UMTRI

# RESEARCH REVIEW

UNIVERSITY OF MICHIGAN TRANSPORTATION RESEARCH INSTITUTE
• OCTOBER–DECEMBER 2000 • VOLUME 31, NUMBER 4 •

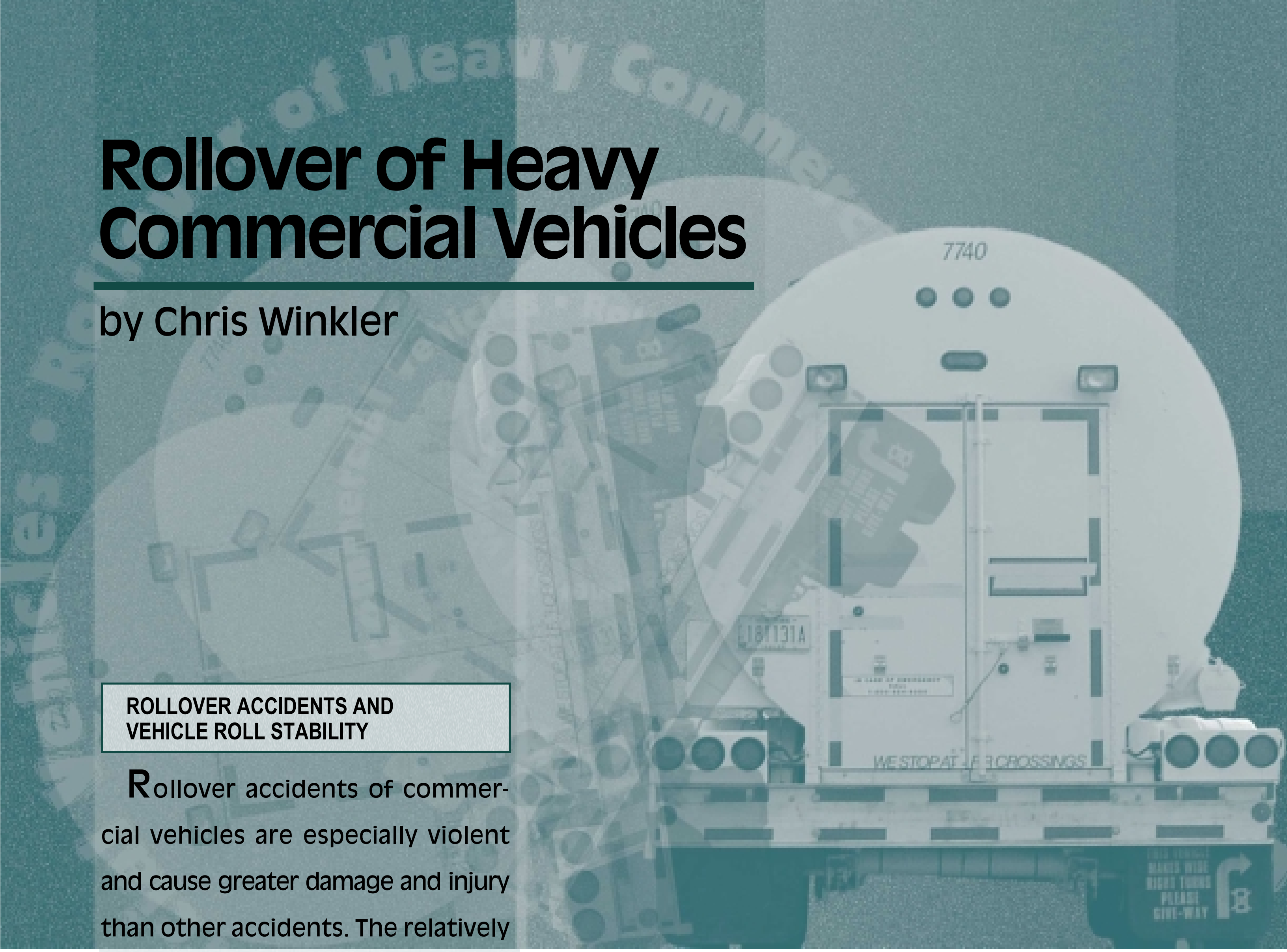

## Rollover of Heavy Commercial Vehicles

UMTRI RESEARCH REVIEW

**ISSN 0739 7100**
**October–December 2000, Vol. 31, No. 4**

| | |
|---|---|
| Editor: | Monica Milla |
| Designer and Illustrator: | Shekinah Errington |
| Original Technical Illustrations: | Chris Winkler |
| Printer: | UM Printing Services |

The *UMTRI Research Review* is published four times a year by the Research Information and Publications Center of the University of Michigan Transportation Research Institute, 2901 Baxter Road, Ann Arbor, Michigan 48109-2150 (http://www.umtri.umich.edu). The subscription price is $35 a year, payable by all subscribers except those who are staff members of a State of Michigan agency or an organization sponsoring research at the Institute. See the subscription form on the inside back cover. For change of address or deletion, please enclose your address label.




# Rollover of Heavy Commercial Vehicles

by Chris Winkler

## ROLLOVER ACCIDENTS AND VEHICLE ROLL STABILITY

Rollover accidents of commercial vehicles are especially violent and cause greater damage and injury than other accidents. The relatively low roll stability of commercial trucks promotes rollover and contributes to the number of truck accidents.

### Rollover and Accident Severity

There are over 15,000 rollovers of commercial trucks each year in the U.S. That is about one for every million miles of truck travel. About 9,400 of these—about one for every four million miles—are rollovers of tractor-semitrailers.

***Commercial truck rollover is strongly associated with severe injury and fatalities in highway accidents.*** As shown in figure 1, about 4 percent of all truck accidents involve rollover, but more than 12 percent of fatalities in truck accidents involve rollover (General Estimates System, 1995 and *Truck and Bus Crash Fact Book*, 1995).

The association of rollover with injuries to the truck driver is even stronger. While only 4.4 percent of tractor-semitrailer accidents are rollovers, 58 percent of the fatal injuries to the truck driver occurred in rollover crashes (General Estimates System and *Trucks Involved In Fatal Accidents*, 1992–1996). Figure 1 shows that rollover is overrepresented in all forms of truck-driver injury and that the level of overrepresentation increases progressively with the severity of injury.

### Roll Stability and the Occurrence of Rollover Accidents

***The low level of basic roll stability of commercial trucks sets them apart from light vehicles and appears to be a significant contributing cause of truck rollover accidents.*** The basic measure of roll stability is the static rollover threshold, expressed as lateral acceleration in gravitational units (g). Most passenger cars have rollover thresholds

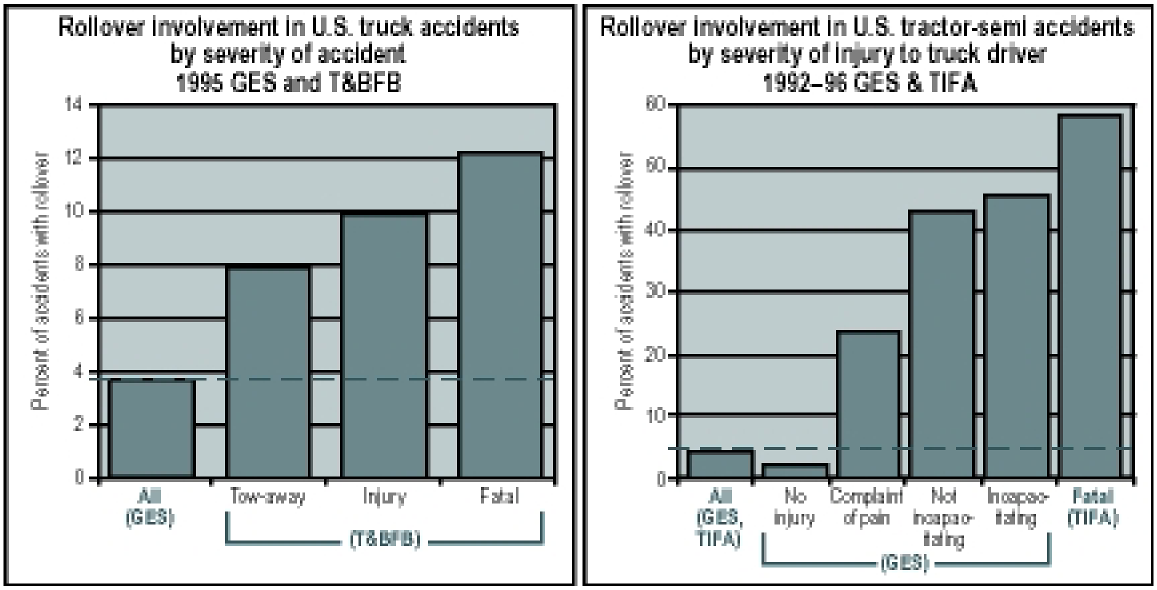



**Figure 1. Rollover is strongly associated with accident severity and with serious injury to truck drivers.**

greater than 1 g, while light trucks, vans, and SUVs range from 0.8 to 1.2 g (Chrstos, 1991 and *Technical Assessment Paper: Relationship Between Rollover and Vehicle Factors*, 1991). However, the rollover threshold of a loaded heavy truck often lies well below 0.5 g.

The typical U.S. five-axle tractor-van semitrailer combination, when loaded to legal gross weight, has a rollover threshold as high as 0.5 g with an optimal high-density, low center-of-gravity (cg) load. This drops to as low as 0.25 g with a worst-case load that completely fills the volume of the trailer (Ervin et al., 1980 and 1983). The typical U.S. five-axle petroleum semitanker has a rollover threshold of about 0.35 g (Ervin and Mathew, 1988). Rollover thresholds of common cryogenic tankers that transport liquefied gases are as low as 0.26 g. El-Gindy and Woodrooffe found a variety of logging trucks operating in Canada with thresholds ranging from 0.23 to 0.31g (Ervin and Nisonger, 1982). Individual vehicles with rollover thresholds well below 0.2 g also occur occasionally (e.g., Sweatman, 1993).

Drivers maneuver their vehicles at well over 0.2 g fairly regularly. The AASHTO guidelines for highway curve design result in lateral accelerations as high as 0.17 g at the advised speed (*A Policy on Geometric Design of Highways and Streets*, 1990). Therefore, even a small degree of speeding beyond the advisory level will easily cause actual lateral accelerations to reach 0.25 g in everyday driving. On the other hand, tire frictional properties limit lateral acceleration on flat road surfaces to a bit under 1 g at the very most. These observations clearly imply that the rollover threshold of light vehicles lies above, or just marginally at, the extreme limit of the vehicle's maneuvering ability, but the rollover threshold of loaded heavy trucks extends well into the "emergency" maneuvering capability of the vehicle and sometimes into the "normal" maneuvering range.

