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Exploration of Tractor Trailer Vehicle Parameters and Evaluation of Vehicle Dynamics During a Wind Induced Rollover Event

Trevor Law, E.I.T., Jacob Stoner, P.E.
SEA Limited
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S-E-A, Ltd.

ABSTRACT

High-sided vehicles are susceptible to rollovers during high or gusting crosswind conditions. The goal of this paper is to create a simple methodology for applying constant approximated aerodynamic forces to a tractor trailer in HVE, as well as examining how the HVE SIMON connection parameters affect rollovers. Parameters such as body torsion, tire/road friction coefficients, and suspension and 5th wheel damping and stiffness were evaluated and then varied to model real-life wind-induced rollovers. These simulations were run with the tractor trailer driving straight with an applied force-moment couple to reflect cross winds. Video review of wind induced tractor-trailer rollovers depict the roll event of the trailer leading the roll event of the tractor, creating a roll angle difference (roll delta) between the tractor and trailer throughout the rollover event. This study explores which of the parameters have the largest impact on the roll delta between the tractor and trailer. A parametric study of parameters affecting roll delta is presented, wherein the 5th wheel stiffness had the greatest effect. The authors found best agreement with the studied cases when a 5th wheel stiffness of approximately $2.5 \cdot 10^4$ in·lb/deg was used, as opposed to the HVE default of $1.2 \cdot 10^7$ lb·in/deg. This change in stiffness was then validated by recreating multiple wind induced rollovers with no further alteration to the vehicle parameters.

INTRODUCTION

Much of the research into the dynamics of high sided vehicles in crosswinds date back to the late 1990s and 2000s. These explorations focused heavily on the aerodynamic influences on the event and the related mathematical computations. In HVE-WP2008-1 critical wind speed for wind related tractor trailer rollover dynamics are studied and a simplified static wind equation is created based on the Saiidi critical wind speed equation. Lift and drag forces, and their respective coefficients, are considered and explained in detail. This paper aims to create an even further simplified approach to the Saiidi critical wind speed equation by considering only the lateral force-moment couple created by the perpendicular component of the wind. In addition to validating this simplification, the authors seek to study how to best accurately replicate the phases of a rollover in HVE.

Rollovers events can be generally classified into three phases: (1) loss of control, (2) trip, and (3) roll. Wind related tractor trailer rollovers are unique in that the wind may directly initiate the trip phase, as opposed to angular momentum and roadway geometry initiating the trip phase. The trip phase is where the largest portion of the tractor trailer roll delta occurs, and as such will be a large focus of this paper, as well as matching general rollover timing.

In most wind rollover cases, the trailer rolls more significantly than the tractor and then pulls the tractor into a more aggressive roll. As seen in Figure 1, if a tractor trailer in SIMON is loaded with no vehicle property alterations, timing of the rollover from beginning to end is generally similar. However, one of the most obvious differences between these events is the roll delta between the tractor and trailer. With no alterations to base parameters, the tractor and trailer roll together, essentially rolling as a unit, rather than reflecting the roll delta observed in real world scenarios. This paper will detail how SIMON can be leveraged to model a more realistic rollover event.

Figure 1: Comparison of unaltered SIMON simulation to a real world rollover

METHODOLOGY

The authors did research to find videos of tractor trailer rollover events. Using news reports and YouTube videos with date and time stamps, the authors were able to determine roadway location, heading direction, and wind characteristics in each of the studied cases. The tractor's make and model were visually determined, then weight was replicated with researched vehicle specifications. Due to the limited knowledge about the loads being hauled, it was assumed that the trailers were empty or nearly empty as it is the most susceptible condition for a rollover.

Many of the cases studied occurred on either March 13, 2019, or March 14, 2025, in Amarillo, TX on the same stretch of Lakeside Drive. As many tractor trailers have rolled over in this location on these specified dates, there were ample videos from which to select for analysis. By analyzing events which occurred on the same roadway in the same location, the authors were able to limit the variability between cases. Having a roadway in Texas with few features that could impact effective wind speed and a negligible grade made analyzing the rollovers on a flat plane in HVE a good representation of roadway characteristics.

