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Yaw Stability of Single Versus Tandem Axle Tractors

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ABSTRACT

Yaw instability was studied for five tractor-semitrailer configurations using EDVDS and SIMON in the HVE 4.10 operating system. Steady-state analyses were performed on the vehicle configurations by implementing a series of trapezoidal steer inputs, roll angles, articulation angle and forward velocity were recorded. Steer angles were incrementally increased until the vehicle experienced yaw divergence, rollover or steer tire saturation.

The five vehicle configurations were:

1. 3-axle tractor with loaded 53-foot semitrailer, nominal GVW of 80,000 lbs

2. 3-axle tractor with partially loaded 53-foot semitrailer, nominal GVW of 67,000 lbs

3. 2-axle tractor with partially loaded 53-foot semitrailer, nominal GVW of 65,000 lbs

4. 2-axle tractor with same trailer as 3 and 4 above, with slider position moved forward

5. 2-axle tractor with fully loaded 27-foot semitrailer, nominal GVW of 45,000 lbs

Handling diagrams were prepared for each vehicle configuration using the data obtained from EDVDS and SIMON. The five vehicle configurations were compared to each other using EDVDS data and again using SIMON data. Relative stability of each configuration was compared.

The results for each individual configuration as reported by EDVDS and SIMON were also compared.

SIMON and EDVDS revealed similar trends among the vehicle configurations. EDVDS and SIMON demonstrated rather different responses within the sensitivity of the handling diagrams. The vehicles modeled in SIMON tended to be more neutral steer than those modeled in EDVDS. That is, 2-axle tractor configurations exhibited more oversteer in EDVDS than in SIMON and 3-axle tractor configurations tended to exhibit more understeer in EDVDS than in SIMON.

A unique characteristic of the vehicle response was observed in the SIMON runs. Between approximately .07 and .12 g's, a spike in the yaw rate was observed in all five runs.

INTRODUCTION

Due to the variability in vehicle design, loading, fifth-wheel position and overall vehicle configurations, many tractors in tractor-semitrailer combinations exhibit oversteer through much of their operating range. A vehicle that is oversteer can become yaw divergent at certain levels of lateral acceleration, while a vehicle that is understeer cannot. Depending upon the vehicle setup, yaw instability can occur at significantly lower lateral accelerations than rollover. Since the end result of yaw instability is most commonly vehicle rollover, the occurrence of yaw instability is often missed by accident reconstructionists, engineers and investigative agencies.

Yaw instability is most likely to occur in a steady turn as opposed to relative quick transient maneuvers [1,2]. This has been attributed to the lag in trailer response [1,2]. Some variables that have been found to negatively influence tractor-semitrailer yaw stability [1,2,3]:

1. One drive axle on a tractor
2. Short tractor wheelbase
3. Low front suspension roll stiffness
4. High rear suspension roll stiffness
5. Bias in tire cornering stiffness to front of tractor as influenced by tire construction and design
6. Fifth wheel position too aft on tractor
7. High trailer CG
8. Low roll stiffness in trailer suspension

Some design changes can improve tractor yaw stability [1,2,3]:

1. Front sway bar or auxiliary front spring
2. Increased stiffness of tractor frame (small compared to 1.)

This paper attempts to hold the above factors constant, except for number of drive axles, to assess the influence of the number of drive axles on tractor yaw stability. Several different trailer/load configurations are analyzed to determine how matching tractors with loads can influence the yaw stability of these vehicles. EDVDS (Engineering Dynamics Vehicle Dynamics Simulator) and SIMON (SIMulation MOdel Non-linerar), within HVE (Human-Vehicle-Environment) 4.10, are utilized for the analysis.

SIMULATION

The Proving Grounds environment was utilized within the HVE operating system for visual background.