Nevertheless, it is relatively hard for truck drivers to perceive their proximity to rollover while driving. Rollover is very much an either/or situation. It is something like walking up to a cliff with your eyes closed: As you approach the edge, you are still walking on solid ground but once you've stepped over, it's too late. Further, the rollover threshold of a commercial truck changes regularly as the load changes, so drivers may not have the chance to get used to the stability of their vehicle. Finally, especially for combinations, the flexible nature of the tractor frame tends to isolate the driver from the roll motions of the trailer, which might act as a cue to rollover. These observations suggest the following safety hypotheses:

- Heavy trucks are more susceptible than light vehicles to rollover accidents caused directly by inadvertently operating the

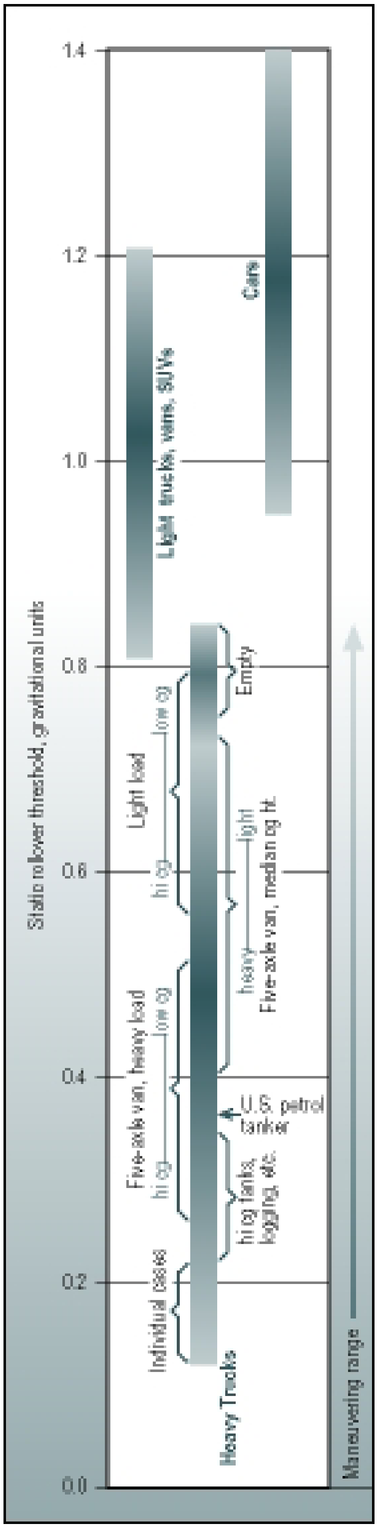



**Figure 2. The rollover threshold of trucks extends deep into the maneuvering range.**

vehicle beyond the rollover threshold.

- Rollover in heavy-truck accidents is strongly related to the basic roll stability of the vehicle.

The first hypothesis describes *single-vehicle accidents* in which the *first significant event* is an untripped rollover. Unfortunately, the perfect accident file for such an analysis does not exist, but GES files for 1993–1996 (which do not indicate first event) show that untripped rollovers occur in more than 20 percent of single-vehicle rollover accidents for tractor semitrailers, but in less than 4 percent of those accidents for passenger cars. Further, the Trucks in Fatal Accidents files (which contain no comparable data for cars) for 1994–1996 show that *untripped, first-event* rollovers account for 26.8 percent of single-vehicle rollover accidents.

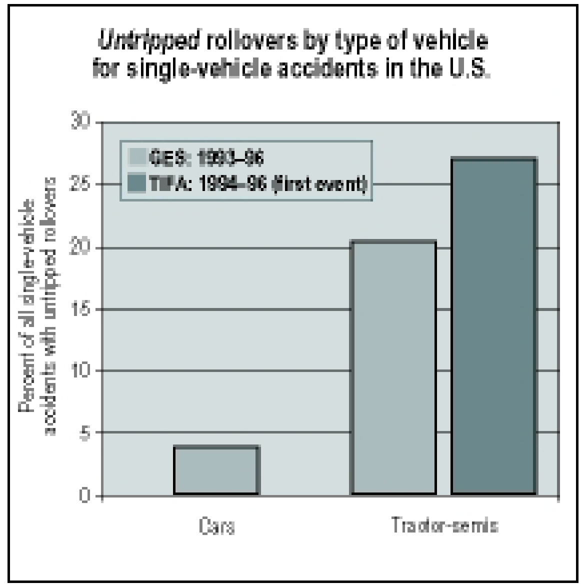



**Figure 3. Untripped rollovers are common for tractor-semitrailer combinations but rare for cars.**

Between 79 and 84 percent of single-vehicle rollover crashes on highway ramps are first-event *untripped* rollovers in which the vehicle struck no other object prior to rolling over (Wang and Council, 1999 and Council and Chen, 1999).

Figure 4 shows a strong relationship between physical roll stability and the chance of rollover in a single-vehicle accident. The relationship is nonlinear; that is, as the vehicle becomes more and more stable, the chance of rollover asymptotically approaches zero. Conversely, as stability decreases, the sensitivity of the probability of rollover to stability increases rapidly and the function becomes quite steep.

Figure 4 demonstrates that, as roll stability declines to low levels, the probability of rollover in an accident increases rapidly until the vehicle becomes very likely to roll over in nearly any

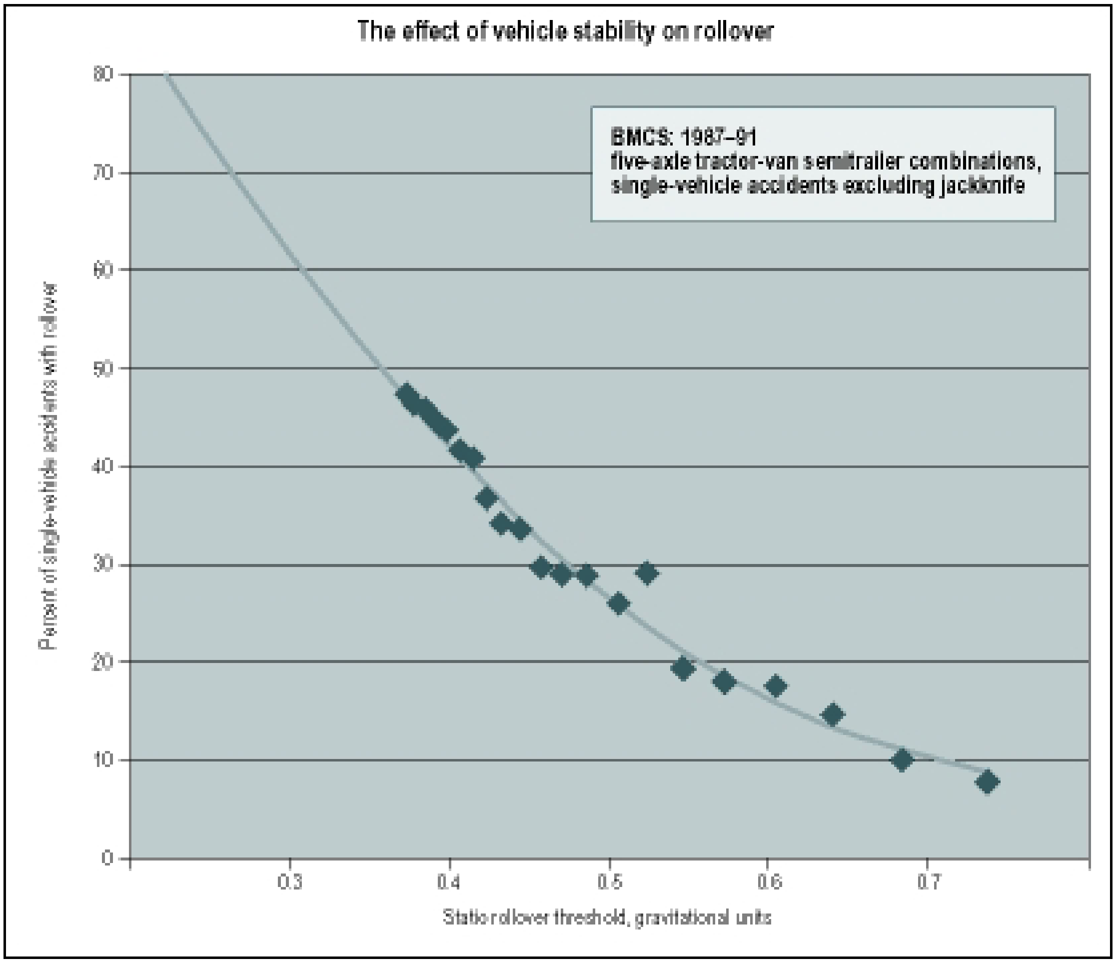



**Figure 4. The chance of rollover is strongly influenced by the roll stability of the vehicle.**

accident. Moreover, for the low-stability vehicles for which rollover is such a great concern, relatively small improvements in physical stability can yield rather large improvements in rollover accident rate.

## THE MECHANICS OF STATIC ROLL STABILITY

All rollover events in the real world are dynamic events; none are truly quasi-static. However, the foregoing analyses of accident data show a very strong relationship between the basic, static roll stability of the heavy vehicle and the actual occurrence of rollover in accidents. Accordingly, this section considers the mechanics of quasi-static rollover to show how this fundamental performance property derives from the mechanical behavior of the various components of the vehicle.

Figure 5 presents a simplified model of a heavy vehicle in a steady turn in which the vehicle, its tires, and suspensions have been "lumped" into a single roll plane. The nomenclature of the figure is as follows:

$a_y$ is lateral acceleration

$F_i$ are the vertical tire loads, i=1, 2

$h$ is the height of the cg

$T$ is the track width

$W$ is the weight of the vehicle

$\Delta y$ is the lateral motion of the cg relative to the track

$\phi$ is the roll angle of the vehicle

The equilibrium equation for roll moment about a point on the ground at the center of the track is:

$$W \bullet h \bullet a_y = (F_2 - F_1) \bullet T/2 - W \bullet \Delta y$$

Qualitatively, two destabilizing (overturning) moments act on the vehicle:

- A moment due to the lateral D'Alambert force acting through the cg, $W \bullet h \bullet a_y$, as a result of the external imposition of lateral acceleration
- A moment due to the weight of the vehicle acting at a position that is laterally offset from the center of the track, $W \bullet \Delta y$

The first moment results from the external imposition of lateral acceleration acting at the center of gravity (cg) of the vehicle; the latter results from the internal compliant reactions of the vehicle (roll and lateral shift).

These two destabilizing moments are opposed by one stabilizing (restoring) moment due to the side-to-side transfer of vertical load on the tires, $(F_2 - F_1) \bullet T/2$. This moment is also due to the internal, compliant responses of the vehicle. The maximum possible value of this moment is $W \bullet T/2$, which occurs when all load is transferred to one side of the vehicle, i.e., when $F_2 = W$ and $F_1 = 0$.

