Determining critical wind speeds for overturning two types of ambulances and a large city bus

Thomas W. Schmidlin, PhD
Barbara O. Hammer, MA
Paul S. King, BS
L. Scott Miller, PhD
Gregory Thumann, MS
Helene Wetherington, MA

ABSTRACT
Two types of ambulances and a city bus were modeled in a wind tunnel for the minimum wind speed required to upset the stationary vehicles. The Type I ambulance was vulnerable to upset with wind speeds of 135 to 150 mph on the vehicle over wind angles of 40° to 145°. The Type II ambulance was vulnerable to upset with wind speeds of 140 to 170 mph over wind angles of 30° to 145°. The 40-passenger city bus was vulnerable to upset with wind speeds of 60 to 75 mph over wind angles of 35° to 145°. These results showed ambulances were more stable in high winds than common passenger vehicles, but the city bus was very vulnerable in high winds. Testing showed that moving ambulances can be driven at low speeds in minimal hurricane-force winds without exceeding the upset wind speeds on the vehicles. This information provides guidance for safe operation of these vehicles during high winds including hurricanes, thunderstorms, and extra-tropical cyclones.

INTRODUCTION
A land falling hurricane poses threats to life and property, including to motorists on the highways. First responders in ambulances are called upon to assist persons injured during the storm, persons trapped by water or debris, and persons in other medical emergencies. The need for first responders will likely continue throughout the storm and may, in fact, peak during the worst storm conditions. However, at some predetermined wind speed (typically 39 mph), authorities may order first responders off the roadways for their own safety. Mile for mile, ambulances may be associated with more injuries from crashes than any type of vehicle, but their vulnerability to high winds is unknown. In addition to emergency vehicles that may operate during the storm, large city buses are used in some communities to evacuate special-needs populations, such as residents of nursing homes or long-term care facilities. There is a need to know the wind speeds at which ambulances and city buses can be operated with relative safety during a land falling hurricane. This knowledge applies to other severe wind events, including thunderstorms and extra-tropical cyclones.

Our previous research reported on field studies of the stability of 291 parked passenger vehicles struck by tornadoes and on wind tunnel tests of the wind speeds required to upset a sedan and minivan. Results showed that common passenger vehicles are vulnerable to upset at wind speeds of about 115 mph on a stationary vehicle. A survey of storm chasers showed that stationary, instrumented passenger vehicles have experienced storm winds of 98 to 105 mph without any adverse effects on the vehicle. Other research on stability of vehicles in strong winds is sparse. Bettle and colleagues showed that a stationary, empty 18-wheeled tractor semi-trailer (32,600 lb) tended to roll over at a cross wind of 87 mph, and a fully loaded truck (87,000 lb) tended to
roll over with a cross wind of 125 mph. Pinelli and colleagues tested a 1:21 scale model of an ambulance in a small (21-inch cross section) wind tunnel and found the ambulance was not at risk of overturning until wind speed reached about 100 mph, if the vehicle was driven slowly. Others have reported on characteristics of wind flow over vehicles, but few made conclusions about upset wind speeds.

The purpose of this research was to conduct wind tunnel experiments to determine the minimum wind speed required to upset two types of ambulances and a city bus. This information will provide guidance for the safe operation of these vehicles during hurricanes and other severe winds.

**Methods**

Scale models of Type I and Type II ambulances and a large city bus were constructed by the Wichita State University National Institute for Aviation Research Machine Shop. Table 1 shows the vehicle geometry specifications. All vehicles were modeled for their loaded condition using the maximum gross vehicle weight, according to their operation. The Type I ambulance was modeled after an American LaFrance Medicmaster on a Freightliner FL-60 extended cab chassis. The Type II ambulance was modeled after a National Ambulance Builders Monarch ambulance on a Ford E-350 Supervan chassis. The city bus was modeled after a Gillig low-floor, 40-passenger bus. Our results should not be considered as specific to these vehicles, but were generalized to these types of ambulances and bus.

