Evaluating Truck Rollover at Roundabouts on High-Speed Roads

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Presentation Outline

• Background and objectives
• Previous roundabout experiences
• Research methods
• Development of heavy vehicle overturning model
• Overview of study and data extraction
• Results
  - Inward vs. outward roundabout circulatory superelevation
  - Effect of aggressive driver behavior on rollover propensity
  - Effect of driver perception error on rollover propensity
• Final remarks and next steps
Background

• Roundabouts are emerging in the United States, primarily due to their capacity and safety benefits

• According to NCHRP 672 – *Roundabouts: An Informational Guide*, for 55 study roundabouts converted from stop (46) and signal (9) controls:
  - 76% reduction in injury crashes
  - 35% drop in total crashes
  - European countries have experienced similar reductions

• Safety benefits due to a variety of factors:
  - Less conflict points, both in number and severity
  - Lower speeds
  - Enhanced pedestrian safety
Background

• Roundabouts traditionally used on low-speed roads (less than 45 mph)

• Becoming more common on high-speed roads, or **those with approach speeds greater than 45 mph**

• Frequently used on the edges of towns and cities for transition from high to low speeds (see NCHRP 737)

• Safety research is limited for roundabouts on high speed roads with considerable truck traffic
Objectives of Research

1. Examine previous studies and crash data

2. Better understand drivers’ safety-related behaviors in roundabouts, particularly related to heavy vehicle rollover

3. Propose recommendations and design remedies
Isebrands (2011) examined 19 rural roundabouts on high-speed roads, converted from stop (18) and signal (1) controls:

- 88% reduction in injury crashes
- 63% drop in total crashes

Before-and-after crash analysis of 12 Wisconsin roundabouts on high-speed roads revealed the following:

<table>
<thead>
<tr>
<th>Category</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total crashes</td>
<td>30% decrease</td>
</tr>
<tr>
<td>Fatal</td>
<td>100% decrease</td>
</tr>
<tr>
<td>Incapacitating injury</td>
<td>75% decrease</td>
</tr>
<tr>
<td>Non-incapacitating injury</td>
<td>60% decrease</td>
</tr>
<tr>
<td>Possible injury</td>
<td>67% decrease</td>
</tr>
<tr>
<td>Property damage only</td>
<td>9% decrease</td>
</tr>
</tbody>
</table>

Before Installation: **121 crashes**  
After Installation: **85 crashes**

Kansas Roundabout Experience

- Since 2000, half of the heavy vehicle crashes at roundabouts on high-speed roads involved rollover
- Excessive speed given the conditions commonly cited in crash reports
- Most rollovers occurred after vehicle traversed the truck apron, causing load shifts or overcorrective steering which flipped the truck

Source: Kansas Department of Transportation
International Roundabout Experience

- United Kingdom experiences 50-60 injury rollovers per year on its roundabouts

- Roundabout factors correlated with rollover include:
  - Lengthy, high-speed approaches
  - Small entry deflection
  - Low circulating traffic volume
  - Excessive visibility
  - Large decrease in radius within roundabout
  - Sudden changes in roadway crossfall

Source: United Kingdom Highways Agency
Research Methods

• Establish pertinent model for rollover
• Collect video data from roundabouts
• Extract information on vehicle speeds and paths
• Determine the critical rollover speed and compare to the actual speed
• Identify critical behavior factors and scenarios
Heavy Vehicle Rollover

• Vehicle factors influencing rollover:
  - Speed
  - Center of gravity height
  - Track width
  - Suspension
  - Tires

• Load factors influencing rollover:
  - Overall weight
  - Lateral weight distribution
  - Longitudinal weight distribution

Source: NCHRP 505 – Review of Truck Characteristics as Factors in Roadway Design and Heavy vehicle stability guide and New Zealand Transport Agency
Articulated Vehicle Rollover
Rollover Condition:
\[(\vec{n}_3) \cdot (\vec{F}_a + \vec{F}_c + \vec{F}_g) > 0\]

Where: \(\vec{n}_3 = \) unit normal vector to rollover plane determined by \(\vec{af}\) (or \(\vec{ad}\)) and \(\vec{ac}\)

\(\vec{F}_a, \vec{F}_c, \vec{F}_g\) are the counteracting forces of longitudinal acceleration, centrifugal acceleration, and gravity

Based on original derivation from unpublished research note (Tarko, Hall, & Lizarazo, 2014)
Proximity to Rollover

Critical rollover speed:

\[ (\mathbf{n}_3) \cdot (\mathbf{F}_a + \mathbf{F}_c + \mathbf{F}_g) = 0 \quad \Rightarrow \quad v_{cr} = \sqrt{\frac{(\mathbf{n}_3) \cdot (-g \mathbf{u}_g - a \mathbf{u}_a)}{(\mathbf{n}_3) \cdot (\frac{1}{r} \mathbf{u}_c)}} \]