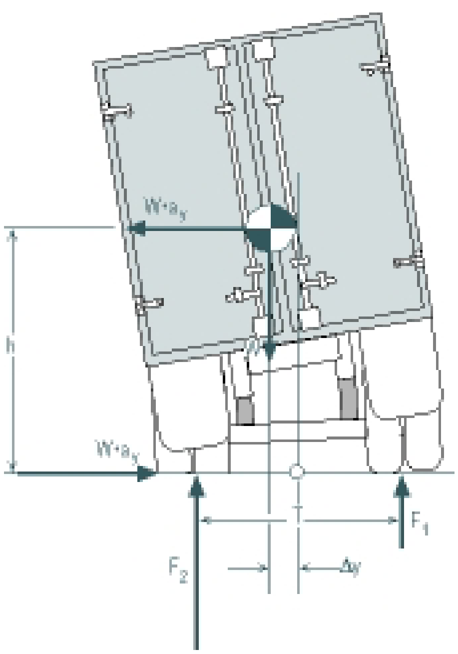



**Figure 5. A simplified freebody diagram of a heavy vehicle in a steady turn.**

One way of interpreting the equation and the observation of two destabilizing moments is that a vehicle's rollover threshold derives from both a reference *rigid-body stability*, which would result if Δy were zero, and the degradation from that reference resulting from the lateral motion of the cg allowed by compliances within the vehicle.

Figure 6 illustrates how various properties of the vehicle contribute to the rollover threshold according to this view. The example shows a rather low-stability vehicle whose heavy load and relatively high payload establish a *rigid-body stability* of 0.45 g. However, the roll and lateral motions allowed by the various compliances and free-plays in the tires, suspension, chassis structures, and even the load itself, can reduce the actual static stability of the vehicle to about 0.26 g.

Starting from the top of the figure, if this vehicle were rigid, then as a turn became more severe and lateral acceleration increased, it could transfer all of its load onto the outside tires without suffering any lateral shift of the cg (Δy in figure 5). This means it

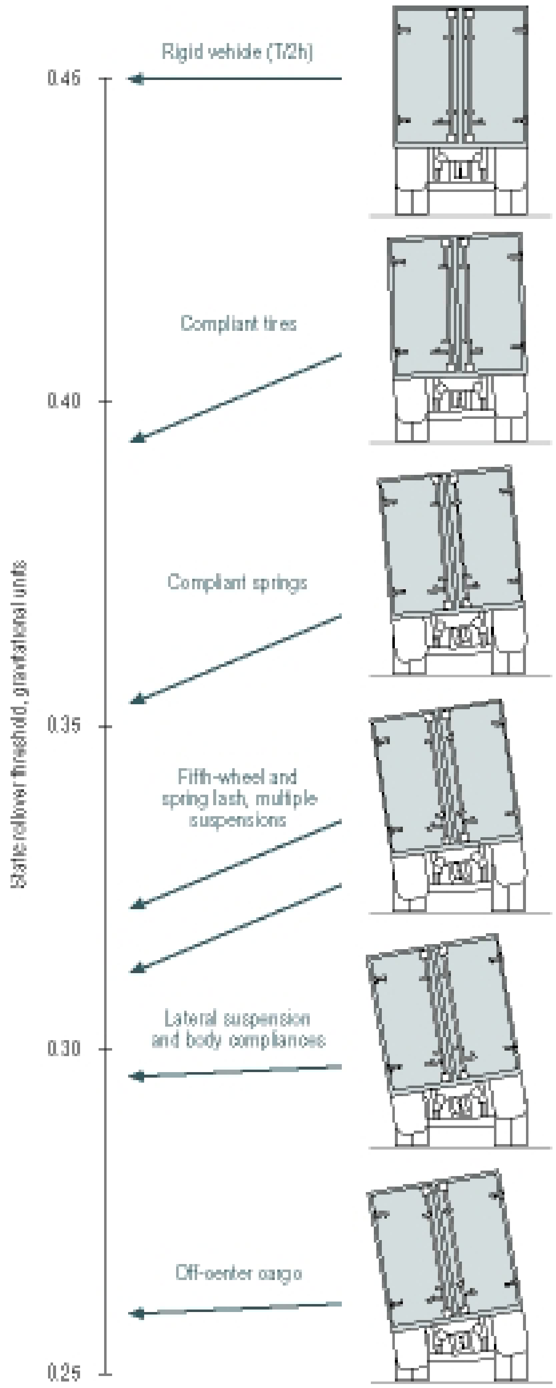



**Figure 6. An example case showing various major influences that determine roll stability.**

could achieve the maximum stabilizing moment (for load transfer) without suffering any destablizing moment from lateral shift. For a given cg height and track, the vehicle would be optimized.

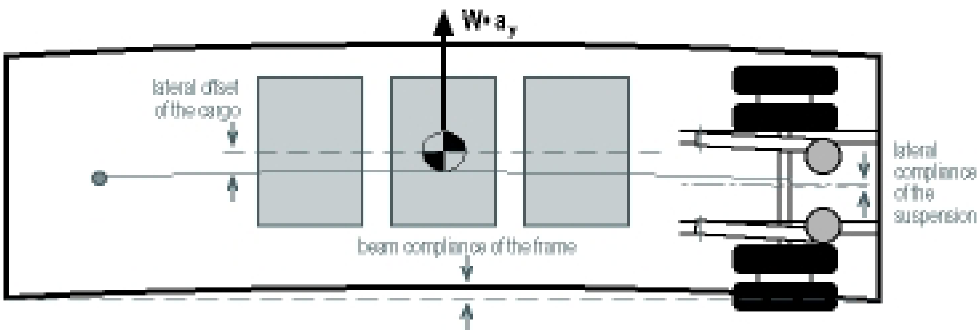



**Figure 7. Examples of other mechanisms that can contribute to the destabilizing offset moment.**

But real vehicles are not rigid. As load is transferred from the tires toward the inside of the turn onto the tires toward the outside, those tires deflect causing roll motion about the center of the track. As a result, the cg moves outboard and some stability is lost.

Similarly, the suspension springs deflect. The roll from this motion takes place about the so-called roll center of the suspension, typically located a few inches above or below the axle.

Some suspension, and virtually all tractor-to-trailer couplings, are designed with some freeplay that comes into play only when the vehicle rolls substantially. This freeplay allows an increment of roll motion to take place without any attendant stabilizing lateral load transfer. The resulting lateral shift of the cg further degrades stability.

The structural elements of the vehicle can simply bend under the high centrifugal loads that develop during severe cornering. Further, the payload itself may deflect sideways as it suffers under the same type of loading. Figure 7 illustrates some of the more significant of these deflections. Figure 8 shows—in rather dramatic fashion—the torsional compliance of the vehicle's structural frame can also contribute to the rollover process.

The significance of lateral displacements occurring from each individual mechanism such as these—or of the total of all—can be judged by comparing Δy to T/2 (the half track). The lateral displacement of the cg is, in effect, a direct reduction of the half track. In round numbers, the half track of an axle with dual tires is about 95 cm. Thus, a 1-cm lateral deflection results in loss of stability equal to about 1 percent of the original rigid-body stability of the vehicle. Lateral suspension deflection may be on the order of 2 cm. Lateral beaming of the trailer may be 3 cm or more. A variety of other compliances may each produce displacements on the order of several millimeters and, of course, the lateral offset of the placement of the cargo

**Figure 8. The rear end of a torsionally compliant flat-bed trailer rolls over nearly independently of the front end.**

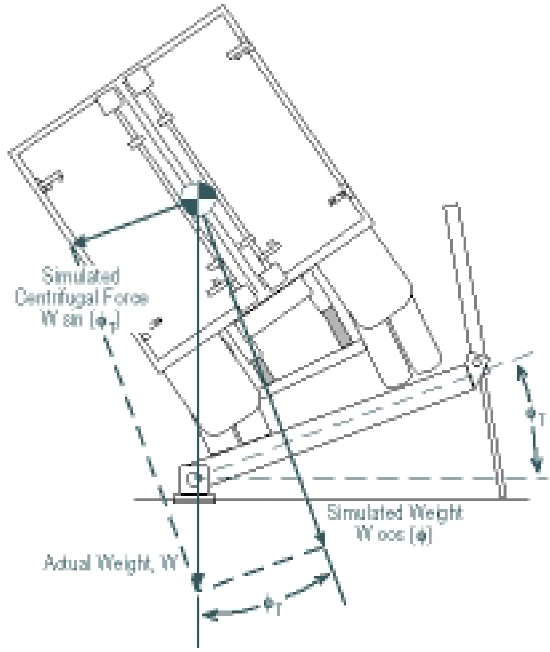



**Figure 9. The tilt-table experiment.**

can be quite substantial. While none of these displacements may seem significant individually, the total influence can easily account for the loss of a significant portion of the rigid-vehicle stability.

The overall message of figure 6, and this discussion, is that roll stability is established by the summated effects of many compliance mechanisms. While the effect of any one compliance may be small, virtually all compliances degrade stability. ***All the compliances combined can reduce roll stability to as little as 60 percent of the idealized rigid-vehicle stability.***

## Measuring Static Rollover Threshold with the Tilt-Table Experiment

The tilt-table test provides a highly resolute method of determining rollover threshold and a convenient means for examining the mechanisms by which this limit is determined. The methodology is a physical simulation of the roll-plane experience of a vehicle during quasi steady-state turning.

In this experimental method, the vehicle is placed on a tilt table and is very gradually tilted in roll. As shown in figure 9, the component of gravitational forces parallel to the table surface provides a simulation of the centrifugal forces experienced by a vehicle in turning maneuvers. The progressive application of these forces achieved by slowly tilting the table serves to simulate the effects of quasi-statically increasing lateral acceleration in progressively more severe, steady turnings. The tilting process continues until the vehicle reaches the point of roll instability and "rolls over." (The vehicle is constrained by safety straps to prevent actual rollover.)

When the table is tilted, the component of gravitational forces parallel to the table surface simulates lateral forces, and the weight of the vehicle is simulated by the component of gravitational forces perpendicular to the table. Both the lateral and vertical forces acting during the tilt-table test are *scaled down* somewhat relative to the real forces they simulate. The amount that these forces are scaled depends on the amount of tilt required. This scaling has multiple effects which, although they tend to cancel one another, can nevertheless reduce the accuracy of the experiment. The quality of the result as a measure of the true static stability limit of the vehicle depends, in part, on not requiring an excessively large tilt angle to achieve rollover. Because heavy vehicles are relatively unstable, they typically do not require a large tilt angle, and therefore the experiment is very well suited for examining these vehicles.

The fundamental aspects of the mechanics of quasi-static rollover, which were discussed briefly above, have been confirmed in numerous tilt-table experiments (Winkler, 1987; Winkler and Zhang, 1995; and Ervin et al., 1998).

## DYNAMIC CONSIDERATIONS IN HEAVY VEHICLE ROLLOVERS

Analyses of the accident records make it clear that static roll stability is the dominant vehicle quality affecting the chance of a given heavy truck being involved in a rollover accident. The previous section reviewed the mechanics of static stability. However, all rollover accidents in the real world are dynamic events to some extent; none are truly quasi-static. This section examines some influences of dynamics on rollover.

### Simple Dynamics in the Roll Plane

Quasi-static rollover is nearly impossible to accomplish, even on the test track. The analyses in the previous section assume that the lateral acceleration condition is a given and is sustained indefinitely (i.e., the condition defining steady state).

