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Forensic Engineering Analysis of Motorcycle Tires Entering Longitudinal Joints/Ruts at Shallow Approach Angles

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Abstract

This paper will examine the effect of a motorcycle driving into a longitudinal joint, sometimes called a rut. If the approach angle is approximately less than ten degrees in the direction of travel, the forces that are generated on the front tire due to striking the rut, joint or curb, may cause the front motorcycle tire to lose its ability to steer or brake, and may initiate a vibration, or caster effect, or wobble, which can result in the instability and capsizing the motorcycle.

Keywords

Motorcycle, longitudinal joint, curb, torque, trail, tire, wobble, weave, vibration

Description of Event Leading to Accident

A motorcyclist while driving his 2003 Harley Davidson Classic motorcycle over a bridge that was undergoing deck rehabilitation was caused to lose control of the motorcycle while entering into a temporary longitudinal construction joint, sometimes referred to as a rut. As a result the motorcycle capsized and the rider was thrown from the motorcycle and injured. It is known in engineering and among motorcycle riders that longitudinal joints are dangerous to motorcycles. In an engineering paper published by the Texas Transportation Institute and the Florida Department of Transportation titled, *"A Friction Testing Method For Open Grated Steel Bridge Decks"*, it is stated;

> "Road longitudinal grooves have also been known to produce unexpected lateral accelerations, or wobbles, of motorcycle wheels, requiring more corrective steering. This is mainly due to the motorcycle tire tread attempt to align itself along the grooves."[1]

However, there were no calculations that the writer could find to analyze the physics of this phenomenon. Although the SAE Paper #2006-01-1561, *"Behavior of A Motorcycle After An Encounter With A Road Irregularity Parallel To Its Direction of Travel"*. By L.D. Metz is a good reference[2] wherein it addresses the problem using math and testing.

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This paper will perform a mathematical analysis examining the effect of motorcycle tires in ruts at shallow approach angles of less than ten degrees which resulted, in this case, to injury and litigation.

Events Leading to Trial

The bridge in question was undergoing a deck replacement. New decking was adjacent to existing decking and a change in level of approximately one and one half to two inches existed. The weather was typical summer weather and it had just stopped raining so the bridge deck was wet. The original contract drawings required any change in level was to be ramped with asphalt at a maximum slope of ten percent. The Contractor prepared a new change in level transition construction detail that was approved by the Bridge Authority Engineer and incorporated into the original plans. The detail indicated how the required transition was to be constructed; this replaced the original 10% slope transition. (See fig. 1.)

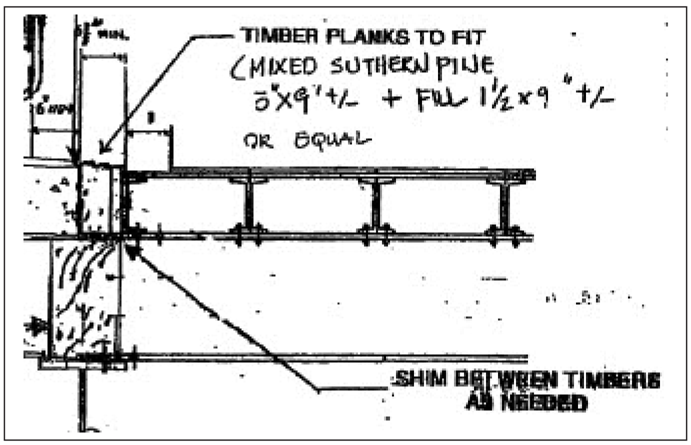

Figure 1
Contractor detail with Bridge Authority approval of transition between adjacent travel lanes in lieu of the maximum 10% asphalt transition originally required.

Because of the irregular configuration of the decking surface some sections of the longitudinal travel lane joints did not coincide with the lane edge configuration. The longitudinal joint in this case shifted from between the right lane and center lane to the middle of the center lane. (See fig. 2.)