Where: \( \mathbf{u}_a, \mathbf{u}_c, \mathbf{u}_g \) = unit normal vectors in direction of forces

\( r \) = instantaneous radius of vehicle path

Difference between critical rollover speed and actual vehicle speed determines proximity to rollover:

\[ \Delta v = v_{cr} - v \]
## Typical Specifications

### Trailer
- Length: **48’**
- Width: **8’6”**
- Height: **13’6”**
- Average box length: **47’6”**
- Average box width: **8’3”**
- Average box height: **9’2-1/2”**
- Weight: **12640 lb**

### Tractor
- Weight: **20,000 lb**

Sources: University of Michigan Transportation Research Institute, YRC Freight, and WB McGuire
Tractor-trailer Combination

- Legal gross weight in US without permits is **80,000 lb**

- Trailer loading is unknown, so both unloaded and fully loaded are considered for the same trailers

Source: Truckers Report
Study Roundabouts

- Focus is on roundabouts on high-speed roads with considerable heavy vehicle presence
- An examination of similar nearby low-speed roundabouts conducted for comparison

<table>
<thead>
<tr>
<th>Roundabout</th>
<th>Number of approaches</th>
<th>Highest approach speed (mph)</th>
<th>Inner radius (ft)</th>
<th>Number of lanes and width</th>
<th>Approach curve radius (ft)</th>
<th>Super-elevation (%)</th>
<th>Year built</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR 25</td>
<td>3</td>
<td>55</td>
<td>56</td>
<td>2 x 16 ft</td>
<td>121</td>
<td>-2 to 2</td>
<td>2012</td>
</tr>
<tr>
<td>Concord Rd/Maple Point Drive</td>
<td>3</td>
<td>30</td>
<td>60.5</td>
<td>1 x 16 ft</td>
<td>90 to 93</td>
<td>2</td>
<td>2012</td>
</tr>
<tr>
<td>SR 32-38/Promise Road</td>
<td>4</td>
<td>55</td>
<td>58</td>
<td>2 x 16 ft</td>
<td>100</td>
<td>2</td>
<td>2011</td>
</tr>
<tr>
<td>SR 32-38/Union Chapel Road</td>
<td>3</td>
<td>55</td>
<td>58</td>
<td>2 x 16 ft</td>
<td>100</td>
<td>2</td>
<td>2011</td>
</tr>
</tbody>
</table>
Data Collection

- Camera position allows for extraction of approach and circulatory speeds and trajectories of same vehicle.
Data Extraction

• Path estimation tool developed in Purdue Center for Road Safety

• Extraction of trajectories by marking the same points on vehicle in successive frames

• Stabilization to reduce effects of wind

• Software calculates the coordinates of up to seven points at different locations on vehicles

• Calibration mode for determining vehicle dimensions
Data Extraction: Vehicle Path

Points marked incrementally at semi-trailer tires to determine path

Additional information regarding environmental conditions, heavy vehicle type, and lane position
Data Collection

- 42-foot pneumatic mast
- Two high-resolution dome cameras

Other features:
- Computer
- Two flat screen monitors
- 8 channel video recorder with 4 terabytes of storage capacity

Purdue Mobile Traffic Lab (MTL)
Approach curve vs. Circulation

Distribution of minimum $\Delta v$ for studied vehicles

Cumulative Percent

$\Delta v$ (mph)
Inward vs. Outward Superelevation

- Outward circulatory superelevation design commonly used in the United States
- However, inward design may offer benefits in reducing rollover risk
- Both scenarios should be compared to quantify whether safety advantage is substantial
- Assumption: Limited changes in pavement elevation do not affect behavior as represented by path and speed selection

Source: Gingrich and Waddell, 2008
Inward vs. Outward Superelevation

Minimum $\Delta v$ at circulation, trailers assumed unloaded
Inward vs. Outward Superelevation

Minimum $\Delta v$ at circulation, trailers assumed loaded
# Inward vs. Outward Superelevation

Comparison of Mean Minimum $\Delta v$ (mph) for Superelevation Scenarios

<table>
<thead>
<tr>
<th>Superelevation</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2% inward vs.</td>
</tr>
<tr>
<td>3% inward</td>
<td>2% outward</td>
</tr>
<tr>
<td>Mean Minimum $\Delta v$</td>
<td>1.94</td>
</tr>
<tr>
<td>Unloaded</td>
<td></td>
</tr>
<tr>
<td>16.67</td>
<td>16.19</td>
</tr>
<tr>
<td>Loaded</td>
<td></td>
</tr>
<tr>
<td>9.63</td>
<td>9.28</td>
</tr>
</tbody>
</table>

Estimate is bounded by the assumed unloaded and loaded cases
Findings

• Circulation more critical location for rollover; may focus analysis here

• While the inward design slightly raises $\Delta v$, it introduces other challenges, namely:
  - Relatively abrupt crossfall change between approach and circulation (linked to rollover)
  - More complex and costly drainage