Eight vehicle parameters impacting both the tractor and trailer were evaluated. These parameters were altered individually, both by increasing and decreasing the selected variable, to study the effect that each specific parameter had on the simulated event. This parametric study was performed with a given set of initial researched wind conditions for one of the rollover events. Once the effect of each parameter was established, parameters were altered to accurately match the dynamics of the rollover, while leaving as many as possible as their default values.

It is important to note that changes in 5th wheel properties will not yield the proposed effect unless the vehicle connection model in SIMON is changed from the default of "Use Heavier Vehicle" to "Use Tow Vehicle" as shown in Figure 2. The different connection model selections in SIMON effect how the connection force, roll moment, and yaw moment between the vehicle combination is calculated. Connection force damping and spring rate are calculated by SIMON if "Use Both Vehicles" or "Use Heavier Vehicle" are selected. When "Use Tow Vehicle" is selected, the spring and damping rate of the connection is drawn from the connection properties dialogue box. For moment calculations, when "Use Both Vehicles" or "Use Heavier Vehicle" are selected, the connection's torsional stiffness is set by the body torsion properties, and the torsional damping is locked at 120 in·lb·sec/deg. By selecting "Use Tow Vehicle" the torsional stiffness and damping values from the connection properties dialogue box are utilized in SIMON. The roll moment is ultimately a result of the roll angle difference between the two connected vehicles.

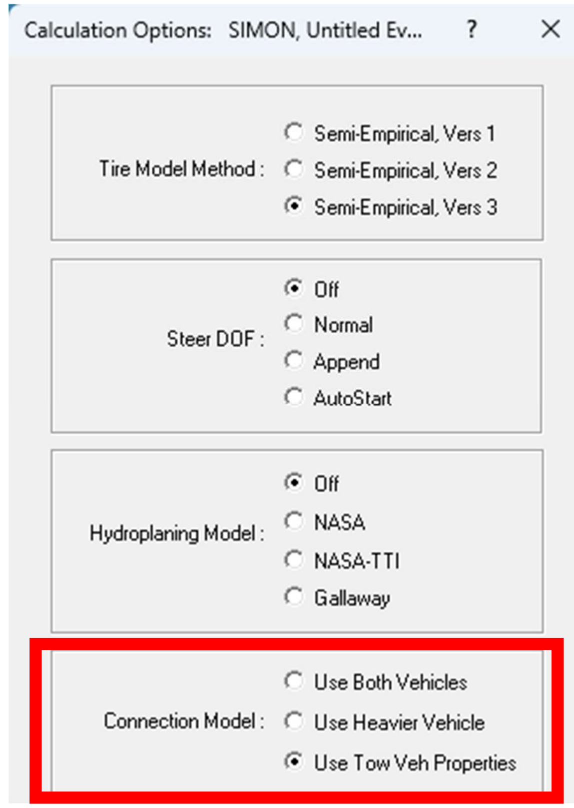


Figure 2: Calculation Options menu for changing the Connection Model

In a high fidelity rollover analysis, the aerodynamic forces of the event are meticulously evaluated, considering all drag effects, including the effect of aerodynamic lift on the trailer roof and lower rails (HVE-WP2008-1). The goal of this exploration is to reduce the complexity of evaluating rollover events, therefore a simplified aerodynamic model has been implemented. This approach approximates the tractor and trailer as individual flat bodies acted upon solely by the perpendicular element of the wind. This yields a force-moment couple for each body described at their most elementary level by the equation for drag force.

$$P_w = C_D \rho \frac{v_w^2}{2} \sin(\theta) \quad (1)$$

Where:

P_w = Lateral Wind Drag Pressure

C_D = Drag Coefficient

ρ = Air Density

v_w = Wind Velocity

θ = Angle of wind to perpendicular

The lateral wind drag pressure can be utilized with the cross sectional area of the tractor or trailer to find the total drag force acting upon that body. It can also be used to find the moment on each body through the equation,

$$M_T = P_w(A_aY_a + A_bY_b) \qquad (2)$$

M_T = Wind Moment about the CG

A = Area above or below vehicle CG

Y = Vertical distance from vehicle CG

The derivation and proper selection of drag coefficient is discussed heavily in HVE-WP2008-1 and for each case it must be selected with engineering judgement. In this study, a value of 1.44 was used and was sourced from the Introduction to Fluid Mechanics 3rd Edition by Fox and McDonald.