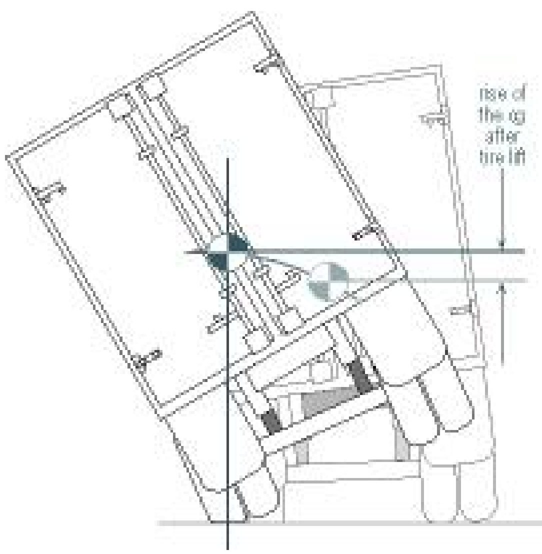



**Figure 10. At the least, rollover requires the dynamic momentum required to lift the cg through its apex height.**

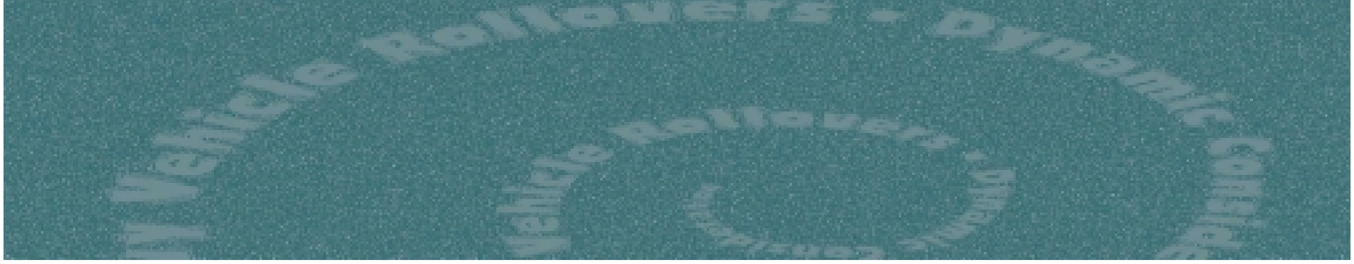
In practice, a test vehicle can approach rollover quasi-statically either by very slowly increasing turn radius at a constant velocity or by very slowly increasing velocity at a constant radius. In either case, the quasi-static condition can be made to hold reasonably well until the tires of the drive axles lift. At this point, however, the vehicle typically loses traction and "scrubs off" speed such that the lateral acceleration immediately declines and the drive wheels settle back onto the surface. The process may be repeated any number of times. At least two exceptions can allow quasi-static rollover: The vehicle may be equipped with a locking differential so that drive thrust can be maintained after lift of tires on the drive axles, or highly compliant (flat bed) trailers may roll over at the rear without lifting drive-axle tires (figure 8). Regardless, in real-world events there is virtually always a dynamic component to the maneuver which, at the least, provides the needed kinetic energy to raise the cg through its apex height after the tires of all axles (or at least all axles other than the steer axle) have left the ground. However, as shown in figure 10, for vehicles with high centers of gravity, the additional elevation of the cg required is not that great.

Several simplified analyses describing minimum requirements for dynamic rollover (i.e., as depicted in figure 10) exist in the literature. These tend to focus on the passenger car and, consequently, on so-called tripped rollovers, i.e., rollovers involving a curb-strike or other mechanism that may produce lateral tire forces well in excess of those generally obtainable on a flat, hard road surface (e.g., Rice et al.).

Cooperrider et al. take a different approach. They present an analysis based on a constant lateral tire force applied to a *rigid* vehicle over a sustained period of time. This approach seems more applicable to rollover of commercial vehicles, particularly in situations of sustained, quasi-steady turning. Cooperrider's results show that the lateral acceleration needed to produce rollover is a function of the length of time it is applied. If the acceleration can be sustained indefinitely, it need only equal the static stability limit (T/2h for this rigid-vehicle analysis). But if the lateral acceleration exceeds the static limit, it need only be sustained for a finite time to result in rollover. For example, for a typical heavy truck, acceleration of 110 percent of the static limit can produce rollover if sustained for about 1 second; 120 percent need be sustained for only about 0.6 seconds.

### Dynamic Considerations in Transient Maneuvers

*Dynamics* become particularly important when the frequency content of the maneuver (and in particular, the lateral acceleration that results from maneuvering) approaches or exceeds the natural frequency of the rolling motion of the vehicle. A lightly loaded tractor-semitrailer can be expected to have natural frequencies in roll in the range of 2 Hz or more—well above the frequency of steering input that the truck driver can muster even in emergency maneuvers. However, a heavily loaded vehicle, with its payload cg at a moderate height



and with suspensions of average roll stiffness, is likely to exhibit a roll natural frequency near 1 Hz. A heavily loaded semitrailer with a high cg and with suspensions of less-than-average stiffness can have a roll natural frequency as low as 0.5 Hz. As indicated below, 0.5 Hz in particular is well within the range of excitation frequencies expected in emergency maneuvering. Thus, one can expect the potential for harmonic tuning and related resonant overshoot to promote rollover in transient maneuvers with higher frequency content. It follows from these considerations that high levels of roll stiffness (and consequently roll natural frequency) and of roll damping generally promote dynamic roll stability in highway operations.

Higher frequency maneuvers also involve yaw dynamics that can complicate—and stabilize—roll behavior of articulated vehicles. Figure 11 shows the response of a tractor-semitrailer during a simulated, 2-second emergency lane change maneuver (ISO 14791). The figure presents time histories of lateral acceleration for the tractor and for the semitrailer and roll angle for the combination. When maneuvering at speed, the semitrailer tends to follow the path of the tractor rather faithfully. Particularly with longer vehicles, this implies a time lag between the actions of the tractor and the trailer. (This is more a result of the tractrix geometry that basically governs the motion of the trailer, rather than a true dynamic phenomenon.) When the frequency content of the lateral motion approaches the roll natural frequency, roll motion can be expected to lag lateral acceleration. Both of these effects are readily apparent in figure 11. With respect to rollover, when the trailer reaches its maximum roll displacement, the tractor is well past its peak lateral acceleration. Consequently, at this critical point, the tractor, with its relatively low cg, is more "available" to resist rollover than it would be in a demanding steady-state turn. Thus, in this maneuver, while roll dynamics are degrading roll stability, the yaw dynamics are compensating to some extent. The situation (even in this relatively simple maneuver) is complex and the net result depends on the tuning of the frequency content of the particular maneuver, the frequency sensitivities of the vehicle in yaw, and the natural frequency and damping of the vehicle in roll.

Dynamics can play a unique role in the rollover of multiply-articulated vehicles. As illustrated in figure 12, vehicles with more

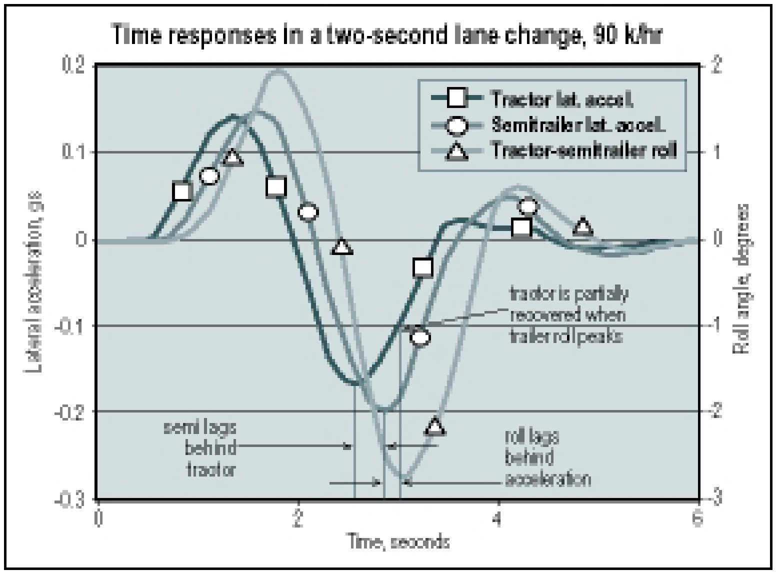



**Figure 11. In a dynamic maneuver, the acceleration of the semitrailer lags the tractor and roll lags acceleration.**

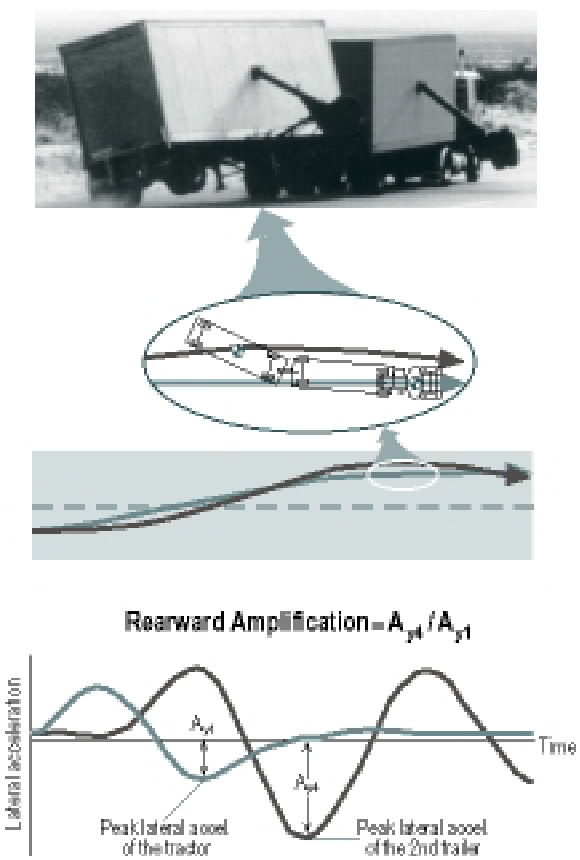



**Figure 12. In rapid obstacle-avoidance maneuvers, rearward amplification may result in premature rollover of the rear trailer.**

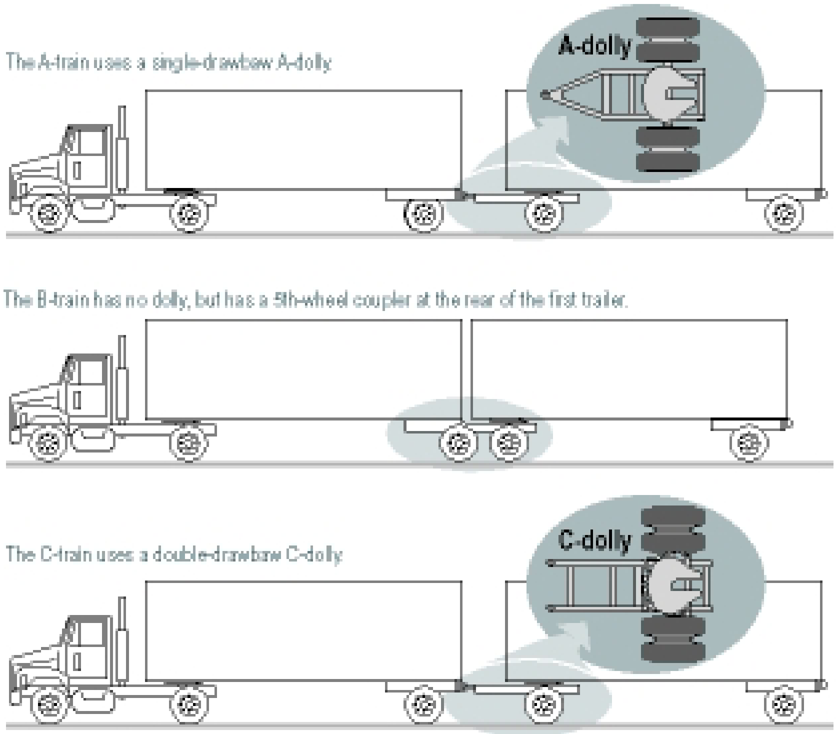



**Figure 13. The B-train and C-train, originally introduced in Canada, exhibit less rearward amplification than the standard A-train.**

than one yaw-articulation joint (e.g., truck-trailer combinations, doubles, or triples) may exhibit an exaggerated response of the rearward units when performing maneuvers with unusually high frequency content. The phenomenon is known as rearward amplification and is often quantified, as shown in figure 12, by the ratio of the peak lateral response of the rearward unit to that of the tractor (ISO 614791 and SAE J2179).