The tests were performed in the Wichita State University Beech Memorial Low Speed Wind Tunnel. The tunnel is a commercial grade facility commonly used by aircraft developers and government labs, with a test section size of 7 by 10 feet. Each model was mounted to the tunnel’s exterior balance via a cylindrical pedestal support that rotated 180°. A circular flat plate with rounded edges served as a ground plane and aerodynamically isolated the vehicle from the support structure below. Model loads were measured using a six-component external balance capable of resolving the lift, drag, and side forces, and the pitching, rolling, and yawing moments. Data were recorded by a high-speed computer-based acquisition system. Classic and widely accepted techniques to reduce and correct measured data (such as for blocking and buoyancy) were applied to assure accuracy.

![Table 1. Vehicle geometry specifications used in the wind tunnel analysis](image)

<table>
<thead>
<tr>
<th></th>
<th>Type I ambulance</th>
<th>Type II ambulance</th>
<th>City bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontal area (ft²)</td>
<td>72</td>
<td>43.6</td>
<td>74.9</td>
</tr>
<tr>
<td>Length (ft)</td>
<td>30</td>
<td>19</td>
<td>40</td>
</tr>
<tr>
<td>Width (ft)</td>
<td>8</td>
<td>6.8</td>
<td>8.5</td>
</tr>
<tr>
<td>Height (ft)</td>
<td>10</td>
<td>8.3</td>
<td>9.5</td>
</tr>
<tr>
<td>Wheelbase (ft)</td>
<td>16.2</td>
<td>11.5</td>
<td>23.6</td>
</tr>
<tr>
<td>Track (ft)</td>
<td>7.7</td>
<td>6.5</td>
<td>8.5</td>
</tr>
<tr>
<td>Weight (lbs)</td>
<td>20,000</td>
<td>9,380</td>
<td>32,000</td>
</tr>
<tr>
<td>Center of gravity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ Fore/-aft of midpoint of wheelbase (ft)</td>
<td>-1.6</td>
<td>-1.2</td>
<td>-2.8</td>
</tr>
<tr>
<td>Height above ground (ft)</td>
<td>2.8</td>
<td>2.0</td>
<td>2.6</td>
</tr>
<tr>
<td>Model scale</td>
<td>1:9</td>
<td>1:7</td>
<td>1:14</td>
</tr>
</tbody>
</table>
Testing for each model was conducted at a flow speed of 160 mph. Results suggested supercritical Reynolds number conditions, so aerodynamic coefficients obtained would indicate full-scale loads with reasonable accuracy. To evaluate the effects of wind direction on the vehicles, the pedestal and vehicle models were moved through a 180° yaw sweep with data on the six components of load collected at 5° yaw increments. Vehicles were tested flat and with 5° of sideward tilt to simulate body roll due to suspension compliance under wind loads and to assess the resulting impact on aerodynamic loads. Actual vehicle tilt under wind load will depend upon wind speed, angle of the wind, and properties of the vehicle, including loading and suspension stiffness. Results are reported here only for the tilted case because it is the most vulnerable to upset.

We calculated components of all six loads for each 5° increment of yaw angle. An upset was said to occur when the static aerodynamic loads exceeded vehicle weight loads; that is, at least one tire would come off the ground. This does not imply that the vehicle was modeled to flip over in each case, since a tire can rise off the ground and then return to a stable position. As weight is removed from a tire, a vehicle can be moved by the wind into a more aerodynamic direction with respect to the wind (behaving like a wind vane) and recover stability. These motions were not modeled, and our results represent worst-case scenarios in this respect. Four modes of upset for the vehicles were examined: lifting, flip nose-up, flip tail-up, and roll. We assumed that the vehicle was in a static position (not moving), with rigid suspension, no translational or yawing motion (sliding or spinning), and in a uniform and steady airflow.

RESULTS

Stationary vehicles

Upset wind speeds for the Type I ambulance are shown in Figure 1. With the model tilted 5° to the side to simulate suspension compliance in strong side winds, the upset wind speed was 135 to 150 mph over wind angles of 40° to 145° as measured from the front of the vehicle (145 to 155 mph without tilt). Much higher wind speeds were required for upset with wind angles from the front or rear of the vehicle, as is typical. The mode of upset was roll.

