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Full-Scale Rollover Testing of Commercial Cargo-Tank Vehicles

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Abstract

Tests were conducted in which a unit tank truck and a tractor-semitanker combination were subjected to full-scale rollovers. The unit truck was equipped with roll bars closely matching the profile of the vehicle and was rolled in four different manoeuvres of varying severity. The combination vehicle was rolled once in a very severe manoeuvre. The instrumentation used allowed detailed analysis of tank motions before, during, and after rollover.

Summary results are presented for all five rollovers. Two of the rollover events, the least severe rollover of the unit truck and the rollover of the combination vehicle, are examined in great detail.

Introduction

US federal regulations require cargo-tank motor vehicles to have “rollover damage protection devices” that are intended to protect valves and other fixtures in the event of a rollover [1]. In 1992, a Special Investigation Report by the National Transportation Safety Board (NTSB) formally recommended that forces acting on rollover protection devices be modelled and analysed, and that new performance standards be promulgated based on this analysis [2].

In response, the Federal Highway Administration (FHWA) funded a simulation study at the University of Michigan Transportation Research Institute (UMTRI) [3]. One part of this study produced 126 simulations of rollovers for each of seven tank vehicles: two unit trucks and five tractor-semitrailer combinations. A variety of manoeuvres at different speeds and with different loads were simulated in an attempt to span a broad range of rollover severity. The description of the simulated vehicles included information on the outer profile of the cargo tank. The results of the simulations were expressed in terms of the angular orientation of the tank and its six components of velocity at the moment of ground impact.

Following the simulation study, the Federal Motor Carrier Safety Administration (FMCSA) funded UMTRI, subcontracted through Battelle Memorial Institute, to conduct full-scale vehicle tests similar to a small sample of the simulated rollovers for the purpose of verifying the results of the simulation study [4]. During these tests, conducted in the late summer and early autumn of 2005, a three-axle tank truck was subject to four rollovers, and a five-axle tractor-semitanker was rolled once. The test vehicles were equipped with a GPS-aided, inertial navigation system that provided detailed descriptions of the tank motion before, during, and following the rollover. This paper presents summary results for the five rollovers and examines two of the experiments in detail.

Test vehicles

The two test vehicles appear in figure 1. The three-axle unit truck was designed for urban de-

Fig. 1: The test vehicles

Fig. 2: The unit truck with roll bars on the UMTRI tilt table

livery of petroleum fuels. The centre of its three axles is the drive axle equipped with dual tyres. The third axle is an air-lift tag axle, also with dual tyres. The tractor-semitrailer combination has the typical North American configuration of a 6x4 tractor pulling a two-axle semitrailer. All axles other than the tractor's steer axle use dual tyres. The experimental design called for rolling the unit truck several times, replicating up to five of the simulated rollovers. Hence, this vehicle was armoured with very sturdy roll bars, front and rear, that closely matched the profile of the tank, the topside protection rails, and the cab, figure 2[1]. The tank of the unit truck contained five separate compartments, the centre three of which were filled with water for testing while the front and rear were left empty. This, along with the extra mass of the roll bars resulted in a total mass (16 406 kg), centre of gravity (cg) position, and moments of inertia very similar to the unmodified vehicle with a full load of petroleum fuel.

The semitrailer had been used for the transport of hydrochloric acid. The experimental design called for only one rollover of this vehicle, so no attempt was made to protect it from rollover damage. A full load of water resulted in a total vehicle mass of 32 696 kg, or about 10 % under its design operating mass.

Both vehicles were subject to tilt-table testing, figure 2, that established their static rollover thresholds as 0.48 g lateral acceleration for the unit truck and 0.40 g for the combination vehicle[2].

