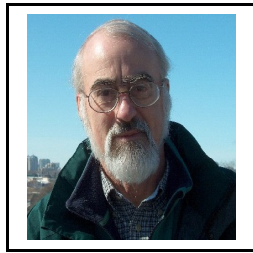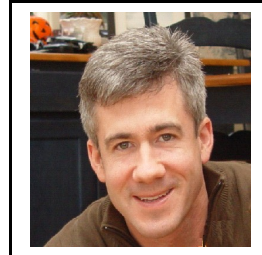# AN APPROACH TO ASSESSMENT OF THE HANDLING PERFORMANCE OF STRAIGHT TRUCKS

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Abstract

It was necessary to evaluate the dynamic performance of 14 straight truck configurations, and it was evident that some of them might be prone to oversteer. Oversteer is an undesirable handling characteristic, and ultimately results in a vehicle spinning out, when it will probably also roll over. Handling performance is difficult to assess, and is difficult to relate to the occurrence of crashes. The high-speed offtracking performance measure was found to provide sufficient insight into the handling of the trucks to distinguish trucks with significant oversteer from those with satisfactory handling. This simple approach obviated the need for a comprehensive handling analysis of these trucks.

1. Introduction

The Centre for Surface Transportation Technology of the National Research Council of Canada (NRC-CSTT) was recently required to evaluate the dynamic performance of 14 straight truck configurations. Some of these configurations had a self-steering axle as their rearmost axle, and it was evident they might become oversteer. It was therefore necessary to devise a simple and practical approach to assess handling performance.

Handling is a measure of the response of a vehicle to steering. If a vehicle is being driven to follow a circular path and lateral acceleration is increased, the handling of the vehicle is described as:

- Understeer if the driver must steer more tightly to follow the path;
- Oversteer if the driver must steer less tightly to follow the path; or
- Neutral steer if the driver does not need to make any change in steer to follow the path, which is usually a region of transition from understeer to oversteer.

Most vehicles are understeer in the region of normal driving. The driver of a vehicle that is understeer at its performance limit is unable to change the heading of the vehicle as there is no more steer available, and the vehicle ploughs out of the turn along a tangent to the turn, and may also roll over if it departs from the roadway. The driver of a vehicle that is oversteer at its performance limit is invariably unable to respond fast enough to regain control of a vehicle that spins out, and it will almost certainly roll over even if it does not trip on a curb or depart from the roadway. An alert driver is able to stabilize a moderately oversteer vehicle. A good example of this is available from closed circuit dirt track races, where the vehicle travels through a curve with its body aligned substantially outside a tangent to the curve, but with the front wheels approximately tangential to the curve. Such a vehicle, typically a motor cycle or car, is well into the oversteer region, but is also (just) under the control of the driver. These vehicles are operated very close to the limit of their yaw stability. Vehicles do spin out when a driver enters a curve too fast, or makes anything other than a small steer adjustment, such as when it might be necessary to avoid another vehicle. Spin-outs, with the possibility of a subsequent multi-vehicle collision, are considered part of the charm of such races. Speeds are low and drivers are well-protected, so the risk to drivers is relatively low, even if a vehicle rolls over. Drivers of these vehicles learn to control their vehicle on the verge of instability, because if they cannot, they are not competitive. In contrast, a truck driver rarely, if ever, comes close to a spin-out. A truck driver who does get in this situation usually gets there fast, has no idea what would be the right thing to do, and would have no time to do it, so the vehicle spins out, and would then almost certainly roll over.

The Canadian CCMTA/RTAC Vehicle Weights and Dimensions Study evaluated handling (Ervin and Guy, 1986), though it did not propose a performance measure. The study addressed trailers, while handling is primarily about power units, and considered only tandem drive tractors. There was no evidence at that time that oversteer was a problem for this class of vehicle, except as it might occur when the drive wheels of a tractor locked up due to over-braking, and the tractor jackknifed. This was a braking issue, not a handling issue, and was addressed by new a vehicle manufacturing standard that required an anti-lock brake system on tractors.

A self-steering tag axle was shown to cause a significant deterioration in the handling of a straight truck (Winkler, 1989).

The Transportation Research Board's Turner Study included an examination of the relationship between performance measures and crash rates (Transportation Research Board, 1990), which included the steering sensitivity performance measure for tractor-semitrailers and double trailer combinations. Details of the vehicle involved in a crash, and the crash itself, were unknown, so generic vehicle properties were assigned. This is a particular concern, as the ultimate handling performance depends intimately on details of the steering system, suspensions and tires that were only represented generically. Nevertheless, the process did identify that a vehicle with a lower steering sensitivity would tend to be over-involved in crashes on a high-speed road. No other study is known that has attempted to relate the handling of heavy trucks to their involvement in crashes.

