SHORT PAPER PCB 11-2006

SPEED ANALYSIS IN SLIDE-OUT AND ROLLOVER ACCIDENTS

ENGINEERING EQUATIONS, INPUT DATA AND MARC 1 APPLICATIONS

By:

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Throughout the Short Papers we will extensively reference the 5th Edition of “Motor Vehicle Accident Reconstructions and Cause Analysis” by Rudolf Limpert, the “Accident Reconstruction Catalog” (ARC) CD, as well as the MARC 1 software.

1.0 INTRODUCTION

On a level roadway, a motor vehicle will be able to travel through a turn safely and at a relatively high speed as long as the changes in vertical wheel loads are at a minimum. When the speed reaches a critical level, one of two limits will be reached. One limit exists when the vehicle slides out, and then either over the front or rear tires, or the other limit, when the vehicle rolls over on its side usually followed by additional roll motions.

The slide-out limit is reached, when the slip angle on the outside tire reaches a limit value. An example is illustrated in Figure 22-7 of the Text for an older tire model. For example, a slip angle of 9 degrees will produce a maximum side force of approximately 650 lb for a normal force of 1200 lb. If the normal or vertical force of a tire increases due to lateral load transfer, then the side force decreases, or to maintain the required side force, in our example the slip angle must increase to a value greater then 9 degrees. Depending on tire design, inflation pressure, and road surface, the tire will reach its limit some where between 15 to 20 degrees. If the driver is also braking while turning, the tire will reach its limit tire slip angle at lower values then the non-braked tire.

As explained in Section 22-5(a) of the Text, the slip angle of a tire is the angle between the plane of the tire/rim and the velocity vector direction of the tire contact patch, that is, the direction in which the tire is actually moving (see Figure 22-5 of the Text).

The rollover limit is reached when the vertical or normal wheel loads of both the front and rear inner wheels become zero, that is, both inner wheels lift off the ground. The entire vehicle weight is now carried by the outer wheels, which usually produce heavy dark tire pavement markings by the outer tires.

Slide-out should occur before rollover, since in general, it is a less dangerous loss of control maneuver. However, with current design practice and dry road tire friction coefficients allowing high lateral accelerations, vehicles with relatively high center-of-gravities in relationship to track width will reach their rollover limit before they slide out.

2.0 SPEED FROM YAW MARKS

2.1. DERIVATION OF EQUATION

The derivation of the relationship between centripetal acceleration, velocity and turning radius is shown in Section 20-2(a)(6) of the Text. We simply considered an object being swung around by a string in a circular path with radius r. The force holding or forcing the object to stay in the circular path is the string force. Equation 20-60 states that the velocity squared divided by path radius equals centripetal acceleration. Although the magnitude of the velocity may remain constant, the change in direction of the velocity vector requires a force.

In the case of a turning motor vehicle, the “string force” is replaced by the side forces of the tires. If the turning maneuver is sufficiently severe for the tires to mark the pavement, then the tires are operating at their side force limit. The summation of all maximum side forcesof the tires cannot exceed the product of vehicle weight and tire-road friction coefficient as discussed in Section 27-3 of the Text. All vehicle dimensions and systems are "collapsed" into a single mass point.

Replacing lateral acceleration a_y by tire-road friction coefficient f yields the standard equation for speed from yaw marks as:

$$V = 3.87\,(f\,r)^{1/2}\ ;\ \text{mph} \qquad (1)$$

where: f = tire-road friction coefficient in side direction
r = radius of circular path of vehicle's center-of-gravity, ft

In Section 20-4(d) of the Text ranges of recommended f-values as a function of the braking skid traction coefficient are shown.

The reader is encouraged to carefully study the limits of application of Equation 1 as discussed in the Text. One of the critical factors is, that the turning maneuver of the vehicle must have been initiated by the driver by a steering input, and not by rear tire defect or by bumping including pit maneuver by another car, or by premature rear brake lockup. Equation 1 is very simple and often used, yet has a great potential for misuse as will be explained later.

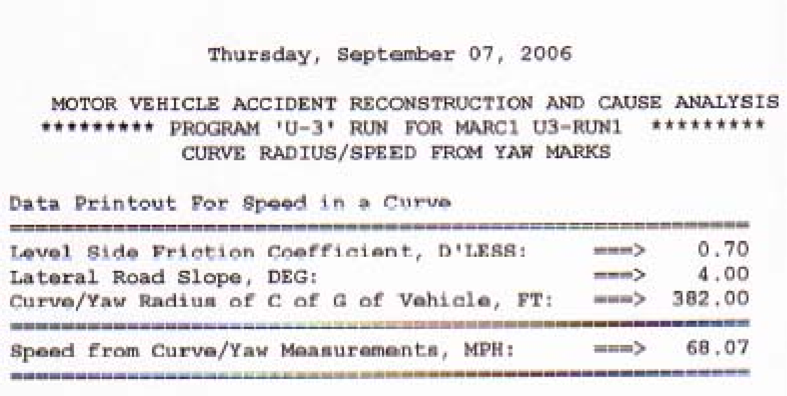
Equation 1 can be expanded to include the effects of super elevation or cross slope α of the roadway as shown:

$$V = 3.87\,(r(f_h + \tan\alpha)/(1 - f_h\tan\alpha))^{1/2}\ ,\ \text{mph} \qquad (2)$$

where: f_h = horizontal (level) road coefficient of friction
r = radius of circular path of center-of-gravity of vehicle, ft
α = slope of super elevation, degrees (use + sign favoring higher speed, otherwise minus sign)

Comparison of Equations 1 and 2 indicates that the quotient term in Equation 2 is the effective lateral acceleration including the effects of super elevation.

Consider a car traveling in a curve with a center-of-gravity path radius of 382 feet with a super elevation of 4 degrees favoring higher speed. If the level side tire-road friction coefficient is 0.7, the effective lateral acceleration is 0.8095 for a slope of 4 degrees. Equation 2 yields a limit turning speed of 68 mph. The same limit turning speed is obtained with MARC 1 U3 RUN 1 as shown. For no super elevation and f = 0.7 the limit speed is 63.3 mph.