Vehicle models include the following configurations:

1. 3-axle tractor with loaded 53-foot semitrailer, nominal GVW of 80,000 lbs

2. 3-axle tractor with partially loaded 53-foot semitrailer, nominal GVW of 67,000 lbs

3. 2-axle tractor with partially loaded 53-foot semitrailer, nominal GVW of 65,000 lbs

4. 2-axle tractor with same trailer as 3 and 4 above, with slider position moved forward

5. 2-axle tractor with fully loaded 27-foot semitrailer, nominal GVW of 45,000 lbs

All vehicles were modeled utilizing the same tire and suspension properties. The semi-empirical tire model was used for SIMON and EDVDS. The 2-axle and 3-axle tractors were modeled with the same effective wheelbase and CG heights. The trailers were all modeled with the same CG heights. Tables 1 and 2 display some significant vehicle properties. Complete vehicle data printouts can be found in the Appendix.

Table 1. Tractor Parameters

	2-Axle	**3-Axle**
Weight (lbs)	15,500	17,800
CG height (in)	44	44
Wheelbase (in)	166	166
Front Suspension	Solid Axle	Solid Axle
Roll Center Height (in)	21	21
Ride Rate at Wheel (lb/in)	1125	1125
Spring Spacing (in)	36	36
Rear Suspension	Solid Axle	4-Spring
Roll Center Height (in)	21	21
Ride Rate at Wheel (lb/in)	6000	5500
Spring Spacing (in)	41	41
Tires – Generic Rib 11.00R20	-	-
Cornering Stiffness @ 2000 lb (lb/deg)	321.9	321.9
Cornering Stiffness @ 4000 lb (lb/deg)	581	581
Cornering Stiffness @ 6000 lb (lb/deg)	823	823

Table 2. Trailer Parameters

	53-ft full load	**53-ft partial load**	**53-ft slider fwd**	**27-ft loaded**
Weight (lbs)	62,000	49,500	49,500	30,000
CG Height (in)	88.5	88.5	88.5	88.5
Wheelbase (in)	487	487	445	252
Track Width (in)	78	78	78	72
Suspension	4-Spring	4-Spring	4-Spring	Solid axle
Roll Center Height (in)	37	37	37	37
Ride Rate at Wheel (lb/in)	5500	5500	5500	6000
Spring Spacing (in)	38	38	38	38
Tires – Generic Rib 11.00R20	Same Data as Tractor Tires			

TESTS

Open-loop simulations were performed similar to the vehicle tests presented in [1]. The vehicles were given an initial forward velocity of 45 mph and a subsequent trapezoidal steer input, reaching maximum steer level in .5 seconds. After a sufficient time for transients to dissipate, steady state values were recorded for a number of variables, the main variables of interest being lateral acceleration and yaw rate. Table 3 indicates the recorded variables.

Table 3. Variables Recorded at Steady State

Tractor	Yaw Rate
	Forward Velocity
	Lateral Acceleration
	Roll Angle
	Steer Angle Input
Trailer	Roll Angle
	Articulation Angle

Trapezoidal steer steps were increased by increments of 4 degrees at the steering wheel until a steer angle was reached at which the vehicle would not reach steady state, but would experience yaw divergence and/or incipient rollover. Vertical tire forces on the tractor and trailer were observed to detect the onset of rollover. The steering gain was 28:1.

The tests were run identically in EDVDS and SIMON. The vehicles in SIMON lost more speed in the transient portion of the simulation than the vehicles modeled in EDVDS. Therefore initial velocities for the SIMON runs were 47 mph so that at steady state the forward velocity was approximately 45 mph.

RESULTS

The steady state values of lateral acceleration, yaw rate, forward velocity and steer angle (at the steer tires) were reduced to create handling diagrams of the type developed by H.B. Pacejka [2], as can be seen in Figures 1-7. These diagrams allow one to quickly determine whether a vehicle is understeer or oversteer [4]. In the case of heavy trucks, often tractors will transition from understeer to oversteer, and the handling diagrams demonstrate at what lateral acceleration this occurs. Previous yaw stability studies of tractor-semitrailers have produced similar diagrams [1,2].

The horizontal axis of the handling diagram is the difference between the wheelbase of the vehicle divided by the radius of curvature and the effective steer angle at the front tires (not accounting for Ackerman steer angles).

L/R – ä (1)

Converting from earth-fixed to vehicle-fixed measurements, the expression becomes the difference between the product of yaw rate and wheelbase divided by longitudinal velocity and the effective steer angle.