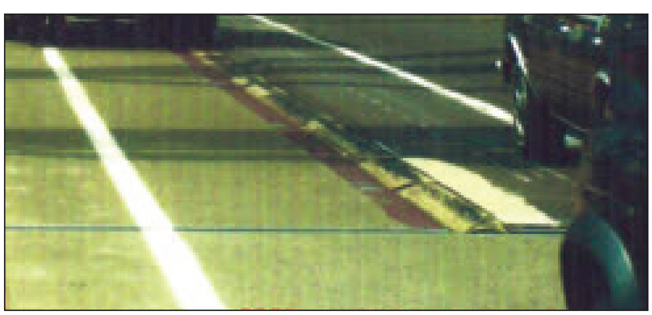

Figure 2
Longitudinal joint shift from between the right and center lanes to the middle of the center lane.

The motorcyclist was traveling approximately 30 MPH a distance of two or three car lengths behind the vehicle in front and therefore had limited forward visibility of the bridge deck surface. The vehicle in front of the motorcyclist obscured the longitudinal joint in the middle of the center lane where both vehicles were traveling. When the vehicle in front of the motorcyclist uncovered the longitudinal joint which shifted to the center of the middle lane, there was not enough time for the motorcyclist to steer away from the joint. Traveling at 30 MPH or approximately 44 feet per second resulted in limited perception reaction time of approximately one second. The front tire entered the joint in the middle of the center lane as the motorcyclist attempted to steer away from the joint. The front tire sidewall struck the side of the joint at a shallow approach angle and the motorcyclist lost control of the motorcycle and capsized. The motorcyclist was injured as he was thrown from the motorcycle and struck the bridge deck pavement and Jersey barrier in the right lane. It should be noted that the flat horizontal surface adjacent to the timber was untreated steel. That is, after the new decking was installed, the steel would be welded to the adjacent steel deck and covered with 3/8" of wearing course. At the time of the accident the steel and timbers were wet due to rainfall. This lowered the static coefficient of friction of the tire contact which was estimated in the calculations as equal to 0.40. It should also be noted that as dynamic friction increases, say from 0.40 to 0.60, the value of the lateral forces decrease because the friction forces increase, hence the torques also decrease. (See the calculations in the appendix.) Therefore storm water on the bridge decking and rut transition becomes the worst case scenario because of the reduced coefficients of friction. Note that in the analysis there are two place holders for different friction values, one for side friction and one for roadway surface friction.

In deposition the motorcyclist, with twenty years of riding experience, described the motion of the front wheel of the motorcycle as sliding, preventing him from steering out of the rut. The motorcycle fishtailed and started to move back and forth within the rut. The motorcycle tires were rotating and sliding. The Motorcyclist attempted to slow the motorcycle from his initial speed of 30 MPH, however the motorcycle would not slow because the front tire was sliding and could not provide the necessary tire friction for steering and braking. The witness driving behind validated the Motorcyclist's description of the event.

The temporary longitudinal joint that the Motorcyclist experienced was a classic motorcycle tire and longitudinal joint effect which occurs when approaching longitudinal joints at shallow angles. The side force (lateral force) on the front tire that is necessary for the tire to function in steering and braking were exceeded by the forces generated as a result of the tire striking the side of the longitudinal raised edge of the joint. The tire acts as a spring mass model when compressed due to the contact to the side of the rut and then is released. The hysteresis properties of the tire were not examined in this case but may be looked into in the future. The tire contact with the side of the joint creates a force due to the acceleration on the tire (See Fig. 6). The tire disengages from the side of the joint. However, before disengagement, forces and torques are created about the steering axes that are substantial. As a result the front tire loses its traction. Steering and braking are lost. The result is that the motorcycle becomes unstable and capsizes. The graphs below show the magnitude of the forces that cause the tire to lose traction. (See Figures 7 through 12).