Area values were determined via analysis in AutoCAD. SIMON allows for user entered loads which act at a vehicle's CG and behave in the same manner as other HVE time-based entry boxes, with linear interpolation between each given point. The forces to the vehicle are applied in the "Collision Pulse" dialogue box under "Set Up" in the event editor. Wind loads were applied as a constant load with predefined magnitude calculated from the equations referenced above.

TESTING

The vehicle property parametric study began with a control run with no altered parameters demonstrating how SIMON depicts a wind induced rollover with only aerodynamic influences being applied. This test run exemplifies the differences between the SIMON model and real world rollover dynamics, most obvious of which is the relationship between the tractor and the trailer as described earlier and shown in Figure 1.

Suspension Properties

The first parameter analyzed was the suspension of both the tractor and trailer. Note that the default values for damping and wheel rate are different between the tractor, trailer, and axle types, but the range of valid values are the same. A 1999-2004 Freightliner Columbia and a 53-foot van trailer were used in the parametric study, and the default and parameter ranges are shown below in Table 1.

		Default	Minimum	Maximum
Steer Axle	Wheel Rate (lb/in)	1503	50	12000
	Damping (lb*in/deg)	13.09	0	50
Drive Axles	Wheel Rate (lb/in)	4705	50	12000
	Damping (lb*in/deg)	17.2	0	50
Trailer Axles	Wheel Rate (lb/in)	5500	50	12000
	Damping (lb*in/deg)	5	0	50

Table 1: Suspension Property Ranges

The tests showed that damping has little to no effect on the dynamics of the rollover, while the wheel rate impacts rollover duration and the relationship between the tractor trailer and wheels. Maximum wheel rate results in a shorter time to full rollover and the axles rotate with the body of the tractor/trailer, opposite is true for minimum wheel rate with the wheels remaining planted on the ground further into the rollover event, which is shown in Figure 3.

Figure 3: Wheel rate comparison at the same duration into the roll event.

Body Torsion

Body Torsion affects how easily and how high along its longitudinal centerline each body rotates about itself. The stiffness defaults to the maximum value of $1.2 \cdot 10^7$ in·lb/deg and the axis of rotation is set at the center of gravity. The stiffness can be adjusted down to a minimum of $1.2 \cdot 10^4$ in·lb/deg while the axis of rotation has a range of 30 inches above the CG to 50 inches below. None of the test simulations varied in any significant way from the control simulation. This result is expected, as this parameter is not considered when "Use Tow Vehicle Properties" is selected. This parameter is only utilized when "Use Both Vehicles" or "Use Heavier Vehicle" are selected in the SIMON calculation options.

5th Wheel Torsional Stiffness and Damping

The 5th wheel attachment properties can be changed in the connection properties dialog box on the tractor. The 5th wheel can have its torsional stiffness and damping altered, and the suggested ranges, absolute ranges, and default values are shown below in Table 2. Note that these ranges can be altered in the language.rsc file in the HVE file directory but the suggested and absolute ranges utilized were the defaults included with HVE.

	Default	Suggested Minimum	Suggested Maximum
Angular Stiffness (in*lb/deg)	1.20E+07	1.00E+06	1.00E+08
Damping (in*lb*sec/deg)	2.1	0.2	8.7
		Absolute Minimum	Absolute Maximum
Angular Stiffness (in*lb/deg)	1.20E+07	1.00E+04	1.00E+09
Damping (in*lb*sec/deg)	2.1	0	174.5

Table 2: Torsional Stiffness Ranges

The simulation runs for the range of damping values showed no significant variation from the control simulation. The simulation runs with stiffness values within the suggested range performed similarly (Figure 4). No significant difference was observed until the stiffness was dropped below the suggested range to around $1.0 \cdot 10^5$ in·lb/deg (Figure 5), at which time the trailer begins to roll earlier and faster than the tractor, appearing to roll to a point before pulling the tractor into a roll. Maximum roll angle delta seen at this stiffness was around 6 degrees.