The core of the instrumentation used was an Oxford Technical Solutions RT3000 inertial navigation system. For test of both vehicles, this unit was mounted on the underside of the tank, as near to directly below the cg as possible. The GPS antenna was mounted directly above on top of the tank. The unit provided detailed monitoring of all six components of tank motion before, during, and after rollover. The combination vehicle was also equipped with a yaw rate transducer on the tractor and a yaw articulation-angle sensor. These, along with the inertial navigation system, allowed adequate monitoring of the trac-

[1]Using protective roll bars clearly altered – indeed, eliminated – the crush of the tank and cab upon striking the ground. However, the primary purpose of the experiments was to determine attitude and velocities *at the moment of impact*. The roll bars, particularly those at the front and rear of the tank were designed to rather precisely match the profile of the original vehicle.

[2]The terms used for angles, angular velocities, linear velocities and accelerations throughout this paper all conform to the definitions given in [5]. Except for polarity, they also generally conform to the definitions that will appear in the forthcoming version of ISO 8855, expected to be published in 2009.

tor motion prior to the rollover. Both vehicles were equipped with steering-wheel angle transducers.

All data signals were recorded continuously using an UMTRI-built digital data-acquisition system (DAS). Data signals were also used as feedback for the closed-loop steering control of the vehicle, implemented by the DAS computer through control of a DC servomotor on the input shaft of the power steering gear. The controller steered the vehicle along predetermined paths, defined in GPS coordinates and stored in DAS memory. The control system also managed clutch, brake, and cruise control actuation, engine kill, and a variety of safety abort functions based on on-board checks and external radio links to test-site observers.

Test site and procedures

The tests were conducted at the Smithers Winter Test Center near Raco, Michigan (46.352 N, 84.815 W), figure 3. The facility is a former air field with three runways, each approximately 1.6 km by 100 m. All tests runs started from the northwest intersection with the vehicle proceeding southeast. Crashes took place just before reaching the southern intersection, which provided a large area for the trucks to continue sliding after they rolled over.

Both trucks were equipped with manual transmissions. No attempt was made to automatically shift gears. Rather, before the run the transmission was put into a gear appropriate for the crash speed and the clutch was held disengaged by an air actuator. The test vehicle was initially pushed up to a speed acceptable for that gear at which time the clutch and cruise control were engaged and the vehicle proceeded along the 1.6 km runway, obtaining the desired test speed under its own power and following the programmed path. The paths, of course, terminated in a manoeuvre designed to generate lateral accelerations at or in excess of the static rollover threshold.

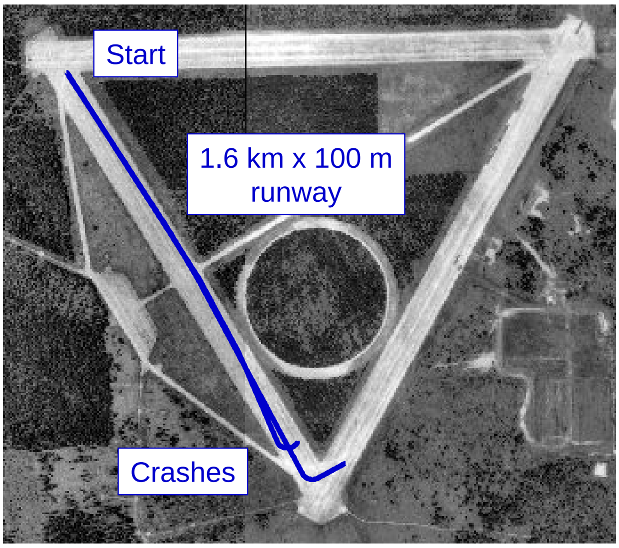

Fig. 3: Smithers Winter Test Center, Raco, Michigan

The five rollovers

Table 1 lists the six manoeuvres conducted during the test program that resulted in five rollover events. The first attempt to roll the unit truck was a constant turn of radius 30.5 m at 12.1 m/s (43.5 km/h). These conditions were intended to produce lateral acceleration slightly in access of the vehicle's rollover threshold as determined during tilt-table testing. However, the loss of speed immediately upon lifting the wheels of the drive axle prevented actual rollover. The ma-