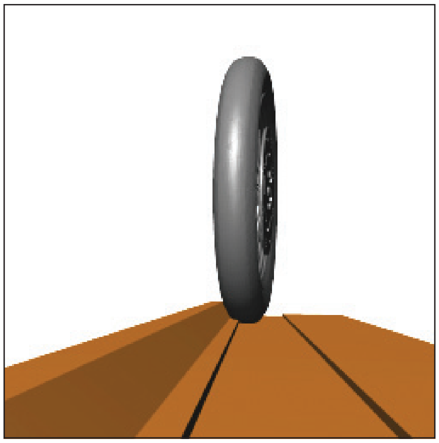

Figure 3
Tire contacts the side slope of the beveled timber wedges as per the Contractor's redesign of the change in level transition. (Distortion due to camera angle.)

The Contractor and Bridge Authorities elected to alter the method of bridging the change in level between the adjacent travel lanes. The method chosen and approved by the Bridge Authority was to insert a timber wedges, 5" by 10" and shave the timber edge into a bevel. The slope of the bevel was 1.5" : 2.5". (See Fig. 3.) The result was that the tire would contact the side slope of the bevel and generate a lateral force on the tire. If the rut had a vertical side instead of the beveled side, ie; similar to a curb, the forces generated would have been higher. The forces were reduced by the sine of the angle created by the bevel. (See calculations in the Appendix.) As the side of the rut is reduced in slope, ie; flatter, the forces generated on the tire sidewall are reduced. Hence the ten percent or less detail in the original plans was adequate to prevent motorcycle tire oscillations.

The torque effect about the steering axis subjected the tire to partial oscillatory motion and probably generated a frequency of approximately 3 Hz. The operator has virtually no time to perceive and react to the steering torque.

As described by both the Plaintiff and witness the motorcycle began yawing as a result of the tire patch forces (lateral forces) being exceeded by the forces generated by the sidewalls striking the temporary longitudinal joint side edges. The motorcycle tires were rolling and sliding in the temporary joint. Both the front and rear tires were oscillating and sliding. When the front tire regains its traction the rear portion of the motorcycle begins to rotate, in this case clockwise about the front tire patch which is in contact with the pavement. The front tire stops sliding as a result. The rear of the motorcycle begins to rotate in two directions; about the "y" axis (which is the transverse axis or pitch axis of the motorcycle) upward; and clockwise or about the "z" axis (which is the vertical or yaw axis of the motorcycle). The result of the rotation about two axis is that Motorcyclist is thrown off of the motorcycle. The motorcycle rotated clockwise and was found with an approximate heading in the opposite direction of travel. The motorcycle, in this case rotated approximately 120 degrees from its original direction at rest.

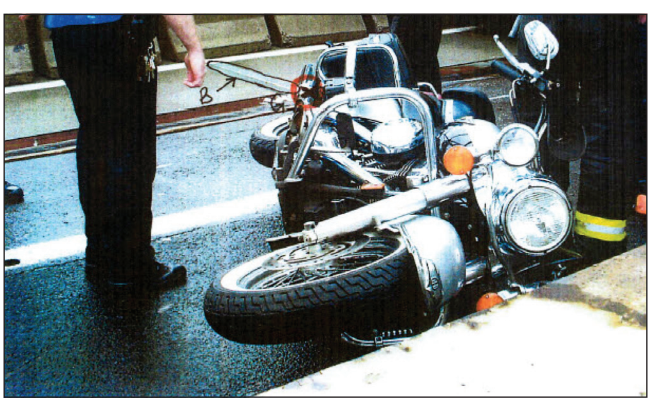

Figure 4
Left to right is the direction of travel. The motorcycle is approximately rotated 120 degrees from its travel route. The joint can be seen in the top portion of the photograph. The plaintiff is out of frame to the right on the pavement.

There are gouge marks in the pavement where the motorcycle slid in the right lane after emerging from the joint. The entire distance from where the front tire entered the joint to where the motorcycle came to rest was approximately 150 to 200 feet.