Yaw Rate*L/U – ä (2)

The vertical axis is the lateral acceleration, a_y.

The slope of the curves is the inverse of the understeer gradient. A negative slope indicates the vehicle is understeer and a positive slope indicates a vehicle is oversteer. A vertical slope indicates neutral steer or the transition between understeer and oversteer. A vehicle that is understeer cannot become yaw divergent, and is therefore the preferred condition. An oversteer vehicle may become unstable in yaw at some level of lateral acceleration.

COMPARISON OF VEHICLE CONFIGURATIONS

Figure 1 presents the data for the five vehicle configurations as modeled in EDVDS. All three 2-axle tractor configurations are shown to be oversteer, with the pup trailer configuration being the most stable of the three. The simulations were only modeled with a single pup trailer rather than in double or triple configuration because the drawbar and pintle-hook connection effectively decouples the rear trailers from yaw stability and rollover analyses.

Predictably, the most stable configuration is the 3-axle tractor and 53-foot trailer with a gross weight of 67,000 lbs. The least stable vehicle configuration comes from matching the same trailer with the 2-axle tractor for a legal (on most highways according to bridge laws) gross vehicle weight of 65,000 lbs. Therefore, it is evident that the manner in which tractors and trailer are matched can greatly affect the handling characteristics of the combination.

The 3-axle tractor combination vehicles are both demonstrated to be understeer over a significant portion of their operating range. They too become oversteer within the operating range of the vehicle prior to rollover.

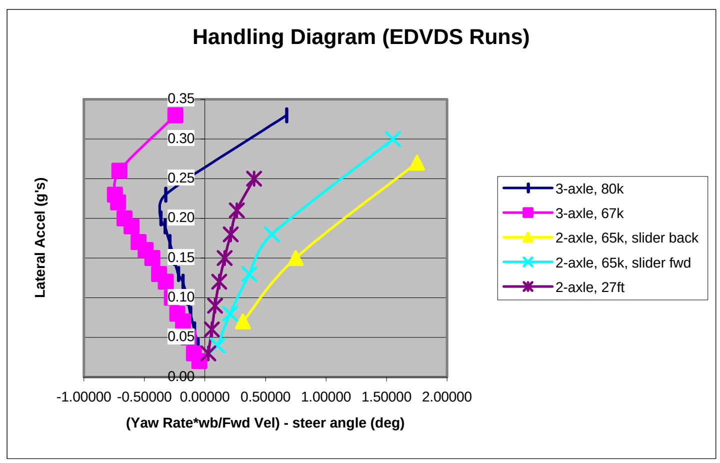

Figure 1. Handling Diagram for EDVDS Runs

Figure 2 presents the data for the five vehicle configurations as modeled in SIMON. The trends observed in SIMON are consistent with those observed in EDVDS. Each of the five runs exhibits a similar phenomenon between approximately .07 and .12 g's of lateral acceleration. There is a spike in the yaw rate that causes movement to the right of the handling diagram for points in this range. The magnitude of this yaw rate spike is on the order of .5 deg/sec or less, which singularly is not significant. However, under the sensitivity of the diagrams it is observable. Transients would not explain this response, as the plotted values are steady state values. No reason for this characteristic of the SIMON runs has been identified.