Rearward amplification is a strong function of the frequency content (and the type) of the maneuver. Because rearward amplification is close to unity at low frequencies, these vehicles behave very well in normal driving. However, since rearward amplification tends to peak in the frequency range characteristic of quick, evasive maneuvers, these vehicles are also quite susceptible to rollover of the rear trailers during emergency maneuvering.

Numerous approaches to reduce rearward amplification of multitrailer vehicles have been proposed, most of which are based on different arrangements for coupling trailers. The most successful have been the so-called B-train and C-train, which are compared to the reference A-train in figure 13. Both of these vehicles eliminate the yaw and roll degrees of freedom associated with the pintle-hitch coupling between the semitrailer and the full trailer. Eliminating the yaw articulation indirectly improves roll stability by reducing rearward amplification. For example, the A-train in figure 13 would typically have a rearward amplification of about 2, but the rearward amplification of the B-train and C-train in the figure would typically be less than 1.5.

However, by coupling the two trailers in roll, the B- and C-train configurations dramatically improve dynamic roll stability. The lateral acceleration and roll motions of the two trailers are about 90 degrees out of phase. Thus, when the second trailer reaches its critical condition of maximum lateral acceleration and roll angle, the first trailer has passed its peak and returned to near-zero in these two measures and actually has substantial roll momentum in the opposite direction. When these two trailers are coupled in roll as in a B- or C-train, the vehicle can perform very severe lane changes (i.e., with peak lateral accelerations of the *tractor* on the order of 0.5 g) without experiencing rollover because it is extremely difficult for one trailer to “drag over” its out-of-phase partner (Winkler et al., 1986). (Of course, the mechanical loads on the coupler and dolly frame may be very high in such maneuvers, introducing the risk of mechanical failure of these parts.)

## THE INFLUENCE OF SLOSHING LIQUIDS

In the majority of commercial truck operations, the load on the vehicle is fixed and nominally centered. In certain cases, however, the load may be able to move in the vehicle, with the potential of affecting the turning and rollover performance. The most common examples of moving loads are bulk, liquid tankers with partially filled compartments; refrigerated vans hauling suspended meat carcasses; and livestock. The performance properties of commercial vehicles used in these applications may be influenced by the free movement of the load in either longitudinal or lateral directions. This section presents material on the first two types of loads.

### Liquid Loads

The most important of these is liquid cargo carried in tanks. In the operation of a bulk-liquid transport vehicle, the moving load that can affect its cornering and rollover behavior is the presence of unrestrained liquid due to a partially filled tank or compartment. A compartment that is filled to anything less than its full capacity allows the liquid to move from side to side, producing a “slosh” load condition. Slosh is of potential safety concern because the lateral shift of the load reduces the vehicle’s performance in cornering and rollover, and the dynamic motions of the load may occur out of phase with the vehicle’s lateral motions in such a way as to become exaggerated and thus further reduce the rollover threshold.

The motions of liquids in a tank vehicle can be quite complex due to the dependence of the motions on tank size and geometry, the mass and viscosity of the moving liquid, and the maneuver being performed (Dalzell, 1967; Komatsu, 1987; and Krupka, 1985). Fundamental analyses of sloshing liquids in road tankers appeared in the literature from the 1970s. A number of more elaborate computer studies arose in the late 1980s and early 1990s. This discussion is constrained to basic elements that provide insight on the mechanisms by which fluid motions influence rollover. The mechanisms of slosh are most readily described in simple steady-state cornering, although it is in transient maneuvers that the most exaggerated fluid displacements take place.

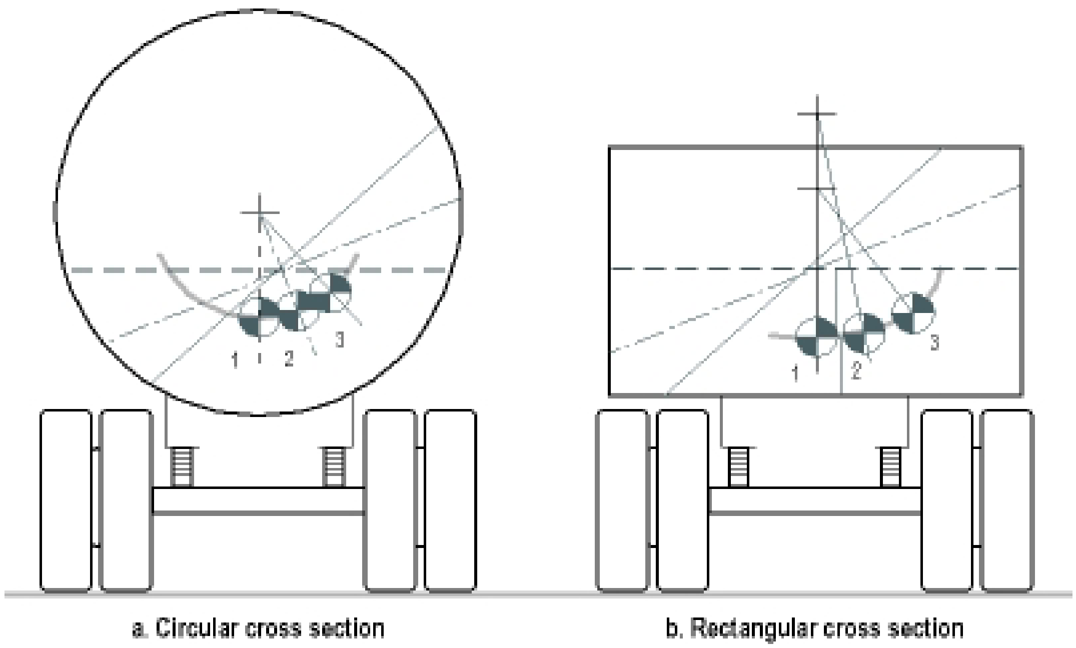



**Figure 14. Liquid position in steady-state turning for circular and rectangular tanks.**

#### *Steady Turning*

When a slosh-loaded tanker performs a steady-state turn, the liquid responds to lateral acceleration by displacing laterally, keeping its free surface perpendicular to the combined forces of gravity and lateral acceleration. Figure 14a illustrates the position of a partial liquid load in a circular tank subjected to a steady-state cornering maneuver. The mass center of the liquid moves on an arc, the center of which is at the center of the circular tank. In effect, the shift of the liquid produces forces on the vehicle as if the mass of the load were located at the center of the tank.

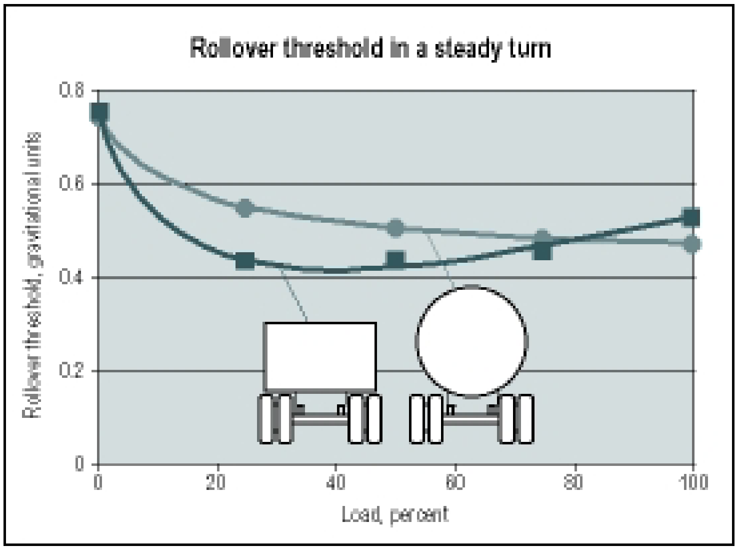



Figure 15. Rollover threshold in a steady turn as a function of the percentage of load of unrestrained liquid and tank shape (adapted from Strandberg, 1978).

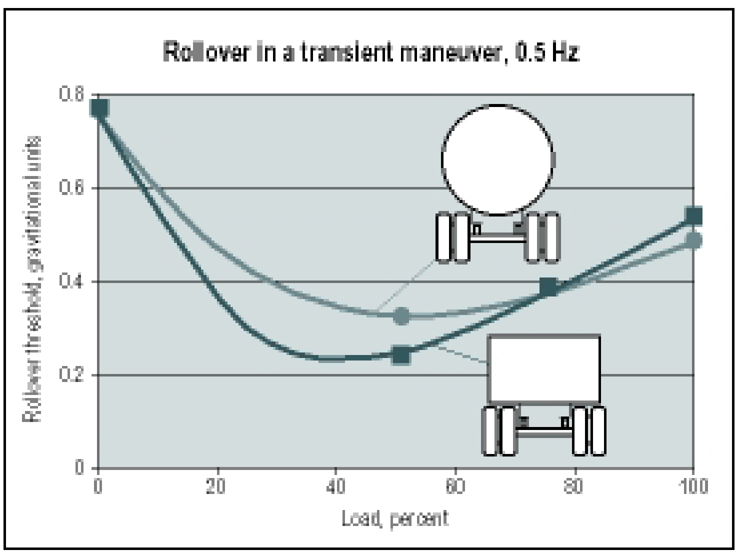



Figure 16. Rollover threshold in a transient turn as a function of the percentage of load of unrestrained liquid (adapted from Strandberg, 1978).

With more complex tank shapes, even the steady-state behavior becomes somewhat difficult to analyze. In particular, with unusual tank shapes it becomes more difficult to describe the motion of the liquid's center of mass as a function of lateral acceleration. As a contrast to the circular tank, figure 14b illustrates the behavior of liquid in a rectangular tank. At low lateral accelerations, the liquid movement is primarily lateral, centered at a point well above the tank center. Hence, its effect is similar to having a very high mass center. With increasing lateral acceleration, the mass center follows a somewhat elliptical path.