NRC-CSTT evaluated a particular model of airport rescue and fire-fighting (ARFF) vehicle that had been involved in a series of rollovers (Preston-Thomas et al, 1997). The vehicle had a static roll threshold of about 0.42 g, but tests conducted by NRC-CSTT and the vehicle's manufacturer both found that it became oversteer in a steady turn at about 0.32 g. While detailed information on the individual rollovers was not available, it was possible that some might have been the outcome of loss of control due to oversteer. It was not practical either to modify this vehicle, or to replace it, so NRC-CSTT developed a training course for ARFF vehicle drivers which demonstrated oversteer and provided instrumentation so that a driver could stay well below the onset of oversteer. This approach worked well where a small number of drivers operated these specialized vehicles in the closed environment of an airport, but would not be feasible for diverse drivers operating diverse vehicles on highways.

A self-steer pusher axle was shown to have a relatively benign effect on the handling of a straight truck, essentially because the axle was placed quite close to the longitudinal centre of gravity of the vehicle (Billing and Lam, 1992). This was reflected in a brief assessment of a straight truck with a self-steering pusher axle conducted by NRC-CSTT, which found that the vehicle was more prone to oversteer with the pusher axle locked tight, rather than with it free to steer (Billing, 2002).

Australia's process to develop a performance-based system (PBS) of regulation for heavy trucks identified that a handling performance measure would be desirable to ensure adequate steering control over a wide range of turn conditions (National Transport Commission, 2007). PBS is now in operation, and includes a number of well-established performance measures, but to date has not established a suitable handling performance measure. The need is still recognised, and appears on the research agenda at the time of writing.

2. Study Scope

NRC-CSTT was required to evaluate the dynamic performance of 14 straight truck configurations, which were in four groups:

- Six with no self-steering axle;
- One with a self-steering pusher axle (ahead of the drive axle group) that equalized load with the drive axles;

- Four with a self-steering auxiliary pusher axle that could carry a maximum load of 6,000 kg (13,227 lb); and
- Three with a self-steering auxiliary tag axle behind the drive axle group.

The truck configurations are shown elsewhere (Billing, Patten, Madill and Corredor, 2010). It was evident that configurations with a self-steering auxiliary tag axle might become oversteer, so it was necessary to assess the handling performance of these vehicles.

3. The Handling Diagram

The steer properties of a vehicle are described by its understeer coefficient U, given by:

$$U = \delta_{sw} / N - L\rho \qquad (1)$$

where δ_{sw} = steering wheel angle (deg);
     N   = overall steering ratio, steering wheel angle/front wheel angle;
     L   = vehicle wheelbase (m); and
     ρ = path curvature (1/m).

The path curvature ρ is difficult to determine directly, but may be represented as

$$\rho \quad = a_y \, g / V^2 \qquad (2)$$

where a_y = vehicle lateral acceleration (g);
     g   = acceleration due to gravity (9.81 m/s/s (386.4 in/s/s)); and
     V   = vehicle forward speed (m/s).

Thus $U = \delta_{sw} / N - L \, a_y \, g / V^2 \qquad (3)$

The critical factor is the understeer gradient dU/da_y. The transition from understeer to oversteer is where the understeer gradient is zero. When the understeer gradient becomes less than the critical value of $-Lg/V^2$, the vehicle is considered unstable in yaw. This formulation implicitly includes the effects of roll steer, suspension compliance and steering system compliance (Ervin and Guy, 1986).

4. Handling Performance

The CCMTA/RTAC Vehicle Weights and Dimensions Study included evaluation of the understeer gradient at a lateral acceleration of 0.25 g as a handling performance measure (Ervin and Guy, 1986). There was also a check to determine whether the critical understeer gradient $-Lg/V^2$ was reached, when a run would be terminated due to yaw instability. No performance standard was set. The commentary noted that:

"Low, and particularly, negative values of the understeer gradient are of concern if they do, in fact, limit the usable maneuvering envelope of the vehicle in less than that range which is otherwise limited by the rollover threshold. The hypothesized significance of the cited research observations has not been demonstrated, nor is there any direct way to link the understeer characteristic to the accident record. Accordingly, it seems premature at this point

to suggest that policymaking bodies evaluate and regulate truck configurations on the basis of the understeer property."