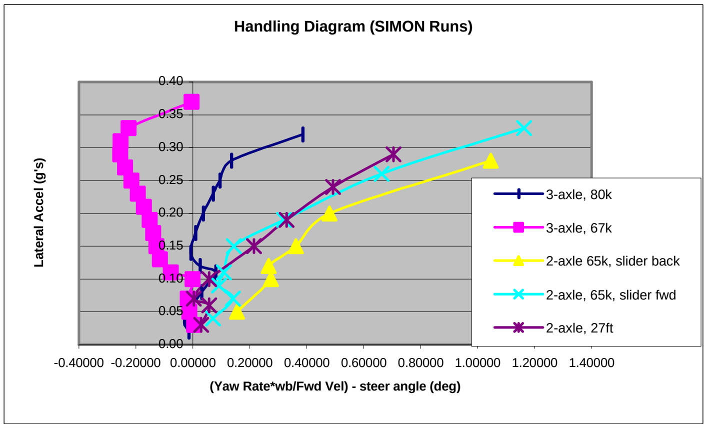

Figure 2. Handling Diagram for SIMON Runs

COMPARISON BETWEEN EDVDS AND SIMON

Figures 3 – 7 compare the EDVDS and SIMON results for each vehicle configuration. Figure 3 demonstrates a trend observed for all vehicle combinations. The SIMON runs trend closer to neutral steer than do the EDVDS runs and the SIMON runs tended to reach a higher level of lateral acceleration before experiencing yaw divergence. However, the SIMON and EDVDS runs mostly reached yaw divergence at approximately the same steer input magnitudes, thus the slopes of the SIMON runs are more vertical than the EDVDS runs. In Figure 3, the SIMON 3-axle tractor with fully loaded 53-foot trailer is fairly neutral steer, while the EDVDS tractor is understeer. However, the EDVDS modeled vehicle becomes yaw divergent at a lower level of lateral acceleration.

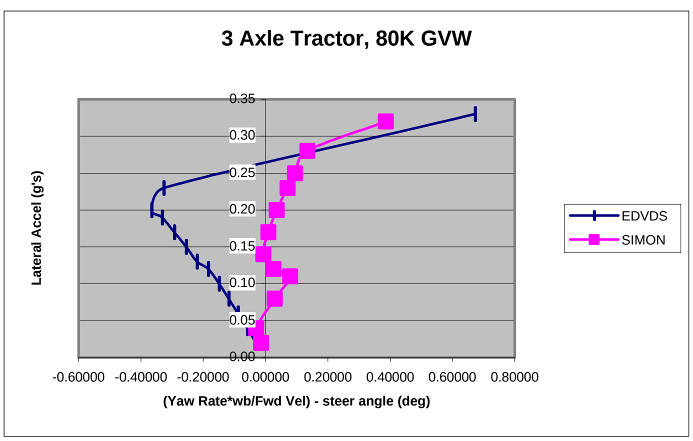

Figure 3. Comparison of EDVDS and SIMON Results for 3-Axle Tractor and 80K GVW

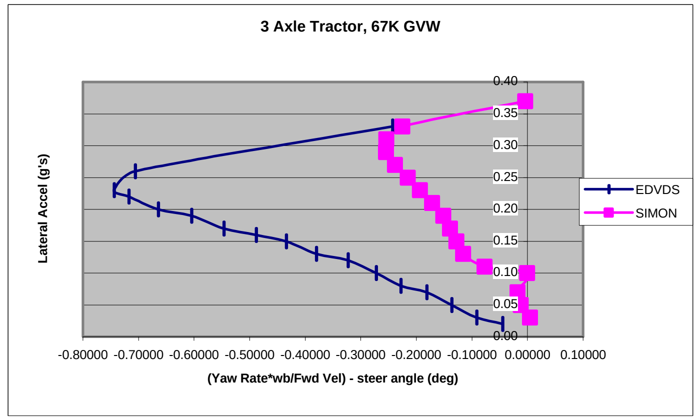

Figure 4. Comparison of EDVDS and SIMON Results for 3-Axle Tractor and 67K GVW

In Figure 4, the SIMON run is understeer, but closer to neutral steer than the EDVDS run. However, the SIMON runs remains understeer to a greater level of lateral acceleration than the EDVDS run.

Figure 5 depicts the calculation method comparisons for the 2-axle tractor with 53-foot trailer at 65,000lbs gross vehicle weight and the slider in a mid position. In this configuration the tractor is oversteer. Again, the SIMON run is closer to neutral steer than the EDVDS run. The EDVDS run became yaw divergent at very small trapezoidal steer input, as is evident by the flat slope. However, the SIMON run was able to reach steady state values for several steps of steer input.

Figure 6 depicts similar trends as Figure 5.