• The safety advantage afforded by inward superelevation is small; it cannot be recommended given its shortcomings

• No strong basis to discontinue the common practice of outward superelvation
Aggressive Driver Behavior

• Certain drivers are prone to aggressive behaviors, such as traveling at excessive speeds

• Drivers classified as aggressive and non-aggressive based on speed far from the roundabout’s influence

• Compared minimum $\Delta v$ at roundabout for aggressive and non-aggressive drivers
Aggressive Driver Behavior

![Graph showing cumulative percent of trailers assumed loaded and unloaded relative to speed difference (Δv) in mph. The graph includes data for trailers assumed loaded and unloaded, separated by 50th-percentile lines. The graph is labeled with 'Cumulative Percent' on the y-axis and 'Δv (mph)' on the x-axis. The speed far upstream is indicated as 800 ft.]
Aggressive Driver Behavior

- No obvious connection between aggressive driver behavior and rollover risk at the roundabout

![Plot Area](image)

- Speed far upstream (800 ft)
  - Below 25th-percentile
  - Above 75th-percentile

Cumulative Percent

\[ \Delta v \text{ (mph)} \]

- Trailers assumed loaded
- Trailers assumed unloaded
Driver Perception Error

• On the roundabout approach, high-speed may indicate a driver misperception on safe traversal of the roundabout

• Studied impact of this driver perception error on rollover risk
Driver Perception Error

Approach speed 250 ft upstream

Approach speed 100 ft upstream
## Driver Perception Error

Mean Minimum \( \Delta v \) at roundabout circulation (mph) based on Approach Speed

<table>
<thead>
<tr>
<th>Approach speed classification</th>
<th>250 feet</th>
<th>100 feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below 50\textsuperscript{th}-percentile</td>
<td>10.87</td>
<td>11.28</td>
</tr>
<tr>
<td>Above 50\textsuperscript{th}-percentile</td>
<td>10.51</td>
<td>10.10</td>
</tr>
<tr>
<td>t-statistic</td>
<td>-0.90</td>
<td>-3.21</td>
</tr>
</tbody>
</table>
Driver Perception Error

Approach speed
250 ft upstream
- Below 25th-percentile
- Above 75th-percentile

Approach speed
100 ft upstream
- Below 25th-percentile
- Above 75th-percentile
## Driver Perception Error

Mean Minimum $\Delta v$ at roundabout circulation (mph) based on Approach Speed

<table>
<thead>
<tr>
<th>Approach speed classification</th>
<th>Distance upstream</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>250 feet</td>
</tr>
<tr>
<td>Below 25$^{th}$-percentile</td>
<td>11.08</td>
</tr>
<tr>
<td>Above 75$^{th}$-percentile</td>
<td>9.97</td>
</tr>
<tr>
<td>t-statistic</td>
<td>-1.88</td>
</tr>
</tbody>
</table>
Preliminary Findings

- Drivers with excessive (errant) speed on the approach come closer to rollover threshold at the roundabout
  - More pronounced effect at 100 ft upstream of yield line

- Approaching a roundabout at a speed higher than 30 mph at 250 ft upstream of the yield line is associated with a higher risk of rollover

- Countermeasures
  - Warning truck drivers whose approach speeds are higher than the critical one (speed trap with vehicle classification, variable message sign)
  - Better driver training
Other Findings

• Literature review and crash reports found the truck apron design may also be causing problems

• Should incorporate more forgiving design
  - Easily mountable
  - Marking with texture and color different from pavement
Next Steps

• Expand sample of heavy vehicles and roundabouts

• Analyze rollover risk during poor weather and night conditions

• Comparative analysis of the rollover risk in roundabouts with low and high-speed approaches

• Recommend other design and signage improvements that can be cost-effectively implemented
Questions?
Data Summary

- **970 trajectories extracted**
  - 485 heavy vehicles
  - 485 non-heavy vehicles (cars, minivans, etc.)

### Type of approach

<table>
<thead>
<tr>
<th>Type</th>
<th>Extracted Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-speed</td>
<td>479</td>
</tr>
<tr>
<td>Low-speed</td>
<td>491</td>
</tr>
</tbody>
</table>

### Roundabout

<table>
<thead>
<tr>
<th>Roundabout</th>
<th>Extracted Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>State Road 25 near Lafayette, Indiana</td>
<td>254</td>
</tr>
<tr>
<td>Concord Road and Maple Point Drive in Lafayette, Indiana</td>
<td>256</td>
</tr>
<tr>
<td>State Road 32 and Union Chapel Road near Noblesville, Indiana</td>
<td>310</td>
</tr>
<tr>
<td>State Road 32 and Promise Road near Noblesville, Indiana</td>
<td>150</td>
</tr>
</tbody>
</table>