Roll No	Vehicle	Manoeuvre Description
–	Unit truck	12.1 m/s (43.5 km/h) 30.5 m-radius
1	Unit truck	13.9 m/s (49.9 km/h) 30.5 m-radius
2	Unit truck	17.9 m/s (64.4 km/h) 30.5 m-radius
3	Unit truck	20.1 m/s (72.4 km/h) Step steer
4	Unit truck	22.4 m/s (80.5 km/h) Swerve (sine steer)
5	Combination	20.6 m/s (74.0 km/h) 30.5 m-radius

Table 1: The rollover manoeuvres

No	Vehicle	Manoeuvre	Test Speed m/s	Vehicle orientation degrees Roll	Pitch	Yaw	Angular velocities degrees/s ω_{Xv}	ω_{Yv}	ω_{Zv}	Linear velocities m/s v_X	v_Y	v_Z
-	Unit	30.5 m turn	12.1	(no rollover)								
1	Unit	30.5 m turn	13.9	90.0	−0.4	−93.0	138.4	−22.8	9.9	9.69	4.60	2.59
2	Unit	30.5 m turn	17.9	92.7	2.2	−45.9	136.5	−34.9	−7.6	14.30	7.59	2.59
3	Unit	step	20.1	91.0	1.2	−47.2	118.7	−21.5	−1.1	17.31	7.89	2.99
4	Unit	Swerve	22.4	87.8	1.2	−35.3	121.8	−15.9	−1.7	18.99	7.50	2.59
5	Semi	30.5 m turn	20.6	107.8	−0.3	−28.8	141.2	−27.7	30.2	17.50	7.59	2.71

Table 2: Angular orientation and velocity components of the tank at the moment of impact

noeuvre was repeated at a slightly higher speed and resulted in what can be described as a rollover of minimum severity. The unit truck was rolled three more times in successively more severe manoeuvres (i. e., at higher projected lateral accelerations and faster speeds). The tractor-semitrailer combination was rolled once in a very severe manoeuvre.

Table 2 presents the primary results of these tests, namely the angular orientation and velocity components of the tank at the instant of first impact with the road surface in each case. These results compared quite well with those of the simulation runs of similar vehicle manoeuvres from the previous study. More details on these results can be found in [4].

Detailed examination of two rollovers

This section examines the least and the most severe of the five rollovers listed in table 1, namely, the first rollover of the unit truck and the rollover of the tractor-semitrailer combination.

Minimal-severity rollover of the unit truck

The rollover to be examined took place in a 30.5 m, constant-radius turn at a speed just adequate to cause rollover. Before examining the rollover itself, however, we examine data for the preliminary run, conducted at a slightly lower speed at which rollover did not take place.

The static rollover threshold of the unit truck had been determined by tilt-table testing to be 0.48 g. Travel on a curve of 30.5 m radius at 12.0 m/s would, in theory, generate 0.48 g lateral acceleration. The preliminary run was conducted with an initial speed of 12.1 m/s (43.5 km/h). Time histories of lateral acceleration, roll angle, and speed from this run appear in figure 4. The reference lateral acceleration of 0.48 g is also shown. The data show that, as the vehicle transitions from straight travel onto the curve, lateral acceleration rises toward the rollover threshold and the vehicle roll angle develops, as expected, slightly lagged with respect to acceleration.

The light-side tyres of the non-driving, tag axle lift from the road surface at a roll angle of about 1°. At a roll angle of slightly more than 6°, the tyres of the drive axle are so lightly loaded that they lose drive traction. This, along with the drag associated with hard cornering, causes the speed to fall off before lateral acceleration reaches the rollover threshold. At this point, the cruise control releases the throttle to avoid over speeding the engine, and lateral acceleration and

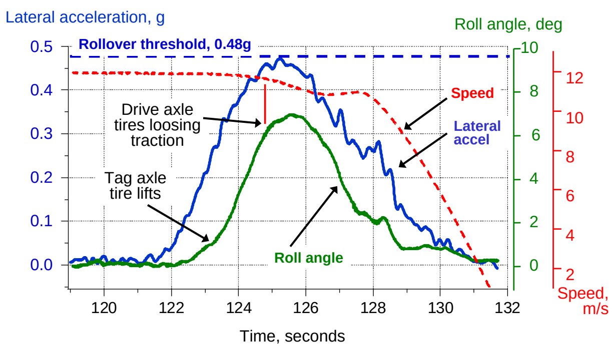

Fig. 4: Motion data – preliminary run of the unit truck

Fig. 5: The first rollover of the unit truck

roll angle decline. Shortly afterwards (at about 128 s), the run is aborted and the brakes are applied.