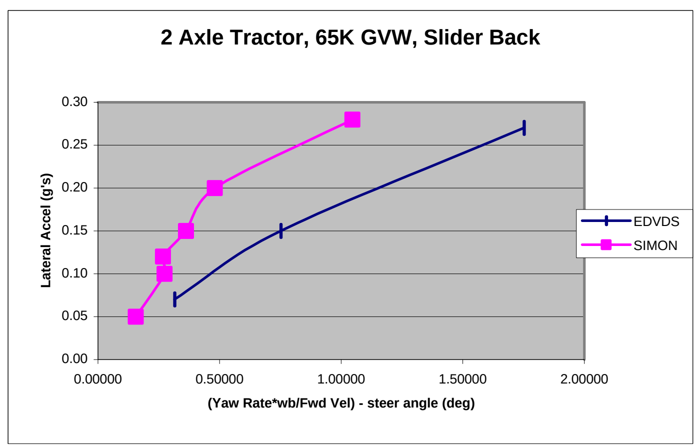

Figure 5. Comparison of EDVDS and SIMON Results for 3-Axle Tractor and 65K GVW

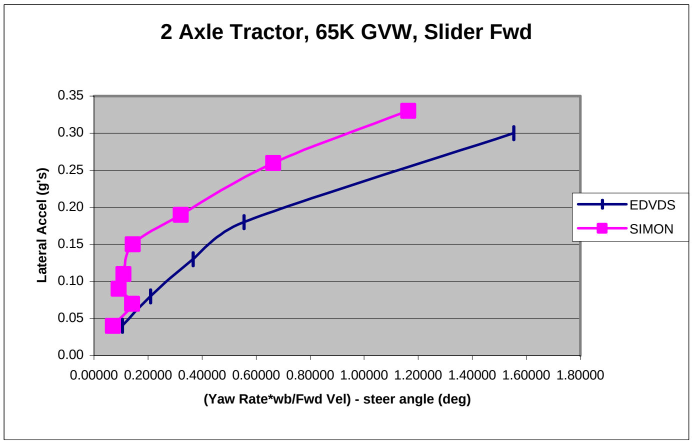

Figure 6. Comparison of EDVDS and SIMON Results for 2-Axle Tractor with Slider Forward

The 2-axle tractor with 27-foot trailer configuration is the lone exception to the SIMON runs always trending towards neutral steer. In Figure 7, the SIMON run begins more neutral steer (less oversteer) than the EDVDS run, but becomes slightly more oversteer at higher levels of lateral acceleration. The SIMON run still reached a higher level of lateral acceleration before becoming yaw divergent.

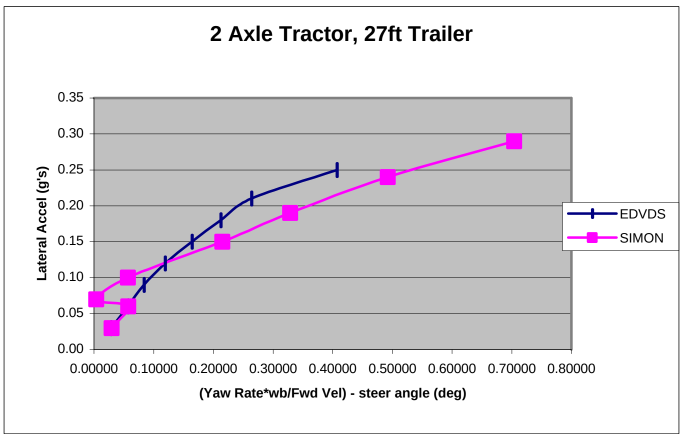

Figure 7. Comparison of EDVDS and SIMON Results for23-Axle Tractor and 27-foot Semitrailer

STEERING DIAGRAMS

Steering diagrams were produced similar to the type presented in [3] for simulated vehicle handling tests. The graph plots steer angle versus lateral acceleration. The slope goes to zero at the level of lateral acceleration at which yaw divergence occurs. These diagrams also demonstrate that the SIMON runs obtained higher levels of lateral acceleration before yaw divergence.