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                 Thursday, September 07, 2006

   MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
  ********* PROGRAM 'U-3' RUN FOR MARC1 U3-RUN1  *********
               CURVE RADIUS/SPEED FROM YAW MARKS

Data Printout For Speed in a Curve
==========================================================
Level Side Friction Coefficient, D'LESS:      ===>    0.70
Lateral Road Slope, DEG:                      ===>    4.00
Curve/Yaw Radius of C of G of Vehicle, FT:    ===>  382.00
==========================================================
Speed from Curve/Yaw Measurements, MPH:       ===>   68.07
==========================================================
```

2.2. ACCIDENT SCENE AND VEHICLE DATA COLLECTION

2.2.1. Lateral Acceleration or Tire-Side Friction Coefficient

The lateral acceleration or limit friction coefficient does not vary much for a given roadway. For example, for a dry roadway the limit lateral acceleration may vary between 0.6 to 0.8g. The specific lateral acceleration is determined by the inflation pressure(s) of the tire(s) that mark the pavement as well as vehicular factors such as suspension design, shock absorber performance, vehicle loading and tire design. Lower inflation pressures produce tire yaw marks at lower lateral accelerations than a properly inflated tire will. The expert must measure inflation pressure and examine the rim and tire carefully. The outer tread edge may reveal excessive edge wear. Often, significant edge wear and rim-to-ground contact are found on the outboard (front) tire of a vehicle involved in a friction roll. Under certain conditions it may lead to a loss of inflation pressure due to partial de-beading.

2.2.2. VEHICLE CURVED PATH DUE TO STEERING INPUT BY DRIVER

The circular path radius is of critical importance for an accurate speed-from-yaw marks analysis. In many cases investigators, law enforcement and experts have calculated incorrectly high speeds based upon a wrong path radius. The speed-from-yaw marks equation can only be applied in cases where the driver produced a curved vehicle path by having turned the steering wheel. Only under these conditions will all four tires be involved in producing tire side forces, and hence, slip angles that may mark the pavement when the slip angles are near or at their limit of adhesion. As a minimum, in a left turn, for example, the outside right front and right rear tires should mark the pavement as illustrated in Figure 20-22 of the Text. Once the two outside tire produce marks with an approximately constant distance between them, the limit turning maneuver can be considered as having reached a quasi steady state process with each tire contributing its proper share of side forces.

The path of the tire mark must be measured and documented. Chapter 37 of the Text presents several methods for measuring accident scene data. If appropriate, the roadway curve(s) prior to the accident curve should also be measured for comparison purposes.

This information may answer the question why the vehicle lost control in the accident curve and not in the prior curve(s).

2.2.3. VEHICLE CURVED PATH DUE TO BUMPING

When the accident scene shows tires marks similar to those depicted in the accident scene diagram of Figure 20-25 of the Text and the scene photographs in Figure 20-26, the speed-from-yaw marks analysis must not be applied. In this accident a 1992 Ford Escort was bumped in the rear by a van causing the Ford to lose its directional stability without its driver turning the steering wheel. The right rear tire began to mark the pavement in basically a straight line at the point marked A in Figure 20-25. The subsequent left-direction curved path of the Ford was not caused by driver steering, and consequently, does not qualify as a yaw mark for speed calculation purposes. The radius would be improperly large resulting in speeds that are too large, and in some actual cases, beyond the horsepower capacity of the vehicle.

An actual case where a dump truck bumped a car is illustrated in ARC Section 2.14. The car was traveling in an area with a speed limit of 45 mph when it was bumped in the left rear corner by a passing dump truck. The right rear car tire began to mark the pavement as indicated in the area marked by red pen (Photo number 42; not to be confused with unrelated dual truck tire skid marks). The associated large path radius must not be used for speed analysis.

2.2.4. VEHICLE CURVED PATH DUE TO REAR TIRE FAILURE

In another single vehicle accident leading to rollover, an Isuzu Amigo lost its directional control when the right rear tire lost its tread. The speed at the moment of tread separation was approximately 65 mph established by an eyewitness following directly behind the Amigo. The accident scene photographs are shown in ARC Section 1.1.8. The curved right rear tire path was not the result of driver steering. The loss of stability was caused by a sudden loss of rear tire cornering stiffness resulting in a left-hand monotone directional instability. The right rear tire mark must not be used for a speed-from-yaw mark analysis.

2.2.5. VEHICLE CURVED PATH DUE REAR BRAKE LOCKUP

Locking of the rear brakes before the front will cause the vehicle to lose its directional stability without steering input by the driver. See Section 24-4(f) for braking instability. Figure 37-6 of the Text shows the tire markings of a passenger car where the rear brakes locked before the front. The left and right rear tire marks (due to braking) are perfectly straight until the front tire marks (without any steering input by the driver) veer to the left. The “radius” of the rear tire marks would be nearly infinite, resulting in a calculated speed far exceeding the actual test speed as well as the maximum vehicle speed based on engine horse power (see Section 23-3(b) of the Text and MARC 1 M1, Speed form Engine Power).

An incorrect application of the speed-from-yaw mark analysis resulted in a bad faith case with a significant jury verdict. Case details are described in Section 41-8 of the Supplement to the Text.

2.3. REASONS FOR REAR TIRE MARKS IN BUMPING OR TIRE FAILURE CASE

The reasons for a (rear) tire marking the pavement without a steering input by the driver in case of bumping or rear tire failure are explained in the following paragraph.