In order to provide sufficient momentum to achieve the rollover threshold after drive thrust was lost, the next run (i. e., the first rollover run) was conducted at an initial speed of 13.9 m/s (49.9 km/h. Figure 5 shows the vehicle as it was rolling over in this test. In the first picture to the left, the light-side tyres of both rear axles have lifted from the road. Hence, at this time, lateral acceleration has already risen to the rollover threshold, and full rollover is virtually inevitable [6].

In the second picture, the tyre of the steer axle has also lifted. In the third, the vehicle's cg is very near the apex height it attained during the rollover. In the fourth photo, the vehicle is "falling" toward the ground and is close to striking the ground. Note that all of the heavy-side tyres remained on the ground. This is a characteristic of only the mildest of rollover manoeuvres [3]. In the last photo, the vehicle has struck the ground and has rolled to slightly more than 90°.

Fig. 6: Skid marks from the first rollover of the unit truck

Figure 6 shows the tyre skid marks made during this event, including the clear imprint of the drive-axle wheel where it struck the ground. Note in particular, that the mark from the drive axle tyre comes right up to the point of drive-wheel strike. Moreover, the mark of the steer-axle tyre passes the wheel-strike mark and, although not in the picture, this mark ends at a distance ahead of the wheel mark that is virtually equal to the wheelbase. Clearly the tyres are marking the ground even as they approach a 90° inclination angle. All of this is clear evidence of a minimal rollover event.

Time histories of acceleration, roll, and speed from this rollover appear in figure 7. The data show that, as the manoeuvre began, lateral acceleration rose to the rollover threshold of 0.48 g

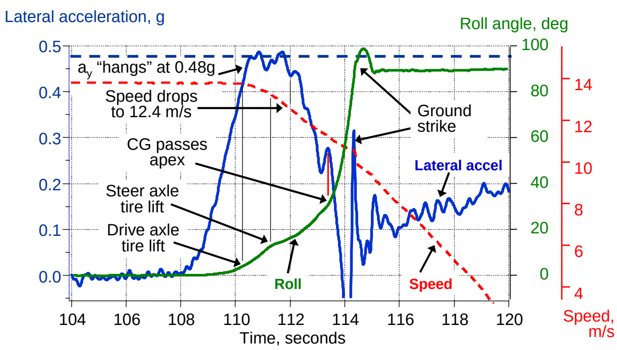

Fig. 7: First rollover of the unit truck – motion data

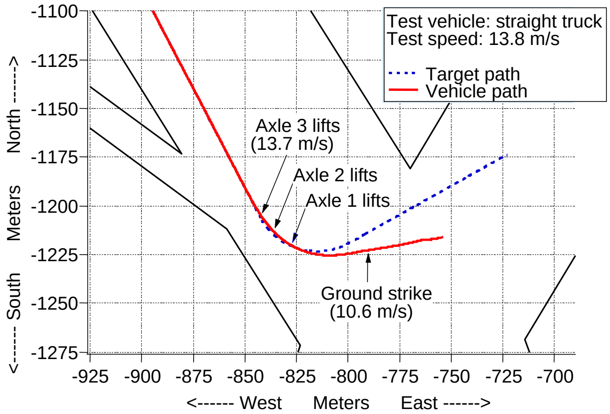

Fig. 8: First rollover of the unit truck – path

while speed remained slightly above 13 m/s. The vehicle rolled gradually during this period. The drive-axle tyres lifted from the ground at about 6° of roll, and the steer-axle tyre lifted 0.75 s later at a roll angle of about 13°. During this period, the lateral acceleration of the cg of the vehicle dwelled near the static rollover threshold until the roll angle increased to the vicinity of 20°.