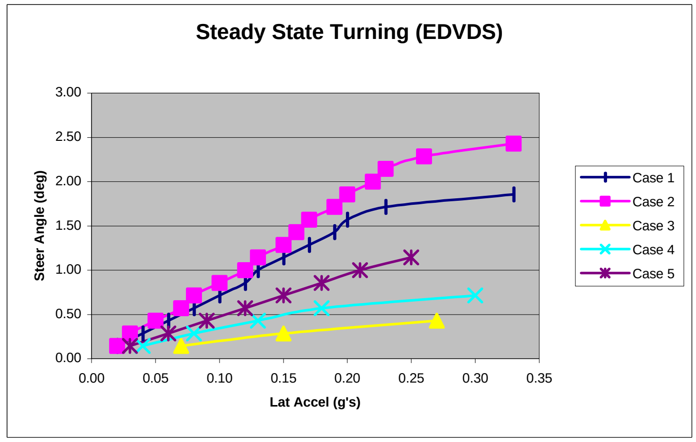

Figure 8. Steady State Turn Diagram for EDVDS Runs

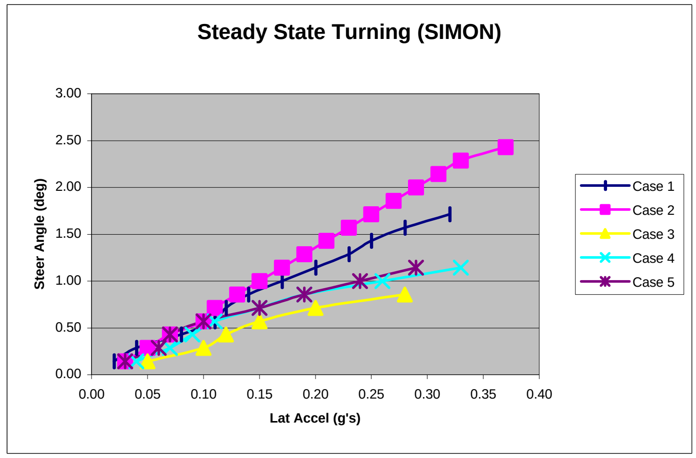

Figure 9. Steady State Turn Diagram for SIMON Runs

CONCLUSIONS

1. The simulated vehicles do not necessarily represent typical vehicles on the road today, although they do represent a portion of the population. Through a combination of CG heights, tire force properties and suspension properties, the simulated vehicles are relatively unstable vehicles to begin with. Therefore the absolute magnitude of the responses measured must be considered carefully. However, by holding all variables possible constant, the relative stability of the various vehicle configurations can be compared and the trends analyzed using SIMON or EDVDS in the HVE 4.10 operating system.

2. Irrespective of whether SIMON or EDVDS is utilized, the trends in yaw stability for the vehicle configurations are consistent. The 3-axle tractor configurations are significantly more stable than the 2-axle tractor configurations. Utilizing 2-axle tractors with 53-foot trailers loaded to a gross vehicle weight of 65,000 lbs is the least stable configuration. Proper load distribution, through moving the slider axles of the trailer forward, improves the yaw stability but the vehicle remains relatively unstable.

3. SIMON and EDVDS did present noticeable differences in yaw responses. EDVDS runs of the 3-axle tractors tended to understeer or "push" more, resulting in lower levels of lateral acceleration and yaw rate at steady state for a given steer input than SIMON. When EDVDS runs transitioned to oversteer, the yaw divergence occurred shortly thereafter in terms of steer magnitude, but occurred relatively slowly in the time domain. The ultimate result was that SIMON runs would reach a higher level of lateral acceleration at the onset of yaw instability.

   In the 2-axle tractor configurations, the SIMON runs, tended to be more neutral steer than the EDVDS runs. Again, the EDVDS runs became yaw divergent at lower levels of lateral acceleration than the SIMON runs.

4. An observed characteristic of all of the SIMON responses was a spike in the yaw rate between approximately .07 and .12 g's. This resulted in a shift to the right of the diagrams of the data points in this region. No reason for this phenomenon has been discovered. It ultimately does not seem to affect the yaw stability of the vehicle.

5. The fact that even the 3-axle tractor configurations transitioned to oversteer prior to incipient rollover is a result of characteristics specific to these simulated vehicles. It does not necessarily represent the response of the majority of real-world vehicles.

6. No conclusions have or can be reached through this testing as to whether SIMON or EDVDS more truly model the real-world vehicle.

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