In order for a tire to produce a side force, it must develop a sideslip angle. The actually existing resultant velocity vector of a tire has two components, namely one in the direction of the tire/rim plan, and on perpendicular to the tire/rim plane (same as wheel axle) as illustrated in Figure 22-5 in the Text. When the rear of a car is bumped, the rear tires respond by producing a side force and a corresponding slip angle. One component of the velocity vector diagram is the existing forward velocity of the tire (speed of car), the other is the lateral velocity component perpendicular to the wheel. Consequently, for a given large forward velocity of the tire, the lateral tire velocity will be relatively “large” (however small in comparison to the forward velocity of the tire/car) to meet the triangular requirements of the slip angle velocity vector diagram. This lateral velocity of the rear tires results in a small lateral movement of the rear of the car and locates the beginning of pavement markings.

3.0 SPEED FROM STEERING INPUT/NO LATERAL LOAD TRANSFER

3.1. DERIVATION OF EQUATION

Equation 26-15 of the Text was derived with the assumption of a linear relationship existing between tire side force and slip angle as expressed by Equation 22-8 of the Text. Inspection of Figure 22-6 indicates a linear relationship for slip angles 4 to 5 degrees. The intent of this section is to provide the reader with the tools to analyze the effects of certain parameters, such as axle loadings, brake force distribution, tire cornering stiffness (effects of inflation pressures), and steering input in comparison with speed-from-yaw marks, where all vehicle parameters are “collapsed” into one single point mass.

Equation 26-15 calculates the limit turning speed on a level roadway as a function of front-to-rear weight distribution, front and rear tire cornering stiffness and braking for a given vehicle for a specified steering input, that is, turning severity. The analysis shown in Section 26-2(d) of the Text (as well as Example 26-1) does not include the effects of braking on longitudinal load transfer. If longitudinal load transfer were included in the analysis, then the front normal force would increase, while the rear normal force would decrease by (h/L)aW. For $a = 0.3g$ and $h/L = 0.22$, the front normal force in Example 26-1 would be 1998 lb with a front traction force $F_{TF} = 1798$ lb (not 1620 lb), the rear normal force would be 1002 lb with a rear traction force of $F_{TR} = 902$ lb (not 1080 lb). Longitudinal load transfer due to braking is included in the MARC 1 U4 program.

For the case of no braking, the turn radius r can be obtained from an analysis of Equation 26-15 as shown below:

$$r = ((57.3/\delta_l)(L))(1 + (C_R(1-\psi) - C_F\psi)(W/g)(V^2))/((2)(C_FC_R)),\ \text{ft} \qquad (3)$$

where tire cornering stiffness is measured in radians.

Substituting the proper non-braking data from Example 26-1, and V_{limit} = 215 ft/sec into Equation 3 yields the turn radius

$$r = 114.6\ (1 + 12.93) = 1{,}595\ \text{ft}$$

For low speed turning with V = 0 ft/sec, r = 114.6(1 + 0) = 114.6 ft (see Equation 26-3 of the Text).

The lateral acceleration is computed with Equation 26-2 as:

$$a_y = (215^2)/((1{,}595)(32.2)) = 0.90g$$

Of course, this answer is expected since all tire road friction is used for turning (f = 0.9) in the absence of braking. The reader is again reminded that the analysis presented above is based upon a linear relationship between tire side force and slip angle. The actual non-linear relationship for larger slip angles will reduce the maximum limit turning speed to values below those calculated above.

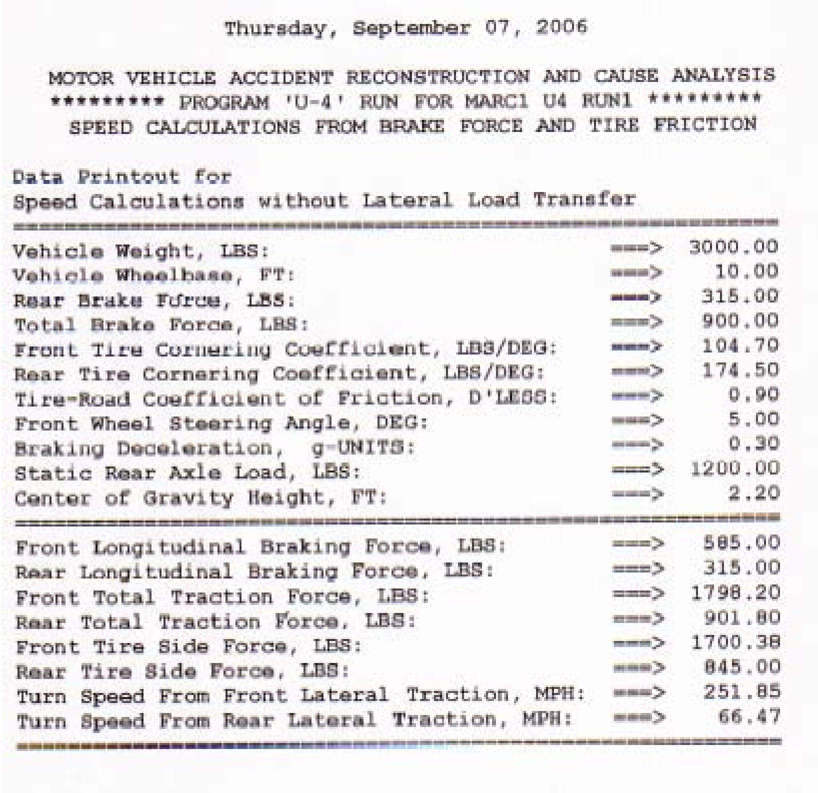
3.2. MARC 1 U4 APPLICATIONS

We will first work Example 26-1 of the Text by analyzing the effects of longitudinal load transfer on the maximum turning speeds as limited by front and rear tire traction. As an inspection of MARC 1 U4 RUN 1 reveals, the maximum turning speed is approximately 66 mph limited by the rear tires as compared with 103 mph in the simplified analysis of Section 26-2(d) of the Text where longitudinal load transfer is not considered.

Equation 3 yields a turn radius r = 421 ft for 66 mph. Equation 26-2 yields a limit lateral acceleration $a_y = 0.69g$ when the rear tires begin to lose side traction in the case of braking at a = 0.3g. The resultant traction utilized by the vehicle at that moment is 0.75, since $(0.3^2 + 0.69^2)^{1/2} = 0.75$, and not 0.9. This observation is similar to straight-line braking of an automobile, when, for example the rear brakes lock at a deceleration of 0.75g on roadway having a tire-road friction coefficient of 0.9.

4.0 SPEED FROM SPIN MARKS

The engineering details are discussed in Section 20-4(e) of the Text. The speed-from-spin marks analysis was used in a case where a Mercedes Benz lost control and impacted a Chevrolet passenger car. The Mercedes had stopped at a red light in the left through lane with another car stopped to the right of him. As the light changed to green both vehicles accelerated with the Mercedes having to yield to traffic to his right since his lane ended. The driver of the Mercedes accelerated to be ahead of the car to his right. After



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                    Thursday, September 07, 2006

  MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
  ********* PROGRAM 'U-4' RUN FOR MARC1 U4 RUN1 *********
   SPEED CALCULATIONS FROM BRAKE FORCE AND TIRE FRICTION

Data Printout for
Speed Calculations without Lateral Load Transfer
============================================================
Vehicle Weight, LBS:                            ===>  3000.00
Vehicle Wheelbase, FT:                          ===>    10.00
Rear Brake Force, LBS:                          ===>   315.00
Total Brake Force, LBS:                         ===>   900.00
Front Tire Cornering Coefficient, LBS/DEG:      ===>   104.70
Rear Tire Cornering Coefficient, LBS/DEG:       ===>   174.50
Tire-Road Coefficient of Friction, D'LESS:      ===>     0.90
Front Wheel Steering Angle, DEG:                ===>     5.00
Braking Deceleration,  g-UNITS:                 ===>     0.30
Static Rear Axle Load, LBS:                     ===>  1200.00
Center of Gravity Height, FT:                   ===>     2.20
============================================================
Front Longitudinal Braking Force, LBS:          ===>   585.00
Rear Longitudinal Braking Force, LBS:           ===>   315.00
Front Total Traction Force, LBS:                ===>  1798.20
Rear Total Traction Force, LBS:                 ===>   901.80
Front Tire Side Force, LBS:                     ===>  1700.38
Rear Tire Side Force, LBS:                      ===>   845.00
Turn Speed From Front Lateral Traction, MPH:    ===>   251.85
Turn Speed From Rear Lateral Traction, MPH:     ===>    66.47
============================================================
```