While the circular tank results in a vehicle with a higher load center, efforts to reduce the load height by widening and flattening the tank can be expected to increase vehicle sensitivity to slosh degradation of the rollover threshold. The effect is illustrated by the plot in figure 15 which is adapted from data by Strandberg (Ranganathan later presented very similar results). The figure shows rollover threshold versus load condition in steady-state cornering. For a circular tank, increasing load lowers the threshold continuously due to the increasing mass of fluid free to move sideways. In this case, the minimum rollover threshold occurs at full load. For a vehicle with a modified rectangular tank, higher levels of rollover threshold occur when the tank is either empty or full, although at intermediate load conditions the rollover threshold is severely depressed due to the greater degree of lateral motion possible for the unrestrained liquid. Thus, the rectangular tank shape (in contrast to the circular) can potentially result in rollover thresholds with sloshing loads that are less than that of the fully loaded vehicle.

### *Transient Turning*

In transient maneuvers such as an abrupt evasive steering maneuver (e.g., a rapid lane change), slosh loads introduce the added dimension of dynamic effects. With a sudden steering input, the rapid imposition of lateral acceleration may cause the fluid to displace to one side with an underdamped (overshooting) type of behavior. The difference between the steady-state and transient maneuvers is primarily a matter of the time involved in entering the turn. The steady-state type of behavior is observed when the turn is entered very slowly, whereas the transient behavior applies to a very rapid turning maneuver. The response of the liquid mass to a step input of acceleration would be seen to displace to an amplitude approximately twice the level of the steady-state amplitude. In a lane-change maneuver in which the acceleration goes first in one direction and then the other, an even more exaggerated response amplitude can be produced.

In general, the degree to which the dynamic mode is excited depends on the timing of the maneuver. The unrestrained liquid will have a natural frequency for its lateral oscillation which depends on the liquid level and cross-sectional size of the tank. For a half-filled, eight-foot-wide tanker, this frequency is approximately 0.5 Hz (cycles per second), while a six-foot-diameter circular tank (typical of an 8,800-gallon tanker) would have a frequency of approximately 0.6 Hz. As for dynamic systems in general, if the frequency content of input (lateral acceleration) stays below this natural frequency, the response is largely quasi-static, but if the input contains substantial power at or above the natural frequency, the response will be dynamic. Although they do not do so in normal driving, drivers in emergency situations are generally capable of generating steering inputs at frequencies in the range of 0.5 Hz (e.g., McLean and Hoffmann, 1973). Indeed, the two-second lane change used as a typical evasive maneuver for evaluating rearward amplification constitutes a lateral acceleration input at just that frequency closely matched to the slosh frequency. Hence it must be concluded that dynamic slosh motions can be readily excited on a tanker of normal size, especially in the course of evasive maneuvers such as a lane change.

In transient maneuvers, rollover thresholds are depressed by this dynamic motion. Figure 16 shows the estimated rollover threshold as a function of load for unrestrained liquids in a transient maneuver, which is adapted from data presented by Strandberg. In the transient case, even the circular tank experiences reduced rollover thresholds when partially loaded because the fluid can “overshoot” the steady-state level. Understandably, the elliptical tanker is even worse. Though the results shown are derived from analytical studies, experimental tests of partially loaded tankers generally confirm these observations (Culley et al., 1978).

### *Partial Liquid Loads*

In the vocational use of many liquid bulk haulers, it is sometimes necessary to run with partial loads. This is especially true with local delivery tankers hauling gasoline and home-heating fuel. The question is: What can be done to reduce the sensitivity and hence the potential risks of using these vehicles, once a substantial fraction of their load has been delivered? Of course, specifying a vehicle with suspension systems most resistant to rollover is a first step. However, at least two other aids are available:

***Baffles.*** Baffles are commonly used in tank vehicles, except in special cases where provisions for cleaning prevent their use (such as bulk-milk haulers). However, the common baffle arrangement is a transverse baffle intended to impede fore/aft movement of the load. These transverse baffles have virtually no utility in preventing the lateral slosh influential to roll stability. To improve roll performance, longitudinal baffles would be required, but design and cost considerations have practically eliminated their use.

***Compartmentalization.*** A more common method for improving cornering performance with tankers under partial loading conditions is to subdivide the tank into separate compartments. Ideally, the compartments are completely emptied on an individual basis at a drop spot so the vehicle is never subject to a sloshing load. The only precaution in this type of use is that the delivery route should be planned to empty from the rear of the vehicle first. When it is not possible to completely empty each compartment, a reduced slosh sensitivity exists, but is often not significant as long as only a fraction of the total load is free to slosh. In these cases, the relevant parameters are the percent of load being carried and the fraction of the load that is free to slosh.

## ROLLOVER AND THE INTELLIGENT HIGHWAY/VEHICLE SYSTEM

Modern electronics are beginning to be applied to the problem of heavy vehicle rollover in the form of intelligent systems in the vehicle or within the highway infrastructure.

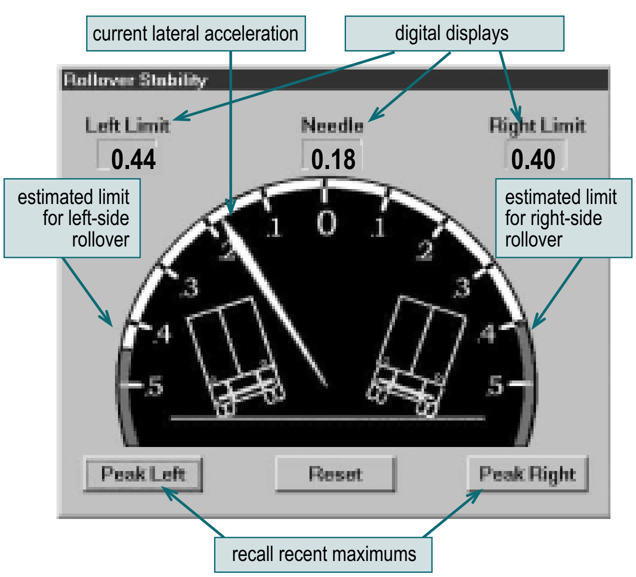
Because a disproportionate number (about 7 percent) of commercial-vehicle rollover crashes occurs on ramps, highway-infrastructure systems have concentrated on active signing for advisory speeds on exit ramps. The methods vary significantly. For example, Freedman et al. examined the effectiveness of speed-advisory signs with flashing lights that activated when a truck was observed entering the ramp at excessive speed. On the other hand, Strickland et al. described prototype installations that selectively display the message “Trucks reduce speed,” based on automated observations of the speed, weight, and height of individual vehicles. Systems of this type have been installed and monitored at three different exit ramps on the Capital Beltway in Washington, D.C. Prior to their installation, truck rollovers occurred once every year or every other year on these ramps. After installation, there were no truck rollovers at any of the sites for the three-year period of the study (Strickland and McGee, 1998).

At least three methods of reducing commercial-vehicle rollover through on-board systems are being pursued. Perhaps the most direct method is active roll control, which aims to improve the roll stability of vehicles during critical events. Kusahara et al. describe a prototype active roll stabilizer installed on the front suspension of a medium duty commercial truck. Similar devices, installed on all suspensions of unit trucks or tractor-semitrailer combinations, have been under development at Cambridge University (Lin et al., 1994 and 1996).

Another approach employing on-board intelligence is the roll-stability-advisory (RSA) or rollover-warning system. A “stability monitoring and alarm system” was advertised for application on commercial vehicles in the late 1980s (Preston-Thomas and Woodrooffe, 1990). More recently, Roaduser Research of Melbourne, Australia, has developed and installed a rollover-warning system in limited numbers on tank vehicles. The system produces an audible warning for the driver based on real-time measurement of lateral acceleration compared to a predetermined, worst-case static rollover threshold for the vehicle. UMTRI has developed a prototype RSA that includes a visual display for the driver that compares the current lateral acceleration of the vehicle to the static rollover threshold of the vehicle in left- and right-hand turns. The rollover thresholds are calculated in real time based on signals from on-board sensors. Thresholds for each new loading condition are determined after only a few minutes of normal driving.

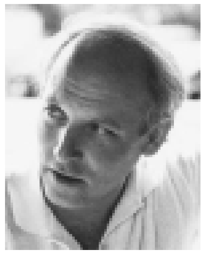
Another approach to reducing rollover crashes is active yaw control of the vehicle, which prevents lateral acceleration from exceeding the rollover threshold of the vehicle. The approach selectively applies individual wheel brakes to submit appropriate yaw moments and/or to simply slow the vehicle. Palkovics, in association with El-Gindy and others, has published research articles on this approach and the ideas are being introduced in commercial applications. In addition, UMTRI has developed and demonstrated a prototype system especially for reducing rearward amplification in multitrailer vehicles (Ervin et al., 1998 and Winkler et al., 1998). Development of this system continues with expectations of commercial application.

**Figure 17. The driver display of the UMTRI RSA (Ervin et al., 1998).**




*This article is a condensed version of an SAE publication.*  *A complete copy of this report can be obtained from SAE by contacting SAE Customer Service at: 724-776-4970 (phone), 724-776-0790 (fax), or publications@sae.org, order number RR-004.*

## ABOUT THE AUTHOR



***Chris Winkler*** is a research scientist in the Engineering Research Division at UMTRI. He received a B.S. degree in mechanical engineering from Bucknell University and an M.S. in mechanical engineering from the University of Michigan. He joined UMTRI in 1969, and has been involved with the analysis and prediction of the dynamic performance of all pneumatic-tired vehicles, but with special emphasis on commercial highway vehicles. Chris has been involved with both theoretical and experimental work on trucks, including the development of specialized equipment for measuring the mechanical properties of vehicles and their components. Recently, many UMTRI projects involve "intelligent vehicle systems," and, in particular, active systems to enhance stability. Recent projects include development and real-world testing of Roll Stability Advisory systems. Chris is active with the Society of Automotive Engineers and the International Standards Organization, and he is a trustee and the vice president for North America of the International Forum for Road Transport Technology.

## REFERENCES


*A policy on geometric design of highways and streets—1990*; AASHTO green book. American Association of State Highway and Transportation Officials, Washington, D.C.

Chrstos, J. P. 1991. *An evaluation of static rollover propensity measures.* Interim final report. National Highway Traffic Safety Administration, Vehicle Research and Test Center, East Liberty, Ohio. Sponsor: National Highway Traffic Safety Administration, Washington, D.C. Report No. VRTC-87-0086/ DOT/HS 807 747.

Cooperrider, N.; Thomas, T.; Hammound, S. 1990. *Testing and analysis of vehicle rollover behavior.* Report No. SAE 900366.

Council, F. M.; Chen, L. 1999. Personal correspondence. HSIS data request. Federal Highway Administration. Washington, D. C.

Culley, C.; Anderson, R. L.; Wesson, L. E. 1978. *Effect of cargo shifting on vehicle handling. Final report.* Dynamic Science, Inc., Phoenix, Ariz. Sponsor: Federal Highway Administration, Bureau of Motor Carrier Safety, Washington, D.C. Report No. 3989-78-22/ FHWA-RD-78-76.