The physics and mathematics of the tire of a motorcycle that strikes a longitudinal joint or rut at an angle less than ten degrees creates lateral forces on the tire of such magnitude that it affects the steering and braking of the motorcycle and creates oscillations about the steering axis of the motorcycle. The forces are large enough to overcome the forces that maintain the front tire contact patch between the tire and pavement so that the tire can slide thereby losing the ability to steer and brake. In addition there are partial oscillations that are created that can vibrate throughout the entire motorcycle. These vibrations can cause the motorcycle to either go into a wobble or weave resulting in the instability and ultimate capsizing of the motorcycle. (See the mathematic calculations in the appendix.)

What about the gyroscopic effect of the front wheel. The gyroscopic effect of the force applied at the contact patch will develop a torque about the x-x axis (roll axis). The Angular Momentum is to the left about the y-y axis (pitch axis). The force creates a torque T_{XX} up, in the (z-z) axis. (See Fig. 7.) The Torque is applied for a short duration the wheel rotates about the (x-x) and (z-z) axis. This can create a vibration about the x-x and z-z axis, (a caster effect). The result is that the gyroscopic effect reinforces the vibration about the steering axis as shown in the graphs below for the two degree to eight degree approach angles. (See Fig. 8.)

The static coefficient of friction (SCOF) required to maintain tire stability at the contact patch is depicted in the graphic below. (See Fig. 8.) The required SCOF could be as high as 1.2 which is most probably not attainable on a wet or dry pavement or on a steel/timber surface as in this case.

Had the transition been 10% as required in the original contract then the effect on the front motorcycle tire would have been 10 times less. That is, the acceleration effect on the sidewall of the tire at the 8 degree approach angle of 3.2 g's would have been 0.32 g's. This would have reduced the lateral forces on the tire and resulting torque values, and more probably than not, would not have substantially affected the stability of the motorcycle.

Reference is now made to Vittore Cossalter's book, "MOTORCYCLE DYNAMICS", 2nd Edition regarding the positive and negative trail or the motorcycle front tire. Positive trail is defined as the contact patch of the front tire as being to the rear of the steer axis. This gives the motorcycle stability as the friction force of the front tire tends to create a moment that tends to align the front wheel. Negative trail is defined as the steering axis being to the rear of the contact patch which creates an increasing moment about the steering axis and creates instability. If the rut is high enough so that the contact patch moves in front of the steer axis, instability will occur. The diagram on the next page shows how the contact patch moves in front of the steer axis when striking and mounting a rut of a height greater than h_1.

The equation to determine h_1 is:

h_1 = M.O. / cos(E) where	E is the caster angle (steering axis angle)
M.O. = (trail/sin(E) – r)	M.O. is the middle ordinate
	r is the radius of the front tire

In this case the height of the rut was approximately 1-1/2" and h_1 calculated to be approximately 1-3/4" and therefore negative trail did not occur. However, the reduced trail was not examined and therefore the result of a dynamic reduction in trail length with respect to time was not examined by the writer.

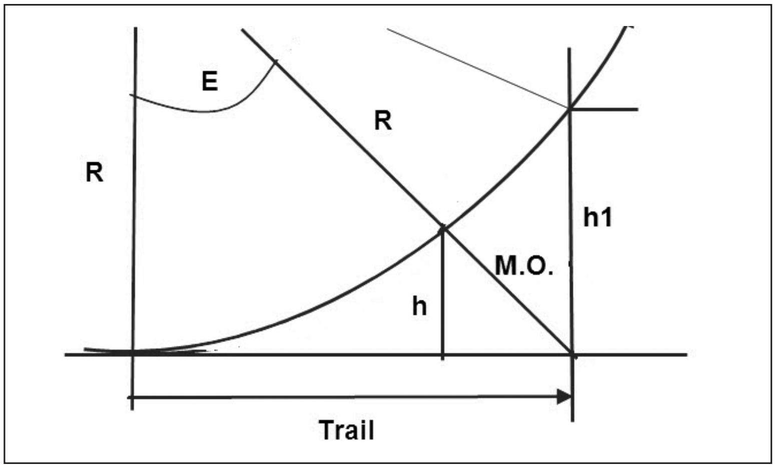

Figure 5
h_1 is the height of the contact patch along the perimeter of the front tire. If h_1 increases along the front tire, then the contact patch will be in front of the steer axis and instability will occur. (See calculations in the Appendix.)