Figure 4: Comparison of the suggested 5th wheel stiffness range

Figure 5: Comparison of the absolute 5th wheel stiffness range

Out of the parameters examined, the one that affected the roll delta of the tractor and trailer the greatest was rotational stiffness of the tractor king pin.

Further analysis was performed to determine reasonable values for recreation of the analyzed scenarios. iteratively by altering the 5th wheel as well as wind speed. Wind speed applied varied within 1 standard deviation of the average of the max gust values for the determined range of time of day in which the event occurred.

Starting with average wind speed, 5th wheel stiffnesses of $1.0 \cdot 10^4$ (absolute minimum), $1.5 \cdot 10^4$, $2.5 \cdot 10^4$, $3.5 \cdot 10^4$, $1.0 \cdot 10^6$ (suggested minimum) in·lb/deg were compared, the results of which are shown below in Figure 6.

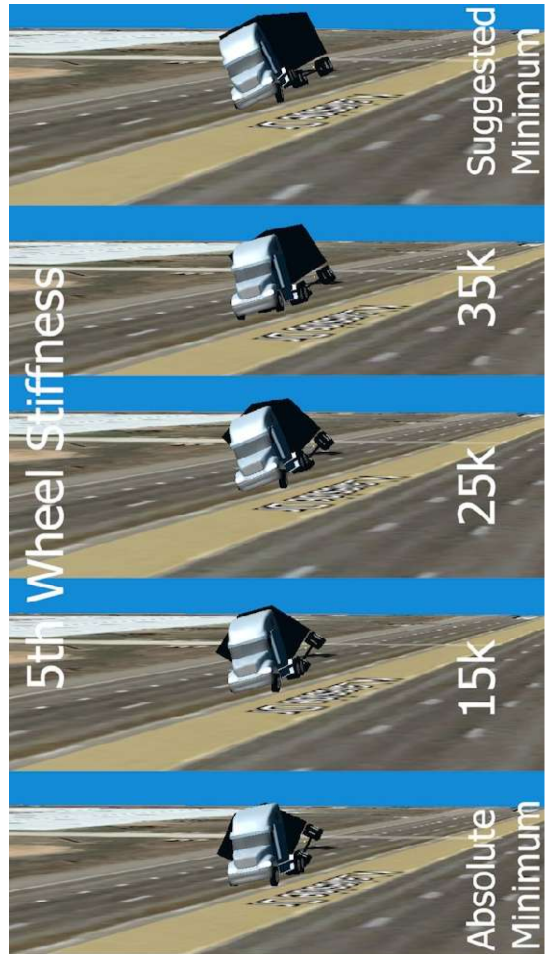


Figure 6: Comparison of 5th wheel stiffness values below the suggested range

Although differences between the sims were minimal, by visually comparing the roll angle deltas between tractor and trailer to the event these simulations are based upon, it was deduced that simulations using a torsional stiffness of $2.5 \cdot 10^4$ in·lb/deg best matched the dynamics of the tractor trailer during rollover. A comparison of the roll angle deltas gathered from these simulation runs can be seen in Figure 7.

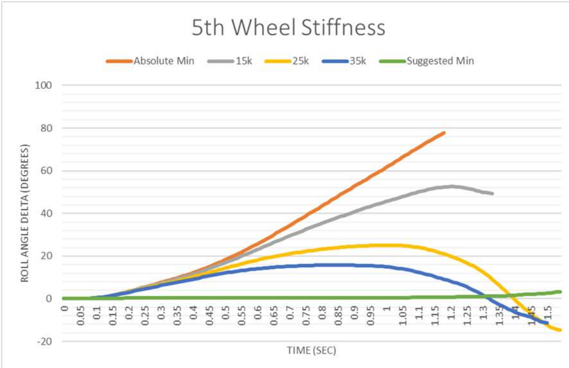


Figure 7: Graphical representation of roll angle delta for values on the lower end of the 5th wheel stiffness absolute range

For some events, using the average wind gust speed in the area for a reasonable timeframe of the incident accurately matches rollover duration. As seen in Figure 8 and again in Appendix A, one of the recorded incidents that occurred in Amarillo, TX on March 13, 2019, was able to be accurately modeled with the average wind speed for a 7-hour window on the date in question (Table 3). The calculated peak roll angle delta from the HVE simulation was 19.5 degrees.