passing, he had to brake sharply to be able to negotiate a left hand turn. His right wheels were on gravel at the right edge of the road while his left wheels were on clean asphalt. The Mercedes began to spin counter-clockwise across the street into a guardrail where it bounced off into an oncoming Chevrolet.

All details including police accent scene diagrams, photographs and accident reconstruction are shown in ARC pages 70 through 87. The reconstruction starts from the rest positions to the head-on inline impact analysis and the spinout analysis.

Although shown in ARC (AAA), the spinout analysis with braking is shown here in MARC 1 Q RUN1. The secondary energy of 180,000 lbft was obtained from the impact analysis, which required that the Mercedes traveled at 36 mph when leaving the guardrail to have enough energy to impact the Chevrolet at 34 mph.

5.0 VEHICLE ROLLOVER

5.1 FRICTION ROLL

5.1.1 SIMPLIFIED ANALYSIS

The engineering details of the simplified “rigid” box model analysis are discussed in Section 27-3 of the Text. In order for a vehicle to experience friction-caused rollover on a level roadway, the tire-road friction coefficient has to be sufficiently high for the vehicle not to slide out. In terms of center-of-gravity height h and track width t, the limit friction coefficient has to be equal to or greater than:

$$f_{\text{limit}} = t/(2h) \qquad (4)$$

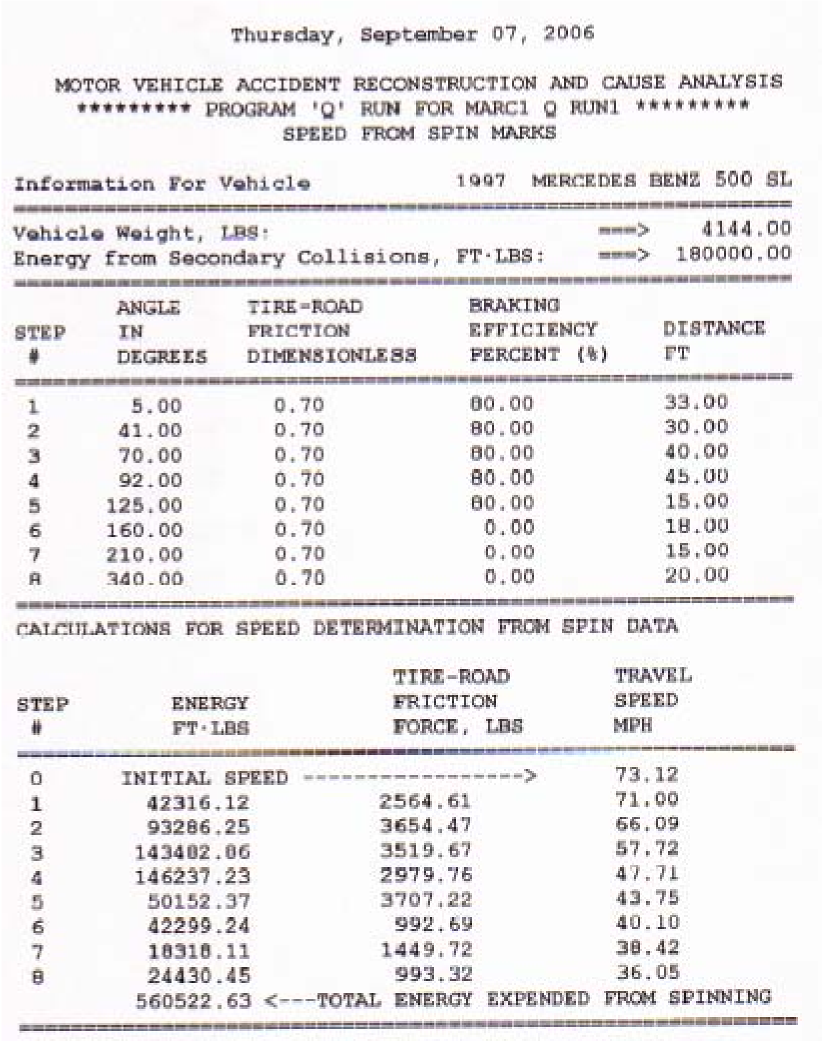
The vehicle velocity as a function of limit lateral acceleration is computed by (Equation 27-3 of the Text):

$$V_{\text{limit}} = (((32.2)\ r\ t)/(2h))^{1/2}\ ;\ \text{ft/sec} \qquad (5)$$

The results of a rollover analysis are shown in MARC 1 O1 RUN 1 for a Geo Tracker. The t/(2h) is 1.09 (Equation 4), indicating that a side tire-road friction coefficient of 1.09 has to exist, in order for the Tracker to roll over. For a curve radius of 204 feet the roll speed is 57.81 mph. The reader is reminded that these calculations are based upon a static model, that is, the steering wheel is held in a fixed position.

For turning on a road with super elevation, the approximate effective lateral acceleration t/(2h) is increased by $\tan\alpha$. For example, for a super elevation of 4 degrees, the effective lateral acceleration will be 1.09 + tan4 = 1.09 + 0.07 = 1.16 and the rollover velocity is 59.5 mph (Equation 26-9).

Equation 5, and hence, the MARC1 O1 rollover analysis is based upon limit lateral acceleration in terms of center-of-gravity height and track width, but does not include the effects of sprung mass body lean. Consequently, the rollover speeds calculated by Equation 5 are somewhat higher than actual rollover speeds since body lean reduces the stabilizing moment due to weight.



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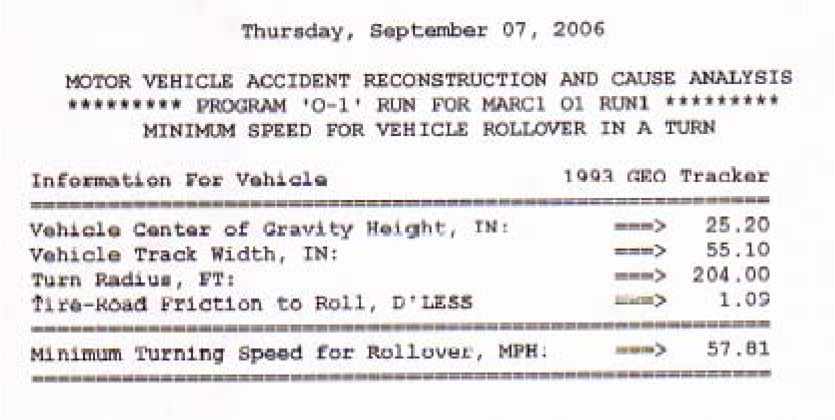
                      Thursday, September 07, 2006

   MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
     ********* PROGRAM 'Q' RUN FOR MARC1 Q RUN1 *********
                        SPEED FROM SPIN MARKS

Information For Vehicle              1997  MERCEDES BENZ 500 SL
=================================================================
Vehicle Weight, LBS:                             ===>    4144.00
Energy from Secondary Collisions, FT·LBS:        ===>  180000.00
=================================================================
        ANGLE     TIRE-ROAD           BRAKING
STEP    IN        FRICTION            EFFICIENCY        DISTANCE
 #      DEGREES   DIMENSIONLESS       PERCENT (%)       FT
=================================================================
 1        5.00       0.70             80.00             33.00
 2       41.00       0.70             80.00             30.00
 3       70.00       0.70             80.00             40.00
 4       92.00       0.70             80.00             45.00
 5      125.00       0.70             80.00             15.00
 6      160.00       0.70              0.00             18.00
 7      210.00       0.70              0.00             15.00
 8      340.00       0.70              0.00             20.00
=================================================================
CALCULATIONS FOR SPEED DETERMINATION FROM SPIN DATA

                               TIRE-ROAD           TRAVEL
STEP          ENERGY           FRICTION            SPEED
 #            FT·LBS           FORCE, LBS          MPH
=================================================================
 0       INITIAL SPEED ---------------->           73.12
 1          42316.12          2564.61              71.00
 2          93286.25          3654.47              66.09
 3         143482.86          3519.67              57.72
 4         146237.23          2979.76              47.71
 5          50152.37          3707.22              43.75
 6          42299.24           992.69              40.10
 7          18318.11          1449.72              38.42
 8          24430.45           993.32              36.05
           560522.63 <---TOTAL ENERGY EXPENDED FROM SPINNING
=================================================================
```



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                      Thursday, September 07, 2006

   MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
    ********* PROGRAM 'O-1' RUN FOR MARC1 O1 RUN1 *********
            MINIMUM SPEED FOR VEHICLE ROLLOVER IN A TURN

Information For Vehicle                       1993 GEO Tracker
==============================================================
Vehicle Center of Gravity Height, IN:            ===>   25.20
Vehicle Track Width, IN:                         ===>   55.10
Turn Radius, FT:                                 ===>  204.00
Tire-Road Friction to Roll, D'LESS               ===>    1.09
==============================================================
Minimum Turning Speed for Rollover, MPH:         ===>   57.81
==============================================================
```

5.1.2. ACCIDENT SCENE/VEHICLE DATA COLLECTION

Tire marks prior to rollover are illustrated in Figure 37-2 of the Text where a cement truck rolled onto its side when traveling too fast around a corner. While the radius of the curved path can be measured easily (see Sections 37-3(b)(6) and 37-4 of the Text), center-of-gravity heights are not easily obtained. Equation 37-3 of the Text calculates the center-of-gravity height based upon raising the rear axle and measuring the axle load of the front axle.

5.2. TRIPP ROLLOVER

Rollover caused by tripping is discussed in Section 27-5 of the Text. A vehicle slides basically sideways when it strikes a curb or lip in the roadway and the leading wheels are suddenly stopped while the body rotates over the trip point. The linear kinetic energy exhibited by the vehicle at the moment of curb strike is changed into rotational energy sufficient to raise the center-of-gravity above the trip point. The minimum speed to cause trip rollover is calculated by Equation 27-10 with the mass-moment of inertia around the trip point calculated by Equation 27-11 of the Text.

Equation 27-10 as well as MARC 1 O2 calculates the speed necessary to just tip the vehicle over on its side. When followed by additional roll motions, energy balance must be employed to determine the speed at the moment of curb strike.

An application of speed due to tripping is shown in MARC 1 O2 RUN 1 for a Geo Tracker.

6.0 ROLLOVER WITH LATERAL LOAD TRANSFER

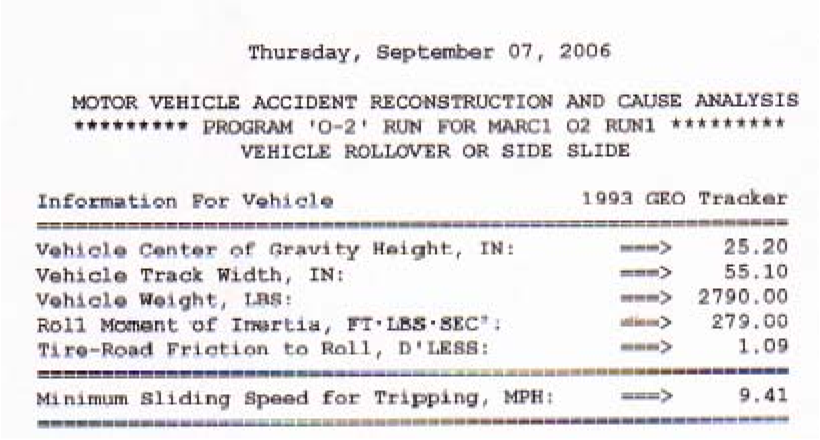
6.1. CARS AND STRAIGHT TRUCKS

6.1.1. DERIVATIONS OF EQUATIONS

The engineering details are discussed in Section 27-4 of the Text. Lateral load transfer on the front and rear axle for turning on a level road is included by use of the normalized front and rear roll stiffness calculated by Equation 26-20 of the Text. If appropriate, braking may be included.

6.1.2. MARC 1 P1 APPLICATION – EXAMPLE 27-1 OF THE TEXT

The rollover speed calculations of Example 27-1 are shown in the MARC 1 P1 RUN1 for the case without braking. The input data are obtained from Example 26-1 and 27-1 of the Text.