Dalzell, J. F. 1967. *Exploratory studies of liquid behavior in randomly excited tanks: lateral excitation.* Southwest Research Institute, San Antonio, Texas. Sponsor: National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Huntsville, Ala. Report No. 2.

El-Gindy, M.; Woodrooffe, J. H. F. 1990. *Study of rollover threshold and directional stability of log hauling trucks.* National Research Council Canada, Division of Mechanical Engineering, Ottawa, Ontario. Report No. TR-VDL-002/ NRCC No. 31274.

Ervin, R. D. 1983. *The influence of size and weight variables on the roll stability of heavy duty trucks.* Michigan University, Ann Arbor, Transportation Research Institute. Report No. SAE 831163.

Ervin, R. D.; Mallikarjunarao, C.; Gillespie, T. D. 1980. *Future configuration of tank vehicles hauling flammable liquids in Michigan.* Volume I. Final report. Highway Safety Research Institute, Ann Arbor, Michigan. Sponsor: Michigan Department of State Highways and Transportation, Lansing. Report No. UM-HSRI-80-73-1.

Ervin, R. D.; Mathew, A. 1988. *Reducing the risk of spillage in the transportation of chemical wastes by truck.* Final report. Michigan University, Ann Arbor, Transportation Research Institute. Sponsor: Rohm and Haas, Bristol, Pa. Report No. UMTRI-88-28.

Ervin, R. D.; Nisonger, R. L. 1982. *Analysis of the roll stability of cryogenic tankers.* Final report. Highway Safety Research Institute, Ann Arbor, Michigan. Sponsor: Union Carbide Corporation, Linde Division, Tarrytown, N.Y. Report No. UM-HSRI-82-32.

Ervin, R. D.; Nisonger, R. L.; MacAdam, C. C.; Fancher, P. S. 1983. *Influence of size and weight variables on the stability and control properties of heavy trucks.* Volume I. Final report. Michigan University, Ann Arbor, Transportation Research Institute. Sponsor: Federal Highway Administration, Washington, D.C. Report No. FHWA-RD-83-029/ UMTRI-83-10/1.

Ervin, R.; Winkler, C.; Fancher, P.; Hagan, M.; Krishnaswami, V.; Zhang, H.; Bogard, S. 1998. *Two active systems for enhancing dynamic stability in heavy truck operations.* Michigan University, Ann Arbor, Transportation Research Institute. Sponsor: National Highway Traffic Safety Administration, Washington, D.C. Report No. UMTRI-98-39.

Freedman, M.; Olson, P. L.; Zador, P. L. 1992. *Speed actuated rollover advisory signs for trucks on highway exit ramps.* Insurance Institute for Highway Safety, Arlington, Virginia / Michigan University, Transportation Research Institute, Ann Arbor.

ISO 14791. *Road vehicles—Heavy commercial vehicle combinations and articulated buses—Lateral stability test procedures.* International Organization for Standardization, Geneva, Switzerland.

Komatsu, K. 1987. “Non-linear sloshing analysis of liquid in tanks with arbitrary geometries.” Japan National Aerospace Laboratories, Tokyo. *International Journal of Nonlinear Mechanics*, Vol. 22, No. 3, pp. 193–207.

Krupka, R. M. 1985. *Mathematical simulation of the dynamics of a military tank.* Northrop Corporation, Electro-Mechanical Division, Anaheim, California. Report No. SAE 850416.

Kusahara, Y.; Li, X.; Hata, B.; Watanabe, Y. 1994. “Feasibility study of active roll stabilizer for reducing roll angle of an experimental medium-duty truck.” Nissan Diesel Motor Company, Ltd., Saitama, Japan. International Symposium on Advanced Vehicle Control. *Proceedings.* Tokyo, Society of Automotive Engineers of Japan, pp. 343-348. Report No. SAE 9438501.

Lin, R. C.; Cebon, D.; Cole, D. J. 1994. “An investigation of active roll control of heavy road vehicles.” Cambridge University, Engineering Department, England. Shen, Z., ed. *The Dynamics of Vehicles on Roads and on Tracks. Proceedings.* 13th IAVSD Symposium. Lisse, Swets and Zeitlinger, 1994, pp. 308–321.

Lin, R. C.; Cebon, D.; Cole, D. J. 1996. “Active roll control of articulated vehicles.” Cambridge University, Department of Engineering, England. *Vehicle System Dynamics*, Vol. 26, No. 1, July 1996, pp. 17–43.

Lin, R. C.; Cebon, D.; Cole, D. J. 1996. “Optimal roll control of a single-unit lorry.” Cambridge University, England. *Institution of Mechanical Engineers. Proceedings.* Part D: Journal of Automobile Engineering, Vol. 210, pp. 45–55.

McGee, H. W.; Strickland, R. R. 1994. “An automatic warning system to prevent truck rollover on curved ramps.” Bellomo-McGee, Inc., Vienna, Va. *Public Roads*, Vol. 57, No. 4, Spring 1994, pp. 17–22.

McLean, J. R.; Hoffmann, E. R. 1973. “The effects of restricted preview on driver steering control and performance.” Melbourne University, Department of Mechanical Engineering, Australia. *Human Factors*, Vol. 15, No. 4, August 1973, pp. 421–430. Sponsor: Australian Road Research Board, Victoria.

Palkovics, L.; El-Gindy, M. 1993. “Examination of different control strategies of heavy-vehicle performance.” National Research Council Canada, Ottawa, Ontario. Ahmadian, M., ed. *Advanced Automotive Technologies—1993. Proceedings.* New York, American Society of Mechanical Engineers, pp. 349–362.

Palkovics, L.; El-Gindy, M. 1995. “Design of an active unilateral brake control system for five-axle tractor-semitrailer based on sensitivity.” National Research Council Canada, Ottawa, Ontario. *Vehicle System Dynamics*, Vol. 24, No. 10, December 1995, pp. 725–758.

Palkovics, L.; Michelberger, P.; Bokor, J.; Gaspar, P. 1996. “Adaptive identification for heavy-truck stability control.” Budapest Technical University, Hungary. Segel, L., ed. *The Dynamics of Vehicles on Roads and on Tracks. Proceedings.* 14th IAVSD Symposium. Lisse, Swets and Zeitlinger, 1996, pp. 502–518. Sponsor: Hungarian Scientific Research and Development Fund.

Palkovics, L.; Semsey, A.; Ilosvai, L.; Koefalvy, G. 1994. “Safety problems and control of a typical European truck/tandem-trailer vehicle configuration.” Budapest Technical University, Hungary/ Hungarocamion Road Safety Division, Hungary. ISATA International Symposium on Automotive Technology and Automation, 27th. *Proceedings for the Dedicated Conference on Road and Vehicle Safety.* Croydon, Automotive Automation Ltd., 1994, pp. 303–310. Sponsor: Hungarian National Scientific Research Fund. Report No. 94SF010.

Preston-Thomas, J.; Woodrooffe, J. H. F. 1990. *A feasibility study of a rollover warning device for heavy trucks.* National Research Council Canada, Vehicle Dynamics Laboratory, Ottawa, Ontario. Sponsor: Transportation Development Centre of Canada, Montreal, Quebec. Report No. TP 10610E/TR-VDL-005.

Ranganathan, R.; Rakheja, S.; Sankar, S. 1989. “Kineto-static roll plane analysis of articulated tank vehicles with arbitrary tank geometry.” Concordia University, Montreal, Quebec, Canada. *International Journal of Vehicle Design*, Vol. 10, No. 1, pp. 89–111. Sponsor: Canada, Transport Canada, Transportation Development Centre, Montreal, Quebec. UMTRI-57246.

Rice, R. S.; Segal, D. J.; Jones, I. S. 1978. *Development of vehicle rollover maneuver.* Volume I. Final report. Calspan Corporation, Advanced Technology Center, Buffalo, New York. Sponsor: National Highway Traffic Safety Administration, Washington, D.C. Report No. CAL-ZQ-5993-V-1/ DOT/HS 804 093.

SAE J2179. 1993. *A test for evaluating the rearward amplification of multi-articulated vehicles.* Society of Automotive Engineers. Warrendale, Pennsylvania.

Strandberg, L. 1978. *Lateral stability of road tankers.* Volume I—main report. Statens Vaeg- och Trafikinstitut, Linkoeping, Sweden. Sponsor: Statens Trafiksaekerhetsverk, Solna, Sweden; Transportforskningsdelegationen, Stockholm, Sweden. Report No. 138A.

Strickland, R.; McGee, H. 1998. *Evaluation of prototype automatic truck rollover warning systems.* Bellomo-McGee, Inc., Vienna, Virginia. Sponsor: Federal Highway Administration, Office of Safety and Traffic Operations, Washington, D.C. Report No. FHWA-RD-97-124.

Sweatman, P. F. 1993. *Overview of dynamic performance of the Australian heavy vehicle fleet.* Road User Research Pty., Ltd., Williamstown, Victoria, Australia. Sponsor: Australian National Road Transport Commission, Melbourne, Victoria. Report No. Technical Working Paper No. 7.

*Technical assessment paper: relationship between rollover and vehicle factors.* 1991. National Highway Traffic Safety Administration, Washington, D.C.

*Truck and bus crash factbook.* 1995. Special report. Michigan University, Ann Arbor, Transportation Research Institute. Sponsor: Office of Motor Carriers, Federal Highway Administration, Washington, D.C. Report No. UMTRI-97-30.

Wang, Jun; Council, Forest M. 1999. “Estimating truck rollover crashes on ramps using a multi-state database.” Appalachian Regional Commission. University of North Carolina. *Transportation Research Record.* No. 1686. Wasshington D.C. Paper no. 99-0657, pp. 29–35.

Winkler, C. B. 1987. *Experimental determination of the rollover threshold of four tractor-semitrailer combination vehicles.* Final report. Michigan University, Ann Arbor, Transportation Research Institute. Sponsor: Sandia Laboratories, Albuquerque, N.M. Report No. UMTRI-87-31.

Winkler, C. B.; Fancher, P. S.; Carsten, O.; Mathew, A.; Dill, P. 1986. *Improving the dynamic performance of multitrailer vehicles: a study of innovative dollies.* Volume I—technical report. Final report. Michigan University, Ann Arbor, Transportation Research Institute. Sponsor: Federal Highway Administration, Washington, D.C. Report No. UMTRI-86-26/I/ FHWA/RD-86/161.

Winkler, C. B.; Zhang, H. 1995. *Roll stability analysis of the TARVAN.* Final report. Michigan University, Ann Arbor, Transportation Research Institute. Sponsor: Naval Air Warfare Center, Indianapolis, Ind. Report No. UMTRI-95-24.

Winkler, C., Fancher, P., Ervin, R. 1998. *Intelligent systems for aiding the truck driver in vehicle control.* The University of Michigan Transportation Research Institute. Report No. SAE 1999-01-1301. Warrendale, Pennsylvania.