Conclusion

The graphs and mathematical and physical analysis show the magnitude of forces that are generated when tires strike the sides of longitudinal grooves or joints in the roadway surface. The transverse forces that are generated are dangerous and can cause instability and capsize the motorcycle which was the cause of the accident in this case. The writer generated a report which included the analysis attached in the appendix indicating the alternate detail suggested by the Contractor was a danger to motorcycles and that the original requirement of a 10% or less ramping of the adjacent travel lanes was adequate. The case settled at the 11th hour prior to trial.

Why did we go through this analysis? Because the defense stated that the Plaintiff didn't know how to ride a motorcycle; that the defense did everything right and it was not our fault that caused his accident. The Plaintiff had to prove that the accident was caused by a defective condition created by the Defendant. In this case the Defendant made a field change that created a rut (longitudinal joint) instead of a smooth transition. It was the field change, without any corresponding analysis, that created the hazardous condition. The lateral forces and resulting torques about the steer axis that were created on the front tire of the motorcycle were unexpected and destabilizing and caused the plaintiff injuries.

References

1. Motorcycle (Quarter-Car) Suspension Simulation MECE 4333 – Vehicle Systems Modeling and Control The University of Texas – Pan American, July 17, 2006

2. SAE 2006-01-1561, "Behavior of a Motorcycle after an Encounter with a Road Irregularity Parallel to it Direction of Travel". By L.D. Metz

3. Motorcycle Dynamics, by Vittore Cossalter, 2nd English Edition.

4. Forensic Engineering Investigation of Motorcycle Instability Induced Crashes, by Mark A. M. Ezra, P.E. (NAFE 641F) National Academy of Forensic Engineers (NAFE) Journal, Vol. 21, No. 1, June, 2004.