At this point, the cg had risen significantly and at the same time was starting to accelerate rather significantly outboard relative to the wheelbase, i. e., opposite the lateral acceleration of the turn. Hence, lateral acceleration at the cg began to fall significantly. Shortly thereafter, the vehicle had rolled to more than 30° and the cg passed its apex height.

The cg then fell under the influence of gravity; lateral acceleration declined at a faster rate and even went negative. Upon striking the ground at almost exactly 90° of roll, lateral acceleration, of course, spiked back onto the graph. The vehicle briefly rolled a few degrees more and then settled back to 90° [3].

The entire process between the initiation of the turn and ground strike took about 6.2 s. From the time the drive axle lifted – when rollover was inevitable – until the instant of ground strike took 3.7 s. Moreover, by the time ground strike occurred, the horizontal speed of the vehicle had fallen substantially from the speed at which it entered the curve, this despite the fact that there was no braking and the cruise control attempted to maintain speed until the drive axle lost traction.

Figure 8 shows a scale drawing of the target path and the path of the vehicle's cg during this rollover. The vehicle had changed heading only about 5.5° from its original path when the drive axle lifted and eventual rollover was established. Yet, by the time ground strike took place, the vehicle track had rotated an additional 54.5° and the vehicle had travelled about 50 m. The horizontal speed at the time of ground strike was 10.6 m/s or 3.1 m/s slower than the speed on entry to the turn.

Figure 9 shows time histories of horizontal speed and roll that reveal more detail about the vehicle's deceleration. The vehicle entered the 0.48 g turn at 13.7 m/s. During the turn, the vehicle decelerated at an average 0.09 g. At the moment of impact with the ground, speed briefly dropped precipitously. For this brief period, the normal force between the vehicle and road surface far exceeded the weight of the vehicle so that frictional drag was, momentarily, very high. (Recall that this vehicle was armoured with very

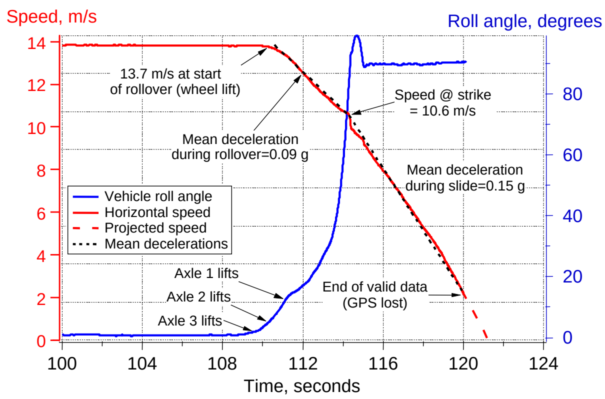

Fig. 9: First rollover of the unit truck – speed and roll

[3]The RT3000 inertial unit was mounted in a unique manner that held it quite rigidly with respect to the vehicle chassis under normal loading. However, to prevent damage to the unit, the rigid mounting was designed to break under high shock loads with the RT3000 then constrained by surrounding protective foam. Hence, after ground impact, lateral acceleration data in particular should be considered approximate [4].

Fig. 10: Rollover of the tractor-semitrailer

stout roll bars and there was virtually no crush involved in this event. Hence, the event was both briefer and more intense than it would have been had the vehicle deformed.) After the impact event, the normal force between vehicle and road returned essentially to the weight of the vehicle. While sliding on the Portland cement concrete surface, the vehicle decelerated at an average of 0.15 g.

Severe rollover of the tractor-semitrailer

The tractor-semitrailer was rolled only once, because it was understood that, while the trailer might be protected in a rollover, it would be impossible to protect the tractor (particularly the tractor frame) from significant damage without substantially altering the roll behaviour of the combination. The test that was conducted on this vehicle involved an attempt to follow the 30.5 m radius turn at 20.4 m/s. This radius and speed imply a lateral acceleration of about 1.4 g, which is, of course, far in excess of the vehicle's rollover threshold of 0.40 g.