This still essentially summarizes the issue.
NRC-CSTT did considerable analytical work on the handling performance of a wide range of heavy vehicles (Woodrooffe and El-Gindy, 1990), and proposed the following three-point performance measure:

- The lateral acceleration at which the vehicle transitions from understeer (or presumably neutral steer) to oversteer should not be less than 0.20 g;
- The understeer gradient at 0.30 g should be greater than the critical understeer coefficient of $-Lg/V^2$; and
- The understeer gradient at 0.15 g should be in the range 0.5 to 2.0 deg/g, to ensure a vehicle would be reasonably controllable in its normal operating range.

This performance measure dealt with handling in the range of normal to hard driving, as a lateral acceleration up to 0.30 g is readily feasible (though not necessarily advisable) for many straight trucks travelling in a ramp or curve at a speed above the posted advisory speed limit. This set the limit for the onset of yaw instability at 0.30 g, which is well below the static roll threshold of 0.40 g commonly used in Canada, though many existing vehicles may operate with a static roll threshold down to 0.35 g, and a few operate between 0.30 and 0.35 g. This has not been assessed by testing.

The commentary to the proposed Australian performance measures noted that the three-point performance measure was very sensitive to minor changes in vehicle design parameters (National Transport Commission, 2007). It suggested that further research would be necessary to determine exactly what constitutes satisfactory or unsatisfactory heavy vehicle handling, so that a suitable method of evaluation, performance measure, and performance standard could be developed. There was concern that a modest performance standard would allow most vehicles to pass the standard, regardless of their performance, and too severe a standard could disqualify vehicles that were not known to have a handling problem.

The static roll threshold is certainly the best-established performance measure, and also the most directly related to highway safety. If a vehicle becomes oversteer and spins out it will almost certainly roll over, when its rear wheels either trip on a curb, depart from the roadway, or regain lateral traction. Since rollover is the outcome of both excessive speed in a curve and oversteer, it would be reasonable that the lateral acceleration at the yaw stability threshold should equal that at the static roll threshold.

5. Developing an Evaluation of Handling Performance

The Yaw/roll model was used for this work (Gillespie and MacAdam, 1982). It was far too cumbersome to construct a point-by-point handling diagram, as done by others (Woodrooffe and El-Gindy, 1990), for the large number of vehicles and parameter variations involved in this work, so an alternative method of evaluation was necessary.

Two manoeuvres are commonly used to assess the handling of a vehicle. In the first, the vehicle is driven at a constant speed, and the steer angle is increased at a steady rate, so that the path of the vehicle is a tightening spiral, a so-called J-turn, because the path of the vehicle

on the ground may resemble the letter J. In the second, the steer angle is adjusted to follow a circle with a fixed radius while the speed of the vehicle is slowly increased, so its lateral acceleration also increased. In either case, if the vehicle does not roll over first, then ultimately it either ploughs out or spins out, depending on whether it was understeer or oversteer at its performance limit.

The Yaw/roll model is restricted to constant forward speed (Gillespie and MacAdam, 1982). However, the model has previously been used successfully to compare computer simulations with full-scale test results, where the measured steer angle was supplemented by the measured varying forward speed of the vehicle during a run as inputs to the simulation (Billing and Patten, 2004). The addition of the varying speed significantly improved the correlation between simulation and test results, even though the model was lacking a degree of freedom for longitudinal acceleration. This outcome was possibly because the variations in speed were minor and slowly varying, so the values of the absent coupling terms would have been small. The major benefit was that variation in speed corrected the spatial discrepancy of external inputs. However, this extension of the model was not considered valid for this work, so it was not possible to consider a vehicle driving in a circle with a fixed radius while its speed was slowly increased.

The performance assessment process in Canada includes a high-speed J-turn that is used to evaluate both high-speed offtracking and static roll threshold. A continuous evaluation of the understeer coefficient U, and the understeer gradient dU/da_y, was added to the simulation as performance measures. In theory, the point at which the understeer gradient became less than $-Lg/V^2$ was the point at which the vehicle became unstable in yaw, if this occurred before rollover. In practice, the understeer coefficient and its gradient were not smooth functions, but contained perturbations. Some of these perturbations resulted in the slope of the understeer coefficient dropping momentarily below the critical value, often at a rather modest lateral acceleration. If these perturbations were a manifestation of the internal working of the computer model, then they would not occur in real life. If they really would occur, then it was presumed that a driver would be able to stabilize a vehicle subject to such a momentary apparent loss of stability. The understeer gradient is a numerical evaluation of a derivative. The understeer coefficient itself may experience a small perturbation, but the perturbation can still have a large slope. It was therefore evident that simply scanning for the first point where the understeer gradient became less than $-Lg/V^2$ could be an unduly conservative estimate of the yaw stability threshold, as there were many cases where one, several or many perturbations resulted in the understeer gradient becoming less than $-Lg/V^2$ well before the ultimate such passage.

