle (Schmidlin et al. 2002; MAR2008a,b; MAR2010). In all instances, the assessed vehicles were parked adjacent to residential structures struck by tornadoes; F-scale and EF-scale ratings assigned to impacted vehicles were based on damage patterns observed to adjacent frame homes. [Schmidlin et al. (2002) conducted vehicle surveys only for homes sustaining F1 or greater damages.] We acknowledge that near-surface wind fields inside tornadoes are complex, and that the surveyed vehicles incorporated into this study may have been exposed to different wind speeds relative to the adjacent homes. Our large sample size of 959 observed vehicles provides confidence for robust results in spite of complex tornadic environments.

Vehicle displacement results stemming from each field survey were grouped into three categories by each survey team; Schmidlin et al. (2002) grouped vehicles according to whether they were “not moved,” “moved > 1 m,” or “tipped over.” Schmidlin et al. (2002) defined vehicles being “moved > 1 m” as vehicles that were displaced laterally without tipping over. Vehicles that were “tipped
over” were known to have been tipped, rolled, or lofted (these three types of upset were not distinguished). Vehicles surveyed by MAR2008a,b and MAR2010 were similarly grouped according to “no vehicle movement,” vehicles that were “shifted laterally,” and vehicles that were “rolled or lofted.” The wording and definitions of the three vehicle displacement categories of Schmidlin et al. (2002) are relatively consistent with those of MAR2008a,b and MAR2010. This study therefore assumes that vehicles observed to have been “tipped over” by Schmidlin et al. (2002) may also be regarded as vehicles that were “rolled or lofted,” as defined by MAR2008a,b and MAR2010. Similarly, this study assumes that vehicles observed by Schmidlin et al. (2002) to have been “moved > 1 m” may be categorized as vehicles that had “shifted laterally” (as defined by MAR2008a,b and MAR2010) without overturning. The 959 surveyed vehicles incorporated into this study are therefore categorized uniformly as having sustained no movement, lateral shifting, or rolling or lofting motions.

Chi-square tests are employed to determine whether significant statistical differences exist in vehicular displacement patterns at different tornado wind speeds. The chi-square tests are confined only to vehicles exposed to winds ranging in magnitude from F1/EF1 to F4/EF4, as Schmidlin et al. (2002) did not assess vehicles exposed to F0 or F5 wind speeds. In addition, Schmidlin et al. (2002) found no significant differences in vehicle displacement frequencies between F1 and F2 winds or between F3 and F4 winds; a significant difference was however found between F2 and F3 winds. For this reason, Schmidlin et al. (2002) reported on frequencies of lateral shifting and tipping only upon aggregating vehicles exposed to either F1 or F2 wind speeds and, separately, vehicles exposed to F3 or F4 winds. Because of these categorizations by Schmidlin et al. (2002), the chi-square tests of this study similarly group together vehicles exposed to F1/EF1–F2/EF2 wind speeds and, separately, vehicles exposed to F3/EF3–F4/EF4 wind speeds.

4. Results

A breakdown of vehicles observed to have been moved or tipped by Schmidlin et al. (2002), MAR2008a,b, and MAR2010 is shown in Table 2; the combined observed frequencies are displayed in Table 3. These results apply to common passenger vehicles in the United States. Larger, high-sided vehicles such as trucks, buses, or other commercial vehicles may yield different results. We do not infer a specific wind speed on the vehicles surveyed since the EF scale is defined at 10-m height levels, the center of each vehicle is at about 1 m above ground, and wind speeds in the lowest 10 m of a tornado are not well known.

Marshall and colleagues included vehicles at homes with EF0 ($n = 52$) and EF5 ($n = 16$) damage. At EF0

<table>
<thead>
<tr>
<th>Table 2. Schmidlin et al. (2002) results for 291 total vehicles in F1–F4 damage swaths, and MAR2008a,b and MAR2010 results for 668 total vehicles in EF0–EF5 damage swaths.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schmidlin et al. (2002)</td>
</tr>
<tr>
<td>F1/F2</td>
</tr>
<tr>
<td>F3/F4</td>
</tr>
<tr>
<td>Total</td>
</tr>
<tr>
<td>MAR2008a,b, MAR2010</td>
</tr>
<tr>
<td>EF0</td>
</tr>
<tr>
<td>EF1</td>
</tr>
<tr>
<td>EF2</td>
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<td>EF3</td>
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<tr>
<td>EF4</td>
</tr>
<tr>
<td>EF5</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3. Combined data from Schmidlin et al. (2002), MAR2008a,b, MAR2010 for 891 vehicles in EF1–EF4 damage.</th>
</tr>
</thead>
<tbody>
<tr>
<td>EF scale</td>
</tr>
<tr>
<td>F1/EF1 and F2/EF2</td>
</tr>
<tr>
<td>F3/EF3 and F4/EF4</td>
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Table 4. Chi-square test for vehicles exposed to F1/EF1 and F2/EF2 wind speeds. The \( \chi^2 \) value (1.56) falls below the critical value of 5.99 where \( \alpha = 0.05 \). No statistically significant differences in motor vehicle displacement are therefore observed between Schmidlin et al. (2002), MAR2008a,b, MAR2010 at F1/EF1 and F2/EF2 wind speeds.