Figure 10 shows the rollover of the tractor-semitrailer. Starting from the left, the vehicle was just beginning to roll; light-side tyres on both the trailer and the tractor drive axles have lifted from the ground. As the trailer tyres are considerably higher off the ground, it is apparent that the trailer axles lifted first, as is typical in tractor-semitrailer rollovers [6].

In the second photo, the cg of the trailer was passing through its apex, and in the third photo, the trailer was falling toward the ground. From this photo it becomes apparent that the trailer had rolled sooner and farther than the tractor cab. This is typical of tractor-semitrailer rollover and happens because

- the tractor frame is very compliant in torsion about its longitudinal axis, and
- the forward section of the tractor, whose massive driveline components sit much lower than the cg of the trailer, is quite a bit more stable in roll than the trailer.

Hence, it is typical that the trailer, sitting on the tractor drive axles and its own axles, rolls over "first" and then "drags" the forward section of the tractor over after "winding up" the tractor frame. In the final picture of figure 10, the vehicle has come to rest. Note that the rotational momentum developed in the very beginning of the turn caused the vehicle to rotated nearly 270° anti-clockwise in the plan view.

Figure 11 presents the time histories of lateral acceleration of the tractor and the trailer, and roll angle and speed of the trailer. Except for lateral acceleration of the tractor, these data derive directly from the inertial navigation system. Lateral acceleration of the tractor, however, is only estimated from the product of speed and trac-

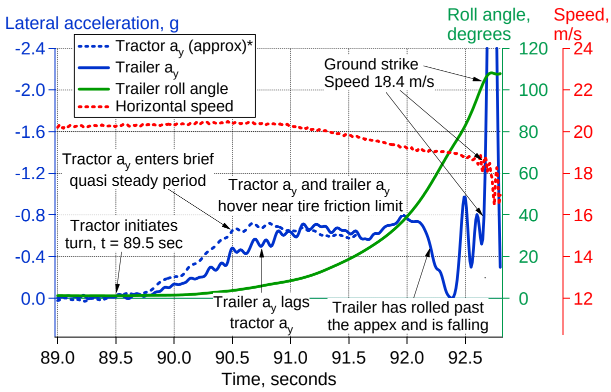

Fig. 11: Rollover of the tractor-semitrailer – motion data

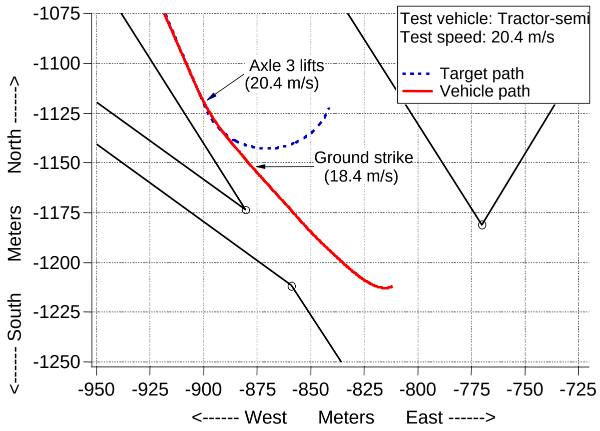

Fig. 12: Rollover of the tractor-semitrailer – path

tor yaw rate. This estimated value is truncated at the point where tractor behaviour becomes highly dynamic and tractor roll angle begins to increase rapidly.

At the beginning of the manoeuvre, the data show the lateral acceleration of the tractor leading that of the trailer as they both rose to a nominal level of about 0.70 – 0.72 g where they dwelled for a bit longer than a full second. During the same period, the trailer was rolling to about 25°. During this portion of the manoeuvre, the lateral acceleration of the vehicle was being limited by the maximum tyre/road friction coefficient.

The limit of 0.72 g may, at first, seem a bit low for truck tyres on dry Portland cement concrete, but at this point the light-side tyres of the tractor drive axles and of the trailer axles are off the ground and the heavy-side tyres are operating

- at nearly twice their rated load and
- at unusually high inclination and slip angles.