There was no doubt that once the understeer gradient became less than $-Lg/V^2$, and remained there, that represented an upper bound for the yaw stability threshold. The following scanning process was implemented to deal with multiple transitions of the slope of the understeer coefficient:

- Find the lateral acceleration a_1 where the understeer gradient is first less than $-Lg/V^2$;
- Find the lateral acceleration a_2 where the understeer gradient becomes less than $-Lg/V^2$, and subsequently remains less than it;
- If a_1 equals a_2, then a_1 is the yaw stability threshold;
- Otherwise, a_1 is less than a_2, and there may be momentary perturbations between a_1 and a_2 where the understeer gradient is less than $-Lg/V^2$, so estimate p, the percentage of time that the understeer gradient is less than $-Lg/V^2$ from a_1 to a_2; then

- If p is less than 50%, use a_2 as the yaw stability threshold, otherwise use a_1.

The choice of 50% in the final step was arbitrary. In practice, many vehicles only had one or two momentary perturbations where the understeer gradient was less than $-Lg/V^2$, and it was believed that a driver could probably stabilize these, as noted above. In this case, p was usually well below 50%, so it seemed appropriate to use a_2 as the yaw stability threshold. However, if p exceeded 50%, then either the understeer gradient at a_1 was usually close to $-Lg/V^2$, or there were many perturbations below this value, when it was reasonable that this might be more attributable to the behaviour of the vehicle than the internal working of the simulation. In this case, it seemed prudent to use a_1 as the yaw stability threshold.

However, this process gave inconclusive results, with no common pattern for the various truck configurations. There were evidently a number of problems with the approach:

- The perturbations in the understeer coefficient were possibly due to the non-linear properties of the model and non-linearities induced by breakpoints in tables of tire and suspension data, possibly supplemented by the slip-stick steering of a self-steering axle on a vehicle so-equipped;
- It was not possible to determine whether the perturbations in the understeer coefficient were a manifestation of the simulation, or inherent characteristics of the vehicle;
- The truck wheelbase used to evaluate the understeer gradient was assumed constant for all vehicles, whereas the effective wheelbase for a vehicle with a self-steering axle varied during the turn, due to Coulomb friction in the self-steering mechanism;
- The ultimate handling characteristic of a vehicle depends on intimate details of the steering system and tires and suspensions that were beyond the level of detail in the model and the component data; and
- Verifying the methodology by full-scale tests was beyond the scope of the work.

However, as a consequence of this work, it became clear that the vehicles being considered divided in two groups:

- Those that were reasonably well-behaved; and
- Those that quickly became highly oversteer.

High-speed offtracking is the lateral offset between the path of the centre-line of the steer axle of the power unit of a vehicle and the path of the centre-line of the last axle of the vehicle in a steady turn, as shown in Figure 1.

Figure 1: High-speed Offtracking
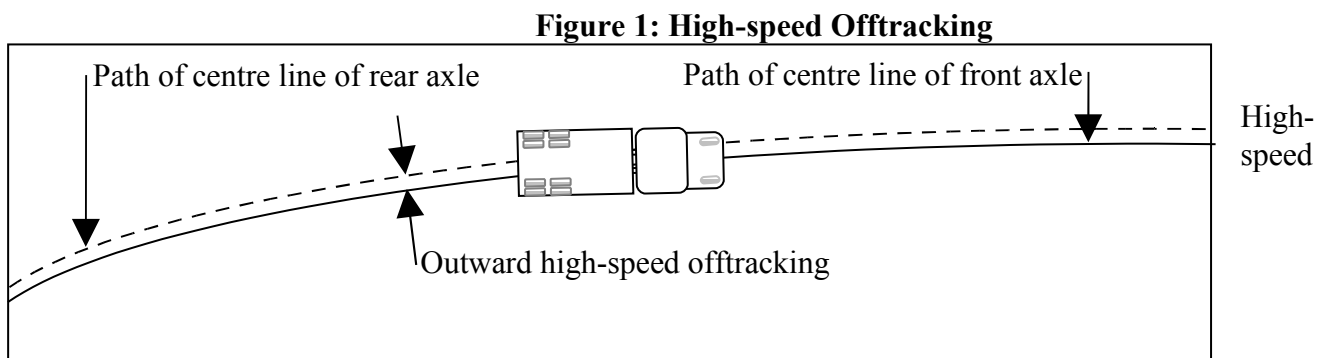
offtracking was computed for all trucks at a lateral acceleration of 0.20 g in the steady turn