Gusts	
71	
62	
72	**AVG**
64	70.7
79	
77	**STD DEV**
79	6.6
64	
68	

Table 3: Wind Gust Speeds for Amarillo, TX incident location on March 13, 2019

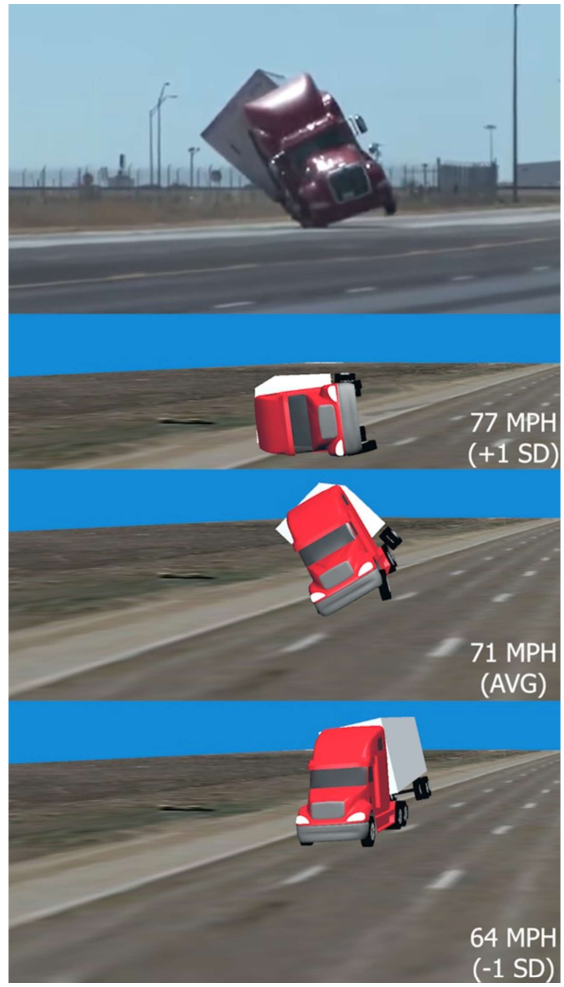


Figure 8: Event 1 at t=1.99s

A slight deviation from the average may be necessary to match the exact timing of the event. An event which also occurred on Lakeside Drive in Amarillo, TX on the following day, March 14, 2019 was simulated using the aforementioned methodology. The gust data in the time proximate to the accident was considered and varied within 1 standard deviation. The timing of the simulation was faster than the original event so with the need for a slower roll, the wind speed was reduced to 60 mph from 68 mph (-1 Std. Dev), the simulation matched the rollover duration as displayed in Figure 9 and shown in Appendix B. The calculated peak roll angle delta from the HVE simulation was 13.5 degrees.