Under these conditions, a friction coefficient in the range of 0.72 is about all that can be expected. After the cg of the trailer passed through its apex, lateral acceleration of the trailer fell rapidly. From about 92.3 s until the time of ground strike, there was a good deal of "confusion" in the lateral acceleration signal as the trailer is influenced by the "windup" and "release" of the tractor frame.

Note that at the time of ground strike, the trailer had rolled well past 90° – up to 104°. This was partly because of the narrow profile of this tank, but also because, in severe rollovers, the heavy-side tyres on the tractor drive and trailer axles often leave the ground late in the process as, in a manner of speaking, the trailer spins in roll faster than the cg falls toward Earth [3, 7]. This entire rollover event took place much more rapidly than the rollover of the unit truck: in this case, ground strike took place about 3.2 s after the initiation of the turn. Nevertheless, because of the high drag of the severe turn, the vehicle still lost 2.0 m/s of speed before hitting the ground at a speed of 18.4 m/s.

Figure 12 presents the track of the trailer cg during the rollover. The rollover was so severe and rapid that the track angle changed only slightly from the initial path. The small hook in the path near its end resulted from the fact that the horizontal speed of the vehicle was rapidly approaching zero, but the vehicle was continuing to rotate in the plan view as it slid, and the cg of the trailer was not at the centre of this rotation.

Figure 13 presents time histories of roll and speed for this rollover. During the turn, prior to ground strike, the average longitudinal deceleration was about 0.11 g. This was higher than the 0.09 g observed for the unit truck, but of course, this turn was far more severe. Once again, a precipitous drop in horizontal speed took place

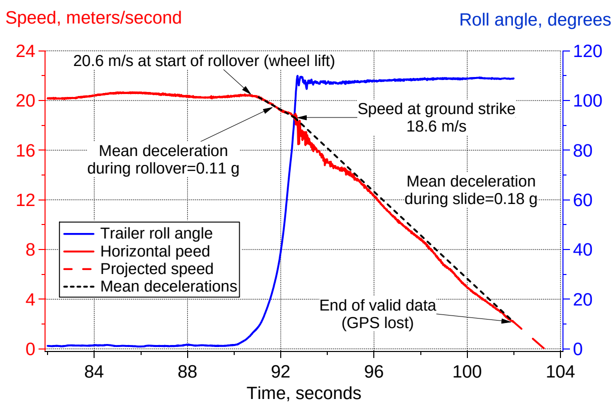

Fig. 13: Rollover of the tractor-semitrailer – speed and roll

at the moment of ground strike. The tractor-semitrailer was a normal vehicle that did not have the very stiff, protective roll bars like the unit truck had. Hence, a good deal of crush took place on impact and the disturbance in speed due to ground strike was drawn out longer in time. The average deceleration during the sliding portion of the event was 0.18 g.

Summary

UMTRI conducted five full-scale rollover tests of commercial cargo-tank highway trucks during the late summer and early autumn of 2005. A three-axle unit truck that was equipped with protective roll bars was subjected to four rollovers. A five-axle tractor-semitrailer was subjected to a single rollover.

Summary data from all five rollovers were presented. Two of the rollovers – the least and the most severe, which involved the unit truck and the combination vehicle, respectively – were closely examined. Quantitative measures of vehicle position, speed, lateral acceleration, and roll angle were used to describe the rollover process in great detail.

Acknowledgements

The primary contractor to the FMCSA for the project under which the described tests were conducted was Battelle Memorial Institute. Mr Douglas Pape of Battelle was the primary liaison for Battelle with UMTRI who oversaw the project from a technical point of view and was a delightful individual with whom to work. Doug and his assistants were on site for all testing and provided all of the video and much of the photographic coverage of the testing. The Battelle crew also provided strain-gauge instrumentation and recording on the semitanker independent of UMTRI's instrumentation.

Regional Enterprises of Hopewell, Virginia, donated the semitrailer to the UMTRI. Dana Corporation of Kalamazoo, Michigan, allowed use of their tractor to pull the semitrailer through the crash.

Last but not least, special thanks to the UMTRI staff including Michael Hagan and his assistants, who developed the DAS and control system, and to John Koch, Ben Powell, and Dan Huddleson who did the real work at the test site.

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