Graphs

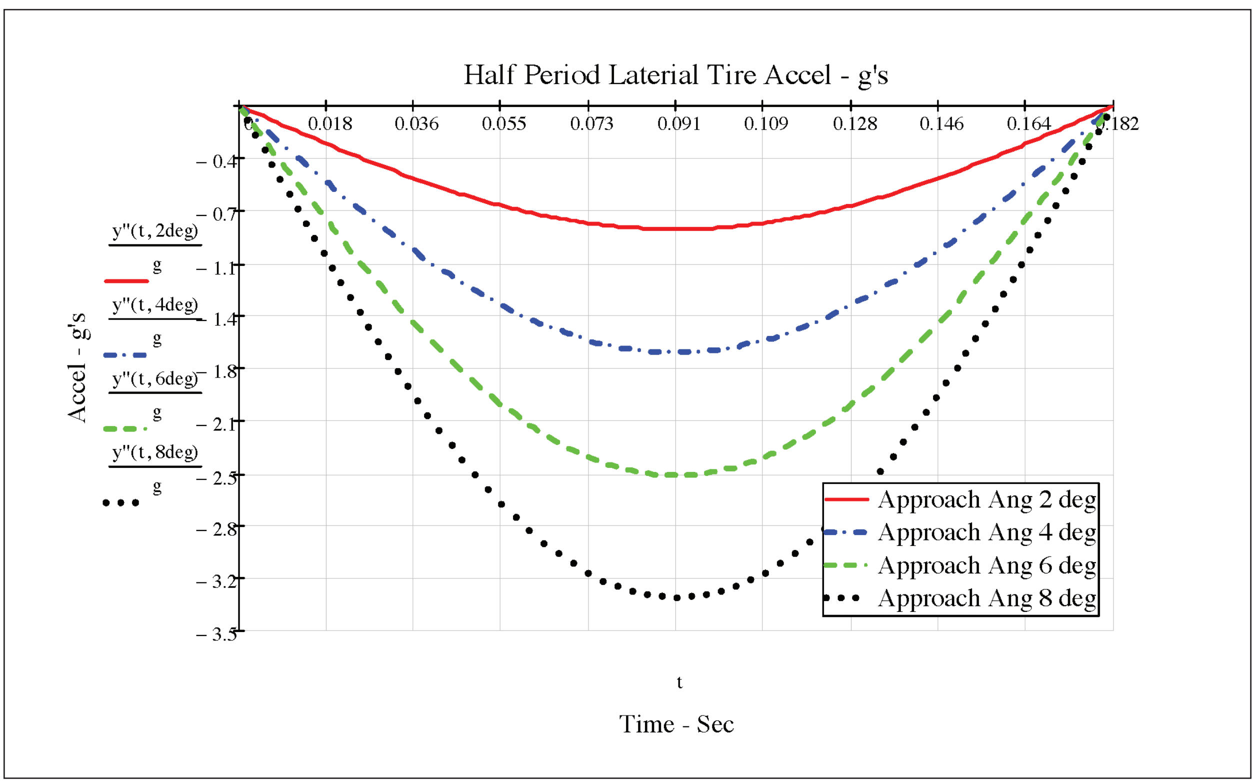

Figure 6
Acceleration (g's) of tire as it strikes the rut at various approach angles.