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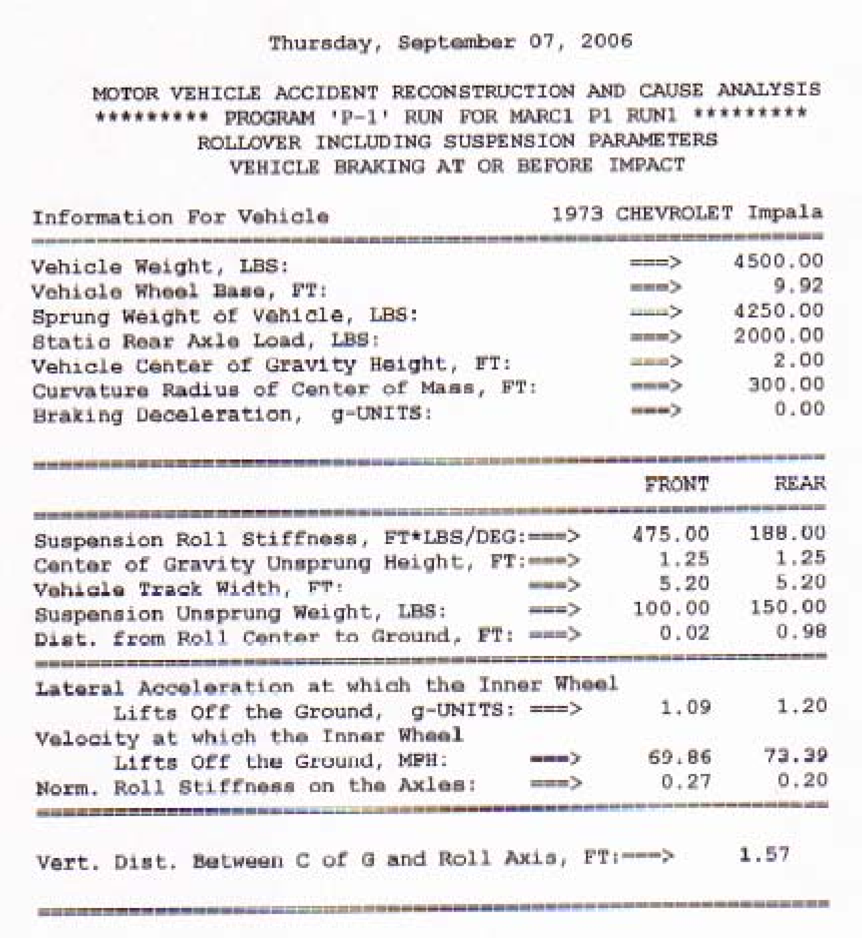
                 Thursday, September 07, 2006

   MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
   ********* PROGRAM 'O-2' RUN FOR MARC1 O2 RUN1 *********
                VEHICLE ROLLOVER OR SIDE SLIDE

 Information For Vehicle                     1993 GEO Tracker
 =============================================================
 Vehicle Center of Gravity Height, IN:         ===>     25.20
 Vehicle Track Width, IN:                      ===>     55.10
 Vehicle Weight, LBS:                          ===>   2790.00
 Roll Moment of Inertia, FT·LBS·SEC²:          ===>    279.00
 Tire-Road Friction to Roll, D'LESS:           ===>      1.09
 =============================================================
 Minimum Sliding Speed for Tripping, MPH:      ===>      9.41
 =============================================================
```



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                 Thursday, September 07, 2006

   MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
   ********* PROGRAM 'P-1' RUN FOR MARC1 P1 RUN1 *********
            ROLLOVER INCLUDING SUSPENSION PARAMETERS
              VEHICLE BRAKING AT OR BEFORE IMPACT

 Information For Vehicle                  1973 CHEVROLET Impala
 ===============================================================
 Vehicle Weight, LBS:                            ===>   4500.00
 Vehicle Wheel Base, FT:                         ===>      9.92
 Sprung Weight of Vehicle, LBS:                  ===>   4250.00
 Static Rear Axle Load, LBS:                     ===>   2000.00
 Vehicle Center of Gravity Height, FT:           ===>      2.00
 Curvature Radius of Center of Mass, FT:         ===>    300.00
 Braking Deceleration,  g-UNITS:                 ===>      0.00

 ===============================================================
                                                FRONT      REAR
 ===============================================================
 Suspension Roll Stiffness, FT*LBS/DEG:===>    475.00    188.00
 Center of Gravity Unsprung Height, FT:===>      1.25      1.25
 Vehicle Track Width, FT:              ===>      5.20      5.20
 Suspension Unsprung Weight, LBS:      ===>    100.00    150.00
 Dist. from Roll Center to Ground, FT: ===>      0.02      0.98
 ===============================================================
 Lateral Acceleration at which the Inner Wheel
       Lifts Off the Ground,  g-UNITS: ===>      1.09      1.20
 Velocity at which the Inner Wheel
       Lifts Off the Ground, MPH:      ===>     69.86     73.39
 Norm. Roll Stiffness on the Axles:    ===>      0.27      0.20
 ===============================================================

 Vert. Dist. Between C of G and Roll Axis, FT:===>     1.57

 ===============================================================
```

6.1.3. STRAIGHT 3-AXLE TRUCK ROLLOVER

The single vehicle accident occurred when a 2000 Freightliner FL80 three-axle straight truck rollover while attempting to drive through an 84-foot right hand curve with a 10-degree super elevation. The roadway also had a 12-degree down slope. The truck rolled 180 degrees onto its roof. The truck had leaf spring suspension in the front and air suspension tandem axles in the rear. The total weight of the truck was 26,000 lb with a center-of-gravity height of 5.48 ft.

The level road rollover analysis is shown in MARC 1 P1-RUN2. The suspension roll stiffness moment data for the vehicle were obtained from SAE Paper 973208, “Ride Performance of Heavy Suspensions: Data Tables”. Inspection of the results indicates, that the inner rear wheels lift off at a lateral acceleration of 0.45g or at a speed of approximately 23.87 mph when considering a level roadway.

When the “rigid” vehicle rollover analysis of Section 27-3 is considered, then the limit rollover lateral acceleration becomes 0.63g with a level roadway rollover speed of 28.25 mph instead of 23.87 mph as shown MARC 1 O1 RUN2.

Using a super elevation slope of 10 degrees increases the effective lateral acceleration to 0.62 and the rollover speed to approximately 28 mph as compared with 31.86 mph for the rigid model analysis.

A calculated roll speed of 28 mph has to be compared with the distance of 50 to 60 feet measured at the accident scene that the truck slid/rolled after begin of roll including a significant down slope of 12 degrees.

It is interesting to note that the legal speed limit was 40 mph at the accident location. Driving through the accident curve with a passenger car at 35 mph was considered to be the maximum limit speed before loss of control due to slide-out.