Upset wind speeds for the Type II ambulance are shown in Figure 2. With the model tilted 5°, the upset...
wind speed was 140 to 170 mph over wind angles of 30° to 145° (170 to 200 mph without tilt). Much higher wind speeds were required for upset with wind angles from the front or rear of the vehicle. As with the Type I ambulance, the upset mode was roll.

Upset wind speeds for the city bus are shown in Figure 3. There was little difference in upset wind speed between the flat tests and those with 5° of tilt. With the model tilted 5° to the side, the upset wind speed was 60 to 75 mph over wind angles of 35° to 145°. The mode of upset was roll.

The minimum wind speeds to cause an upset of two common styles of ambulances were 135 to 140 mph, or about 20 mph higher than for a typical passenger car or minivan. This was the wind centered on the vehicle, about six feet above the ground. Because a brief gust may cause upset of a vehicle, we assumed the minimum upset wind speeds presented here represented a three-second gust at a six-foot height. Gusts can be converted to a fastest one-minute wind at 33 feet (10 m), as used in the Saffir-Simpson Hurricane Scale, using 1) a gust factor that converts three-second gusts to one-minute mean wind speeds, and 2) a logarithmic wind profile that converts a six-foot wind to a 33-foot wind.

In the first step, the gust factor used to convert a one-minute mean wind speed to a three-second gust is 1.19. Thus, the minimum three-second gust speed of 135 mph required to upset an ambulance, as shown in this research, can be expected to occur with a maximum one-minute mean wind speed of 113 mph at a six-foot height.

Next, we used the logarithmic wind profile in equation 1 taken from Stull and used by Beatty and colleagues for hurricane winds to convert mean one-minute winds on the vehicle (U_2) at six-foot height (z_2) to the mean wind speed (U_1) at the standard 33-foot height (z_1).

**Equation 1**

\[ U_1 = U_2 \left( \frac{\ln (z_1/z_0)}{\ln (z_2/z_0)} \right) \]

We used a roughness length, z_0, of 0.033 foot (0.01 m) for open terrain, such as a prairie or farm field environment to allow for a worst case scenario. A mean wind speed of 113 mph at a six-foot height, identified above as the minimum to cause an upset of an ambulance, converts to a mean one-minute wind speed of 156 mph at a 33-foot height. This wind speed is the lower threshold for Category 5 on the Saffir-Simpson Hurricane Scale. A 156 mph wind speed is a rare occurrence and an even rarer wind speed inland where ambulances would operate.

We tested the logarithmic profile for validity below 33 feet with wind data collected at 10-foot (3 m) and 33-foot (10 m) heights on a portable tower during Hurricane Isabel. The profile was part of the WEMITE Experiment provided by Becca Paulsen at Texas Tech University. The results showed that equation 1 is suitable for use in adjusting mean wind speeds for heights of 33 feet and below in hurricanes.

While the two styles of ambulances were relatively stable, the city bus was very vulnerable in high winds. This research showed that a loaded bus can be upset in winds as low as 60 mph on the vehicle. If this wind speed is taken as the maximum three-second gust at a six-foot height, then the conversions described above can be applied to convert to a 33-foot one-minute mean wind speed of 70 mph. This is below hurricane strength on the Saffir-Simpson Hurricane Scale.

**Moving vehicles**

The previous discussion applies to stationary vehicles. The aerodynamic effects of severe wind on a moving vehicle can be approximated by adding the vehicle motion vector to the wind vector. In equation 2, A is the vehicle speed. B is the ambient wind speed measured as the maximum three-second gust at vehicle height. B is obtained by converting the one-minute mean wind at a 33-foot height to the maximum three-second gust at a vehicle height of six feet with the multiplier 0.85 (obtained through the two-step process above; the gust factor and equation 1). That is, a hurricane wind speed of 75 mph at 33 feet will be (75)(0.85), or a 64 mph gust on the stationary vehicle. The angle between vehicle motion and the ambient wind direction is d. Using equations 2 and 3, we obtain the resultant wind speed on the vehicle (C), and the resultant wind angle on the vehicle (e).
Equation 2
\[ C^2 = A^2 + B^2 - (2AB \cos(180-d)) \]

Equation 3
\[ e = d - \sin^{-1}(A \sin(180-d)/C) \]

Four examples of vehicle speed and wind speed combinations are discussed. The ambient winds in these examples are the maximum three-second gusts at vehicle height, about 0.85 of the Saffir-Simpson Scale winds at 33 feet.