used to evaluate the static roll threshold. It was not initially reported, as the high-speed offtracking of a straight truck has not generally been considered of any great interest. However, detailed inspection of the results revealed that high-speed offtracking did provide insight into the effect of an auxiliary axle on the behaviour of a vehicle so-equipped, and actually separated the two groups of vehicles quite effectively. The performance standard of 0.46 m (18 in) used for combination vehicles was probably not meaningful for a single unit vehicle, so was not applied, and did not need to be, as the raw results provided the necessary insight.

6. Results

14 straight truck configurations were considered (Billing, Patten, Madill and Corredor 2010). Configurations A, BL, BH and E had a single steer axle and a single, tandem, tandem or tridem drive axle, respectively.   Configurations C and F had a twin steer and a tandem or tridem drive axle, respectively. Configuration D had a single steer axle and a tandem drive axle with an added pusher self-steer axle (ahead of the drive axles) equalized to carry the same load as each drive axle. Configurations A1, B1, C1 and E1 were configurations A, BH, C and E with an added auxiliary pusher axle that could carry a maximum load of 6,000 kg (13,227 lb). Configurations B2, C2 and D2 were configurations BH, C and D with an added auxiliary tag axle (behind the drive axles) that could carry a maximum load of 6,000 kg (13,227 lb).   High-speed offtracking was computed at a lateral acceleration of 0.20 g, with each truck loaded to its allowable gross weight in Ontario. Gravel was used as a payload, because it is relatively dense. The modest height of the payload centre of gravity generally ensured that any yaw stability limit would be reached before the static roll threshold.

Figure 2 shows the high-speed offtracking of each truck plotted against the load on the auxiliary axle. The result appears as a horizontal line for configurations A, BL, BH, C, D, E and F, which have no auxiliary axle.

High-speed offtracking for a vehicle with an auxiliary axle was least when that axle was raised, and increased when it was lowered and as the load on the auxiliary axle increased.

High-speed offtracking of configuration A1, with an auxiliary pusher axle, increased rapidly as the load on the auxiliary axle increased, because the auxiliary axle was quite close to the single drive axle, so 1,000 kg of load on the auxiliary axle removed about 766 kg of load from the drive axle. This allowed the rear of the truck to slide outwards, which increased high-speed offtracking, as seen in Figure 2. This configuration would typically be used for local pick-up and delivery, and might be driven predominantly by occasional or non-professional drivers with little or no understanding of the operation of the auxiliary axle. It is difficult to see how this configuration could be made reliable for the life of the vehicle.

High-speed offtracking of configurations B1, C1, and E1, which also had a pusher auxiliary axle, increased more moderately than configuration A1 as the load on the auxiliary axle increased, because the auxiliary axle was further ahead of the drive axles than for configuration A1, and because the drive axles carried a much higher load than the single axle of configuration A1, so there was proportionately much less unloading of the drive axles. This moderated the tendency of the rear of the truck to slide outwards.