<table>
<thead>
<tr>
<th>Vehicle movement</th>
<th>Vehicle shifted laterally</th>
<th>Vehicle rolled or lofted</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>No vehicle</td>
<td>112</td>
<td>46</td>
<td>165</td>
</tr>
<tr>
<td>F1/EF1 &amp; F2/EF2</td>
<td>(Schmidlin)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F1/EF1 &amp; F2/EF2</td>
<td>(Marshall)</td>
<td></td>
<td></td>
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<tr>
<td>Total</td>
<td>240</td>
<td>116</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 5. Chi-square test for vehicles exposed to F3/EF3 and F4/EF4 wind speeds. The \( \chi^2 \) value (2.09) falls below the critical value of 5.99 where \( \alpha = 0.05 \). No statistically significant differences in motor vehicle displacement are therefore observed between Schmidlin et al. (2002), MAR2008a,b, MAR2010 at F3/EF3 and F4/EF4 wind speeds.

<table>
<thead>
<tr>
<th>Vehicle movement</th>
<th>Vehicle shifted laterally</th>
<th>Vehicle rolled or lofted</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>No vehicle</td>
<td>40</td>
<td>63</td>
<td>126</td>
</tr>
<tr>
<td>F3/EF3 and F4/EF4 (Schmidlin)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>189</td>
<td>251</td>
<td>79</td>
</tr>
</tbody>
</table>

5. Discussion

There are currently 28 damage indicators in the EF scale, although passenger vehicles, which are remarkably similar in size and shape, are not included; this issue was previously addressed by Edwards et al. (2013). Using vehicles as a damage indicator could fill gaps in storm intensity assessment where vehicles are present but few other structures are struck. A general agreement on EF-scale winds likely to move or tip vehicles is needed to allow vehicles to be useful as damage indicators. In addition, it would be crucial for surveyors to establish whether any tornado-stricken vehicles are absent at damage sites when surveys are conducted, as less damaged vehicles are often being driven or are in glass/repair shops in the days following a tornado event.

Based on the results of this survey, if a vehicle is moved laterally, a rating of EF1 or higher is appropriate. If several cars are moved but none or few are tipped, then EF2 is appropriate. If more than half of vehicles are moved and several are tipped, then an EF3 rating is appropriate. In the absence of other damage indicators, we may assume that the observation of passenger vehicles tipped over probably indicates EF3 or stronger wind strength. For example, if mobile homes are the strongest structures in a local area and are totally destroyed while most vehicles are not tipped, an EF2 rating would be appropriate. On the other hand, if most mobile homes are destroyed and several vehicles are tipped, an EF3 rating would be appropriate. If most vehicles are tipped then an EF4 rating may be appropriate.

damage, 10% of vehicles were moved and none was tipped; these values are smaller than for vehicles observed in the combined EF1 and EF2 damage swaths. At EF5 damage, 69% were moved and 31% were tipped, and both of these values are greater than those for the combined EF3 and EF4 damage swaths. In both the Schmidlin and Marshall vehicle datasets, the percentages of vehicles moved or tipped increase nearly monotonically as EF-scale intensities increase (Table 2 and 3).

Results from both survey teams suggest that vehicles are rarely moved (~1 in 10) in EF0 wind zones, but the likelihood of lateral movement increases to about 1 in 3 vehicles in EF1 and EF2 zones, 1 in 2 in EF3 and EF4 zones, and 2 in 3 for a small sample of vehicles exposed to EF5 wind speeds. For vehicles tipped, results from all surveys incorporated into this study suggest that passenger vehicles are rarely rolled or lofted (~1 in 25) in wind zones at EF2 or lesser intensities. Even in EF3 and EF4 damage, only about 15% (~1 in 7) vehicles are tipped. A smaller sample of vehicles in EF5 damage indicates that 31% (~1 in 3) are tipped.

In assessing the distributions of passenger vehicle displacement patterns between Schmidlin et al. (2002), MAR2008a,b, MAR2010, two 3 \times 2 contingency tables were employed for chi-square testing; one test was conducted for vehicles exposed to F1/EF1 and F2/EF2 wind speeds, and the second was conducted for vehicles exposed to F3/EF3 and F4/EF4 wind speeds. In testing for differences in observed movement frequencies between datasets of Schmidlin et al. (2002), MAR2008a,b, MAR2010 at 95% confidence intervals, each chi-square value falls below its respective critical value; the hypothesis of no difference in displacement pattern distributions therefore cannot be rejected for either test (Tables 4 and 5). The conclusion in each case is that the observed frequencies of vehicular movements at these tornado wind speeds are similar enough for the survey subjects of Schmidlin et al. (2002), MAR2008a,b, MAR2010 to be considered one population.
Information on the fate of vehicles exposed to tornadic winds may also be useful for improving shelter recommendations for residents of mobile homes, motorists, or those outdoors during a tornado warning. These results may be used to estimate casualties in the hypothetical scenario of a violent tornado striking an urban region, as discussed by Rae and Stefkovich (2000). Furthermore, information and knowledge about motor vehicle stability in high winds may potentially contribute to highway and bridge design, provide risk measures for wind-induced vehicle accidents, determine wind thresholds to slow or stop traffic, and improve safety recommendations for motorists in high winds (Baker 1987, 1991, 1994; Baker and Reynolds 1992; Schmidlin and King 1996; Snaebjörnsson et al. 2007).

6. Summary

This study compiled passenger vehicle data collected by Schmidlin et al. (2002) and MAR2008a,b and MAR2010 in the aftermaths of tornado events. Statistical distributions of vehicular displacement patterns were shown to display no significant differences across 12 surveyed events spanning the years of 1994–2008. The ratios of passenger vehicles sustaining lateral shifting or rolling/lofting motions at various F-scale and EF-scale thresholds were found to be relatively consistent among the tornado survey sites. The results of this study may therefore provide a greater frame of reference for expected tornado-induced vehicular damage outcomes, and may potentially build a case for utilizing motor vehicles as an EF-scale damage indicator.

Acknowledgments. The authors thank and recognize professors Rebecca Parylak and Richard Meindl of Kent State University for their assistance with this project.

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