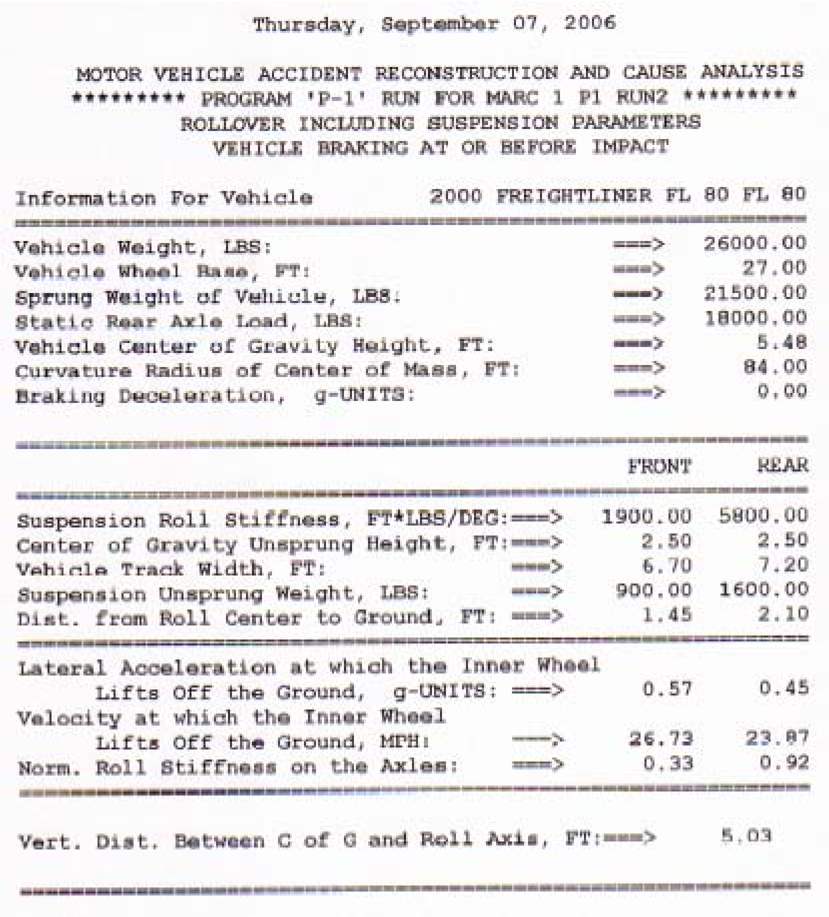
6.2. TRACTOR/TRAILER ROLLOVER

6.2.1. DERIVATION OF EQUATION

When a loaded tractor/trailer rolls over on a flat surface, it always begins with the trailer. The equations for calculating the limit lateral acceleration for fixed and swing loads are shown in Section 27-6(b) of the Text.

6.2.2. STATIC ROLLOVER TESTING

Static rollover testing with a tilt table had been done in Germany more than 30 years ago. UMTRI of the University of Michigan has a tilt test facility as illustrated in Figure 1. The tilt test results correlate well with Equation 27-12 of the Text.



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                  Thursday, September 07, 2006

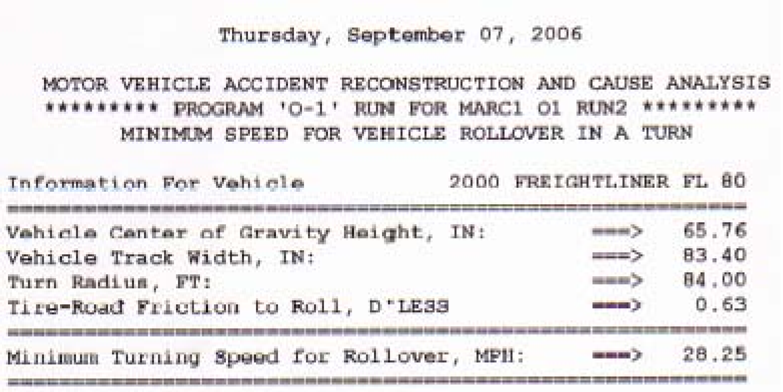
   MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
   ********* PROGRAM 'P-1' RUN FOR MARC 1 P1 RUN2 *********
          ROLLOVER INCLUDING SUSPENSION PARAMETERS
              VEHICLE BRAKING AT OR BEFORE IMPACT

Information For Vehicle         2000 FREIGHTLINER FL 80 FL 80
==============================================================
Vehicle Weight, LBS:                              ===>  26000.00
Vehicle Wheel Base, FT:                           ===>     27.00
Sprung Weight of Vehicle, LBS:                    ===>  21500.00
Static Rear Axle Load, LBS:                       ===>  18000.00
Vehicle Center of Gravity Height, FT:             ===>      5.48
Curvature Radius of Center of Mass, FT:           ===>     84.00
Braking Deceleration,  g-UNITS:                   ===>      0.00

==============================================================
                                                FRONT      REAR
==============================================================
Suspension Roll Stiffness, FT*LBS/DEG:===>    1900.00   5800.00
Center of Gravity Unsprung Height, FT:===>       2.50      2.50
Vehicle Track Width, FT:              ===>       6.70      7.20
Suspension Unsprung Weight, LBS:      ===>     900.00   1600.00
Dist. from Roll Center to Ground, FT: ===>       1.45      2.10
==============================================================
Lateral Acceleration at which the Inner Wheel
      Lifts Off the Ground,  g-UNITS: ===>       0.57      0.45
Velocity at which the Inner Wheel
      Lifts Off the Ground, MPH:      --->      26.73     23.87
Norm. Roll Stiffness on the Axles:    ===>       0.33      0.92
==============================================================

Vert. Dist. Between C of G and Roll Axis, FT:===>      5.03

==============================================================
```



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                 Thursday, September 07, 2006

  MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
  ********* PROGRAM 'O-1' RUN FOR MARC1 O1 RUN2 *********
        MINIMUM SPEED FOR VEHICLE ROLLOVER IN A TURN

Information For Vehicle           2000 FREIGHTLINER FL 80
==========================================================
Vehicle Center of Gravity Height, IN:          ===>   65.76
Vehicle Track Width, IN:                       ===>   83.40
Turn Radius, FT:                               ===>   84.00
Tire-Road Friction to Roll, D'LESS             ===>    0.63
==========================================================
Minimum Turning Speed for Rollover, MPH:       ===>   28.25
==========================================================
```

Figure 1: UMTRI Tilt Table

6.2.3. MARC 1 P2 APPLICATION

An actual rollover accident of a loaded tractor/semi-trailer is shown in ARC Section 5.2. The accident scene photographs clearly show the left side trailer tire path up to the point where the left trailer tires slapped the pavement. As always in slide-out or rollover accidents, the curvature of the tire marks must be measured to determine the path of the center-of-gravity at the moment of tip-up. In addition, the actual center-of-gravity height must either be measured, or calculated from basic vehicle loading information.