High-speed offtracking of configurations B2, C2, and D2, which had an auxiliary tag axle, increased rapidly as the load on the auxiliary axle increased, because the auxiliary tag axle caused the greatest unloading of the drive axles, and also provided no significant resistance to the tendency of the rear of the truck to slide outwards. A steady turn at a higher lateral acceleration would progressively increase the high-speed offtracking, and ultimately, a truck with an auxiliary tag axle would spin out.
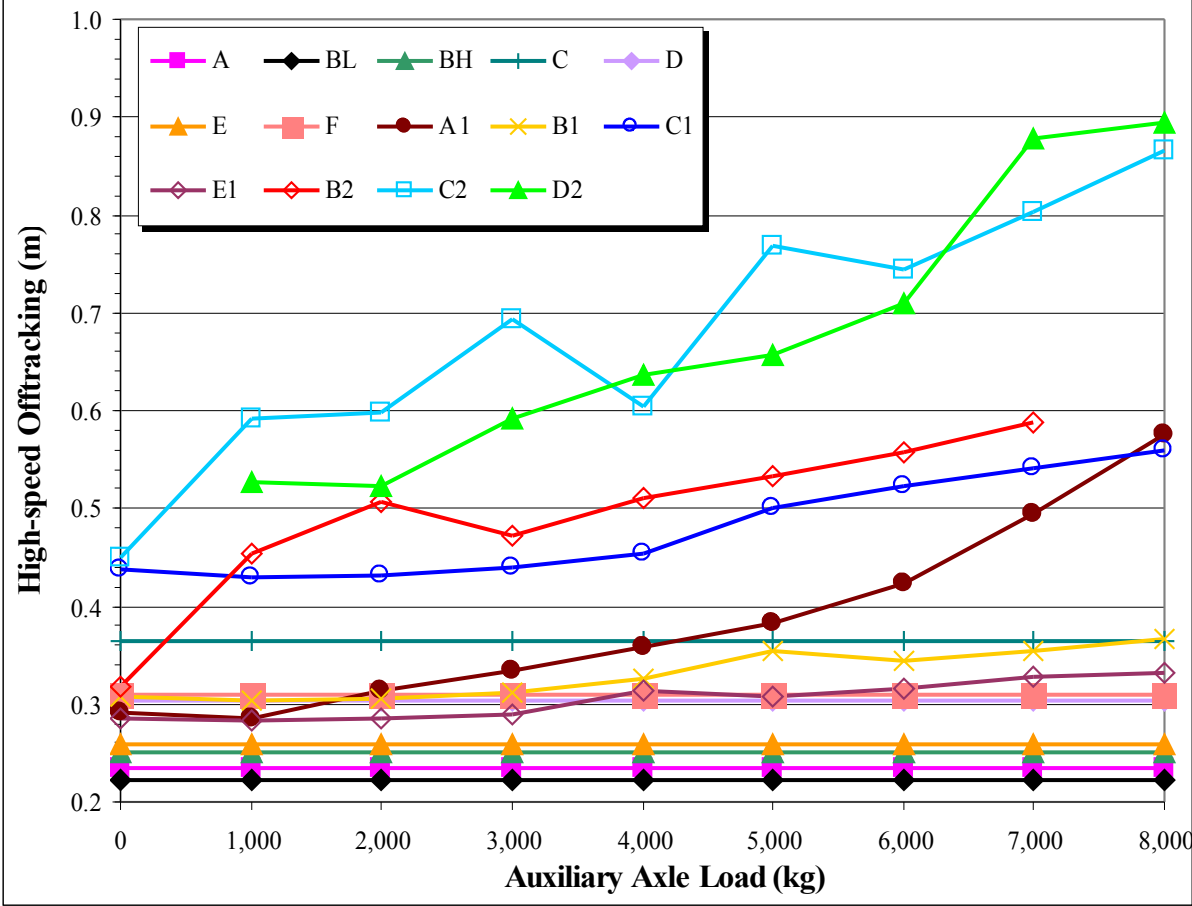

Figure 2: High-speed Offtracking of Truck Configurations for Auxiliary Axle Load

Values of high-speed offtracking distinguished rather clearly between trucks with an auxiliary tag axle that became significantly oversteer at a moderate lateral acceleration, and other configurations with more benign behaviour. Oversteer is a highly undesirable performance characteristic.

The simulation considered a lock on the steering of an auxiliary axle at high speed. This resulted in similar high-speed offtracking for those vehicles as when the auxiliary axle was raised. However, reliable operation of the lock would be critical to the safety of the vehicle. It is difficult to ensure a lock would be reliable for the life of a vehicle.

An electronic stability and control system was not included in the simulation. Such a device would be expected to prevent spin-out as a consequence of oversteer, but probably would not prevent the significant high-speed offtracking that developed between 0.15 and 0.20 g during entry to the turn.

7. Conclusions

Oversteer of a heavy vehicle may often result in rollover, and understeer may also result in rollover if the vehicle departs from the roadway. A suitable performance standard for loss of yaw stability might therefore be the same lateral acceleration as the static roll threshold performance standard. However, handling performance is difficult to assess, and is difficult to relate to the occurrence of crashes. If a reliable method of assessment could be developed, such a performance standard might well be unduly restrictive, as most "normal" vehicles have handling performance that is not known to result in problems with yaw stability.

Some straight truck configurations have a significant tendency to oversteer, even at a low lateral acceleration. The high-speed offtracking performance measure rather clearly demonstrated the tendency of some vehicle configurations with a self-steering auxiliary axle to oversteer. This was sufficient to discount them from further consideration.

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