In the first example (Figure 4), a vehicle traveling at 60 mph (A) with a 60 mph (B) ambient crosswind blowing at 90°(d) to the vehicle direction has a resultant wind of 85 mph (C) at an angle of 45°(e) from the front of the vehicle. The 60 mph ambient wind gust on the vehicle (B) was converted from a one-minute mean wind of 71 mph at 33 feet (Saffir-Simpson Scale speed).

In the second example (Figure 5), slowing to 30 mph in the same 60 mph ambient crosswind gives a resultant wind of 67 mph at an angle of 63.5° from the front of the vehicle.

Driving at 30 mph into a 90 mph quartering headwind (45° from the front of the vehicle) gives a resultant wind of 113 mph at an angle of 34° from the front of the vehicle (Figure 6). The 90 mph gust on the vehicle (B) was converted from a Saffir-Simpson scale wind of 106 mph.

Driving 30 mph with a 90 mph quartering tailwind (135° from the front of the vehicle) gives a resultant wind
speed of 72 mph at an angle of 118° from the front of the vehicle (Figure 7).

Equations 2 and 3 can be used as in the previous four examples to show that the two types of ambulances can be driven at 30 mph in wind speeds up to hurricane force (one-minute mean at 33 feet of 75 mph), without the likelihood of upset. In that situation, the maximum wind gust encountered at vehicle height is only 94 mph, well below the upset wind speeds of 135 to 140 mph.

CONCLUSIONS

These results show that ambulances are quite stable in high winds and can be operated at higher wind speeds than common passenger vehicles. It is unlikely that their low tendency to overturn in wind will be a limiting factor in their operation. Other hazards must be considered including debris in the air and on the highways, flooded highways, the difficulties of working outdoors in severe winds and heavy rains, and impacts of the driver’s reactions while operating an ambulance in high winds and heavy rains. The city bus has a shape and size similar to a small mobile home and becomes unstable at about the same wind speed as an unanchored mobile home. Therefore, the operation of city buses must be stopped at relatively low wind speeds. A threshold of tropical storm force, 39 mph, would be reasonable.

This research reports on an initial study of the stability of three types of vehicles in severe winds through wind tunnel testing of the minimum wind speed required to upset stationary vehicles. Results showed that a minimum one-minute mean wind speed of 156 mph at 33 feet is required to upset ambulances (lower Category 5 on the Saffir-Simpson Scale). However, a mean one-minute wind of 70 mph may upset a city bus. Calculations of wind speeds on a moving vehicle indicated that ambulances are unlikely to be upset by wind even when traveling 30 mph in a hurricane force wind (75 mph). Local conditions must always be evaluated; however, the typical threshold of 39 mph used to stop operation of ambulances during hurricanes may be too low.

ACKNOWLEDGMENTS

This research was funded by the Division of Emergency Management of Palm Beach County, Florida, and Department of Emergency Management in Lee County, Florida. We appreciate the assistance provided by William O’Brien, Palm Beach County, and John Wilson, Lee County.

Thomas W. Schmidlin, PhD, Department of Geography, Kent State University, Kent, Ohio.
Barbara O. Hammer, MA, Department of Geography, Kent State University, Kent, Ohio.
Paul S. King, BS, Boyce Thompson Institute, Cornell University, Ithaca, New York.
L. Scott Miller, PhD, Department of Aerospace Engineering, Wichita State University, Wichita Kansas.
Gregory Thumann, MS, Department of Aerospace Engineering, Wichita, Kansas.
Helene Wetherington, MA, Division of Emergency Management, West Palm Beach, Florida.

REFERENCES