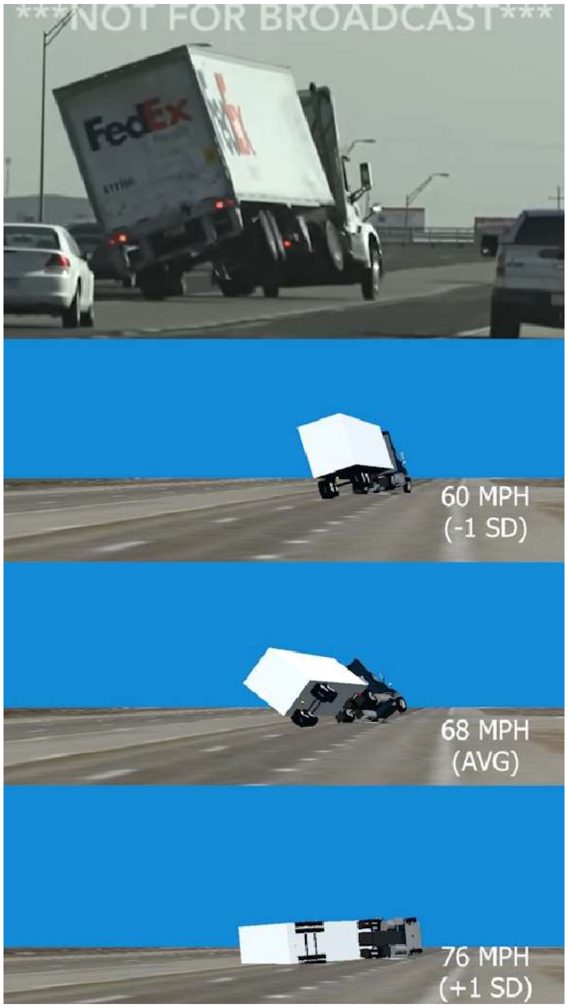
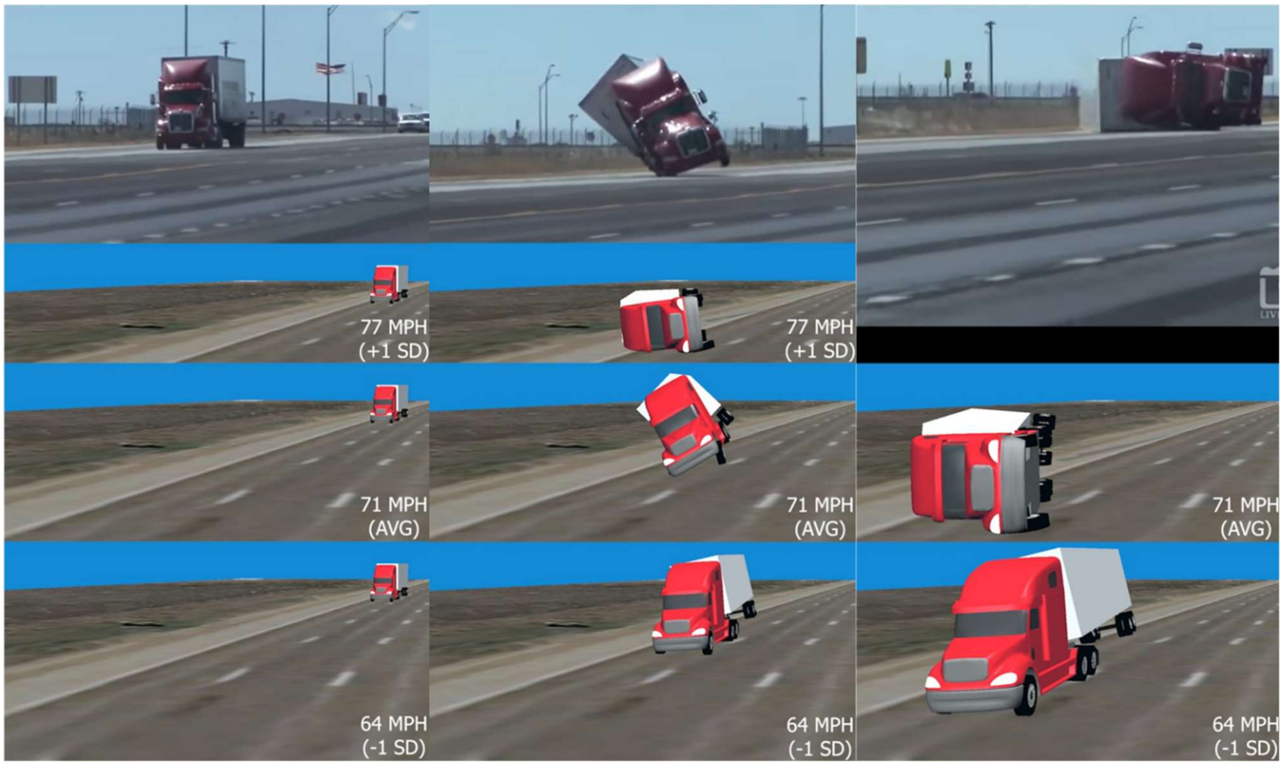


Figure 9: Event 2 at 1.67 s.