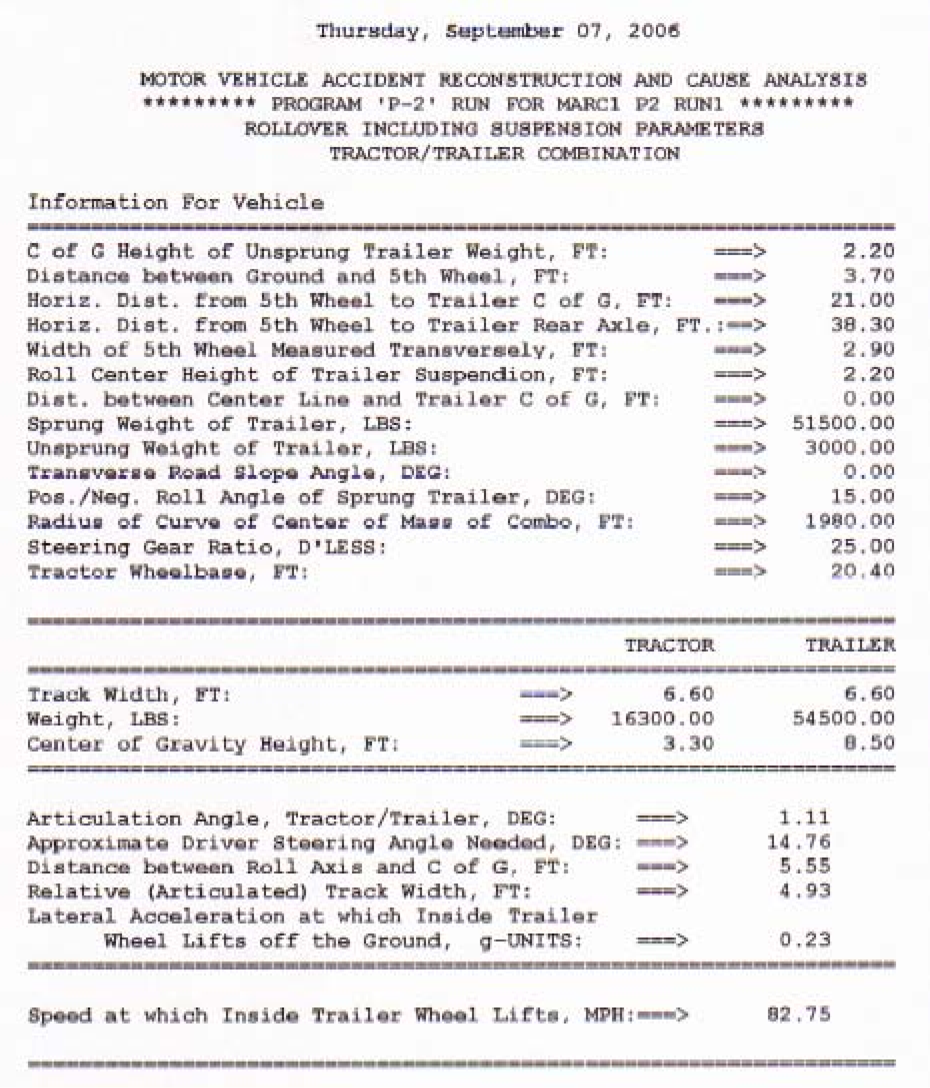
In a particular accident, freeway travel was channeled through a construction zone involving a curve radius of 1980 ft. The speed limit was 45 mph. The roadway was level. Based upon these two data the turning severity is 0.068g.

A tractor/trailer combination weighing 70,800 lb had roll onto its right side while traveling through the construction site. The speed based upon all accident scene data was reconstructed at approximately 62 mph at a point when the trailer tires had slapped the pavement. The UMTRI tilt table measurements for an exemplar tractor/trailer/loading configuration determined an average static tip-up/rollover limit of 0.229 or 0.23g.
The theoretical center-of-gravity height of the loaded trailer based upon trailer and loading data was estimated at 102 inches or 8.5 ft. The tractor center-of-gravity height is approximately 40 inches, which is the distance from the upper frame rail to the ground.

The rollover speed calculations are shown in MARC 1 P2-RUN1. Inspection of the results shows that the trailer inside wheels lift off the pavement at a lateral acceleration of 0.23g, and for a turn radius of 1980 ft, at a speed of approximately 83 mph.

A trailer lean angle of 15 degrees was assumed to account for torsional frame deflection. The roll center height of the four-leaf spring rear suspension of 2.2 ft was obtained from SAE 973208, “Ride Performance of Heavy Suspensions: Data Tables”.

Equation 2 can be used to calculate the probable turn radius that the driver of the subject tractor-trailer combination traveled in order to roll the trailer at a speed of 62 mph for a limit lateral acceleration of 0.23g. The result is a radius of 1115 ft as compared with a design radius of 1980 ft. The conclusion is that driver error caused the rollover accident by not following the designated path curvature.



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                    Thursday, September 07, 2006

        MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
        ********* PROGRAM 'P-2' RUN FOR MARC1 P2 RUN1 *********
                ROLLOVER INCLUDING SUSPENSION PARAMETERS
                     TRACTOR/TRAILER COMBINATION

Information For Vehicle
==================================================================
C of G Height of Unsprung Trailer Weight, FT:        ===>      2.20
Distance between Ground and 5th Wheel, FT:           ===>      3.70
Horiz. Dist. from 5th Wheel to Trailer C of G, FT:   ===>     21.00
Horiz. Dist. from 5th Wheel to Trailer Rear Axle, FT.:===>    38.30
Width of 5th Wheel Measured Transversely, FT:        ===>      2.90
Roll Center Height of Trailer Suspendion, FT:        ===>      2.20
Dist. between Center Line and Trailer C of G, FT:    ===>      0.00
Sprung Weight of Trailer, LBS:                       ===>  51500.00
Unsprung Weight of Trailer, LBS:                     ===>   3000.00
Transverse Road Slope Angle, DEG:                    ===>      0.00
Pos./Neg. Roll Angle of Sprung Trailer, DEG:         ===>     15.00
Radius of Curve of Center of Mass of Combo, FT:      ===>   1980.00
Steering Gear Ratio, D'LESS:                         ===>     25.00
Tractor Wheelbase, FT:                               ===>     20.40

==================================================================
                                              TRACTOR       TRAILER
==================================================================
Track Width, FT:                      ===>       6.60          6.60
Weight, LBS:                          ===>   16300.00      54500.00
Center of Gravity Height, FT:         ===>       3.30          8.50
==================================================================

Articulation Angle, Tractor/Trailer, DEG:       ===>       1.11
Approximate Driver Steering Angle Needed, DEG: ===>      14.76
Distance between Roll Axis and C of G, FT:      ===>       5.55
Relative (Articulated) Track Width, FT:         ===>       4.93
Lateral Acceleration at which Inside Trailer
      Wheel Lifts off the Ground,  g-UNITS:     ===>       0.23
==================================================================

Speed at which Inside Trailer Wheel Lifts, MPH:===>      82.75

==================================================================
```