## Investigation of Hip Fractures and Aortic Injuries in Motor Vehicle Crashes

Van Ee

NHTSA is sponsoring a five-year research program at UMTRI to investigate different types of injuries resulting from motor vehicle crashes with a specific focus on hip and aorta injuries. Larry Schneider, head of UMTRI's Biosciences Division, is the project director and **Chris Van Ee**, assistant research scientist in the Biosciences Division, is the principal investigator. This program brings together both analysis of CIREN investigations of real-world automotive crashes and controlled biomechanical testing in the laboratory to define and investigate automotive injury mechanisms.

While many of the biomechanical factors of the knee and femur injuries have been investigated, the important factors leading to disabling hip injuries in frontal crashes remain largely unknown. Reducing the stiffness of the knee contact point (bolster/instrument panel) has been shown to decrease th incidence of knee fractures. However, because of the lack of experimental data, it is unknown if these energy-absorbing knee bolsters are protecting the knees at the expense of the hip. Currently it is estimated that approximately 10,000 cases of hip fractures and dislocations occur each year in motor-vehicle crashes with a total annual cost 2.4 billion dollars. The objectives of this project are to define the important biomechanical factors leading to these clinically observed disabling hip injuries, and to interpret and apply these hip-injury factors to define a comprehensive injury criteria for the entire knee-thigh-hip complex. This information will be used to improve the design of both anthropomorphic test devices (i.e., crash dummies) and vehicle interiors to help reduce the frequency of crash-induced hip fractures.

Aortic ruptures have historically been a leading cause of death in motor vehicle accidents, second only to brain injuries. Aortic injuries are serious and often fatal with more than 80 percent of victims expiring before reaching the hospital. Despite its importance, the mechanisms of aortic injury are not well understood and previous experimental efforts have not been successful in reproducing aortic injuries in the laboratory. The UMTRI investigation will examine the relationships between organ positions and movements, lung pressure, and circulatory system pressure to aortic strains and failure of aortic tissue. Both static and dynamic testing is planned, with the goal of realizing an experimental model that is capable of quantifying the biomechanical factors of aortic injuries.

## Effects of Adjustable Pedals on the Distributions of Driver Seat Positions and Eye Locations

Reed

In response to concerns about the proximity of drivers to steering wheel airbags, some vehicles are now equipped with pedals that can be moved rearward on a motorized track to accommodate shorter drivers. Ford Motor Company is sponsoring in-vehicle research to examine how drivers use the new adjustment feature. Do adjustable pedals produce the desired effect of increasing the spacing between the driver and the steering wheel airbag? The principal investigator of the new project is **Matt Reed**, an assistant research scientist with UMTRI's Biosciences Division.

The study will examine the pedal adjustment behavior and driving postures of people with a wide range of body dimensions. People who have experience with adjustable pedals in their own vehicles will drive each of three Ford Expeditions equipped with different adjustable pedal configurations. Driving postures will be recorded with coordinate measurement equipment (FARO Arm) and the drivers will rate several characteristics of the pedal systems.

Data analyses will determine the effects of pedal adjustment on the distributions of driver-selected seat position and eye location (eyellipses). Regression methods developed in previous UMTRI studies will be used to estimate percentiles of the seat position distributions for comparison with the UMTRI seating accommodation model. Empirical eyellipses will be established using analogous methods and compared both within vehicle (driver-selected vs. full-forward pedal positions) and with respect to the UMTRI eyellipse model.

The results of the study will be used to improve the design of vehicles equipped with adjustable pedals. Models of the distribution of seat positions, eye locations, and clearances to the steering wheel will provide an opportunity to improve interior component locations and restraint system design.

## UMTRI BIBLIOGRAPHY

### TECHNICAL REPORTS

Cole, D. E.; Londal, G. F. 2000. *DELPHI X: forecast and analysis of the North American automotive industry. Volume 1: technology.* Michigan University, Ann Arbor, Transportation Research Institute, Office for the Study of Automotive Transportation. 206 p. Report No. UMTRI-2000-3-1.

Eby, D. W.; Vivoda, J. M.; Fordyce, T. A. 2000. *A study of Michigan safety belt use prior to implementation of standard enforcement.* Michigan University, Ann Arbor, Transportation Research Institute, Social and Behavioral Analysis Division. 54 p. Sponsored by Michigan State Office of Highway Safety Planning, Lansing. Report No. UMTRI-2000-08.

Eby, D. W.; Fordyce, T. A.; Vivoda, J. M. 2000. *Michigan safety belt use immediately following implementation of standard enforcement.* Michigan University, Ann Arbor, Transportation Research Institute, Social and Behavioral Analysis Division. 63 p. Sponsored by Michigan State Office of Highway Safety Planning, Lansing. Report No. UMTRI-2000-25.

Joksch, H. C. 2000. *Vehicle design versus aggressivity.* Michigan University, Ann Arbor, Transportation Research Institute. 136 p. Sponsored by Transportation Department, Research and Special Programs Administration, Cambridge, Mass. Report No. UMTRI-2000-22.

Kostyniuk, L. P.; Shope, J. T.; Molnar, L. J. 2000. *Reduction and cessation of driving among older drivers in Michigan: final report.* Michigan University, Ann Arbor, Transportation Research Institute, Social and Behavioral Analysis Division. 144 p. Sponsored by General Motors Corporation, Warren, Mich. Report No. UMTRI-2000-6.

Nowakowski, C.; Utsui, Y.; Green, P. 2000. *Navigation system destination entry: the effects of driver workload and input devices, and implications for SAE recommended practice.* Michigan University, Ann Arbor, Transportation Research Institute, Human Factors Division. 69 p. Sponsored by Mitsubishi Electric Corporation, Amagasaki (Japan) Report No. UMTRI-2000-20.

Reed, M. P.; Lehto, M. M.; Flannagan, M. J. 2000. *Field of view in passenger car mirrors.* Michigan University, Ann Arbor, Transportation Research Institute. 51 p. Sponsored by Michigan University, Ann Arbor, Industry Affiliation Program for Human Factors in Transportation Safety. Report No. UMTRI-2000-23.

Rumar, K. 2000. *Relative merits of the U.S. and ECE high-beam maximum intensities and of two- and four-headlamp systems.* Michigan University, Ann Arbor, Transportation Research Institute, Human Factors Division. 51 p. Sponsored by Michigan University, Ann Arbor, Industry Affiliation Program for Human Factors in Transportation Safety. Report No. UMTRI-2000-41.

Sayer, J. R.; Mefford, M. L.; Huang, R. 2000. *The effect of lead-vehicle size on driver following behavior.* Michigan University, Ann Arbor, Transportation Research Institute, Human Factors Division. 37 p. Sponsored by Michigan University, Ann Arbor, Industry Affiliation Program for Human Factors in Transportation Safety. Report No. UMTRI-2000-15.

Schumann, J. 2000. *Post-mounted delineators and perceptual cues for long-range guidance during night driving.* Michigan University, Ann Arbor, Transportation Research Institute, Human Factors Division. 21 p. Sponsored by Michigan University, Ann Arbor, Industry Affiliation Program for Human Factors in Transportation Safety. Report No. UMTRI-2000-42.

Sivak, M.; Flannagan, M. J.; Schoettle, B.; Nakata, Y. 2000. *Simultaneous masking of front turn signals by headlamps and other front lamps.* Michigan University, Ann Arbor, Transportation Research Institute, Human Factors Division. 149 p. Sponsored by Michigan University, Ann Arbor, Industry Affiliation Program for Human Factors in Transportation Safety. Report No. UMTRI-2000-44.

Streff, F.; Spradlin, H. 2000. *Driver distraction, aggression, and fatigue: a synthesis of the literature and guidelines for Michigan planning.* Michigan University, Ann Arbor, Transportation Research Institute, Social and Behavioral Analysis Division. 40 p. Sponsored by Michigan State Office of Highway Safety Planning, Lansing. Report No. UMTRI-2000-10.

## JOURNAL ARTICLES

Gillespie, T.; Karamihas, S. 2000. "Simplified models for truck dynamic response to road inputs." Michigan University, Ann Arbor, Transportation Research Institute, Engineering Research Division. 12 p. *Heavy Vehicle Systems*, Vol. 7, No. 1, 2000, pp. 52–63.

Maio, R. F.; Shope, J. T.; Blow, F. C.; Copeland, L. A.; Gregor, M. A.; Brockmann, L. M.; Weber, J. E.; Metrou, M. E. 2000. "Adolescent injury in the emergency department: opportunity for alcohol interventions?" Michigan University, Ann Arbor, Section of Emergency Medicine/ Michigan University, Ann Arbor, Transportation Research Institute, Social and Behavioral Analysis Division/ Veterans Administration Hospital, Ann Arbor, Mich. 6 p. *Annals of Emergency Medicine*, Vol. 35, No. 3, Mar 2000, pp. 252–257.

Nowakowski, C.; Green, P.; Kojima, M. 2000. "How to design a traffic-information web site: a human factors approach." Michigan University, Ann Arbor, Transportation Research Institute, Human Factors Division. 11 p. *ITS Quarterly*, Vol. 8, No. 3, Summer 2000, pp. 41–51.

Sivak, M.; Flannagan, M. J.; Miyokawa, T. 1999. "Quantitative comparisons of factors influencing the performance of low-beam headlamps." Michigan University, Ann Arbor, Transportation Research Institute, Human Factors Division. 9 p. *Lighting Research and Technology*, Vol. 31, No. 4, 1999, pp. 145–153. Sponsored by Michigan University, Ann Arbor, Industry Affiliation Program for Human Factors in Transportation Safety.

Waller, P. F.; Olk, M. L.; Shope, J. T. 2000. "Parental views of and experience with Michigan's graduate licensing program." Michigan University, Ann Arbor, Transportation Research Institute. 7 p. *Journal of Safety Research*, Vol. 31, No. 1, Spring 2000, pp. 9–15. Sponsored by National Highway Traffic Safety Administration, Washington, D.C.

## CONFERENCE PAPERS

Fancher, P. S.; Baraket, Z. 2000. "Manual and automatic control of the longitudinal dynamics of individual motor vehicles." Michigan University, Ann Arbor, Transportation Research Institute. 11 p. Froehling, L., ed. *The Dynamics of Vehicles on Roads and on Tracks. Proceedings of the 16th IAVSD Symposium.* Lisse, Swets and Zeitlinger, 2000. Pp. 270–281.

Winkler, C. B.; Ervin, R. D.; Hagan, M. R. 2000. "On-board estimation of the rollover threshold of tractor semitrailers." Michigan University, Ann Arbor, Transportation Research Institute, Engineering Research Division. 11 p. Froehling, L., ed. *The Dynamics of Vehicles on Roads and on Tracks. Proceedings of the 16th IAVSD Symposium*. Lisse, Swets and Zeitlinger, 2000. Pp. 540–551.

## To subscribe to the *UMTRI Research Review*

Complete the form below and send it with a check for $35 made out to the University of Michigan. This entitles you to a one-year subscription to the UMTRI Research Review.

Name ____________________________________________ Date __________

Title ____________________________________________________________

Organization _____________________________________________________

Address __________________________________________________________

City __________________________________ State _____ Zip ____________

Mail your check for $35 and the form above to:

Monica Milla, Editor
UMTRI RESEARCH REVIEW
University of Michigan Transportation Research Institute
2901 Baxter Rd
Ann Arbor MI 48109-2150