CONCLUSIONS

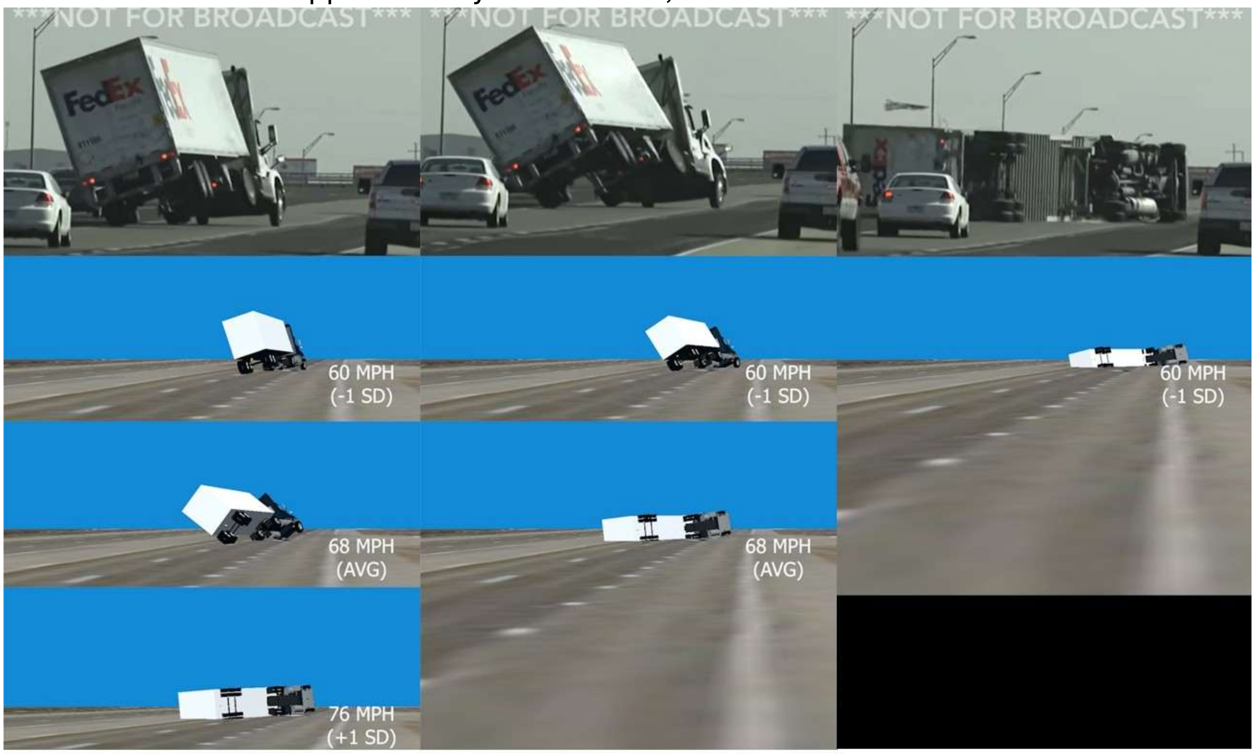
1. Selecting the "Use Tow Vehicle Properties" in the SIMON connection model dialogue box increased roll delta agreement in simulated cases, with additional changes.
2. Tractor trailer rollovers were simulated with good agreement by using a simplified force-moment couple derived from perpendicular wind speed and trailer area by varying wind speeds within a range of one standard deviation from a mean of gust wind speeds.
3. By changing the 5th wheel rotational stiffness from the default of $1.2 \cdot 10^7$ in·lb/deg to $2.5 \cdot 10^4$ in·lb/deg, the authors found a greater correlation of simulated tractor trailer roll delta and comparable rollover timing when compared to real world scenarios.

APPENDIX A: Rollover Timing Event 1
March 13, 2019 – Lakeside Dr. Amarillo Texas
Approximately: 35.2040391, -101.7420185



t = 0.00s t = 1.99s t = 2.62s

APPENDIX B: Rollover Timing Event 2
March 13, 2019 – Lakeside Dr. Amarillo Texas
Approximately: 35.2040391, -101.7420185



t = 0.00s t = 1.67s t = 2.99s