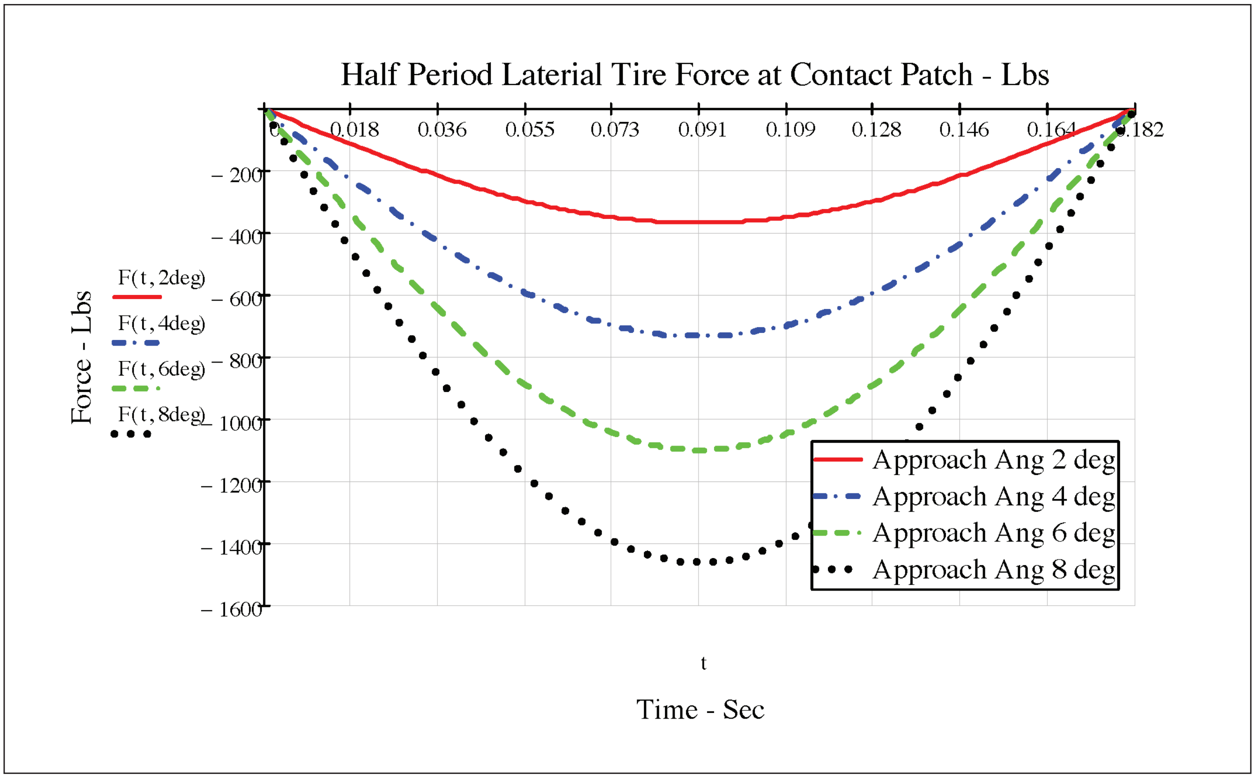

Figure 7
The force on the tire as it strikes the rut at various approach angles.

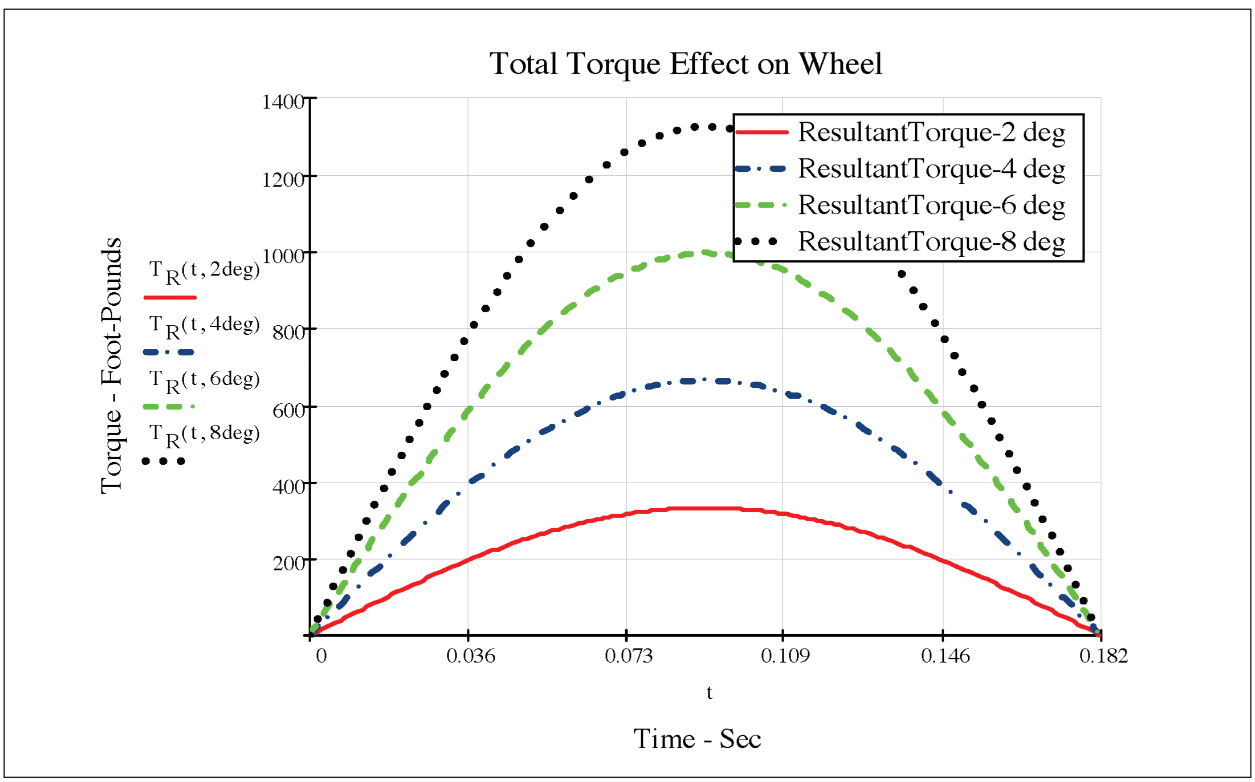

Figure 8
The resultant of the superposition of the gyroscopic effect and
lateral force effect on the front motorcycle tire.

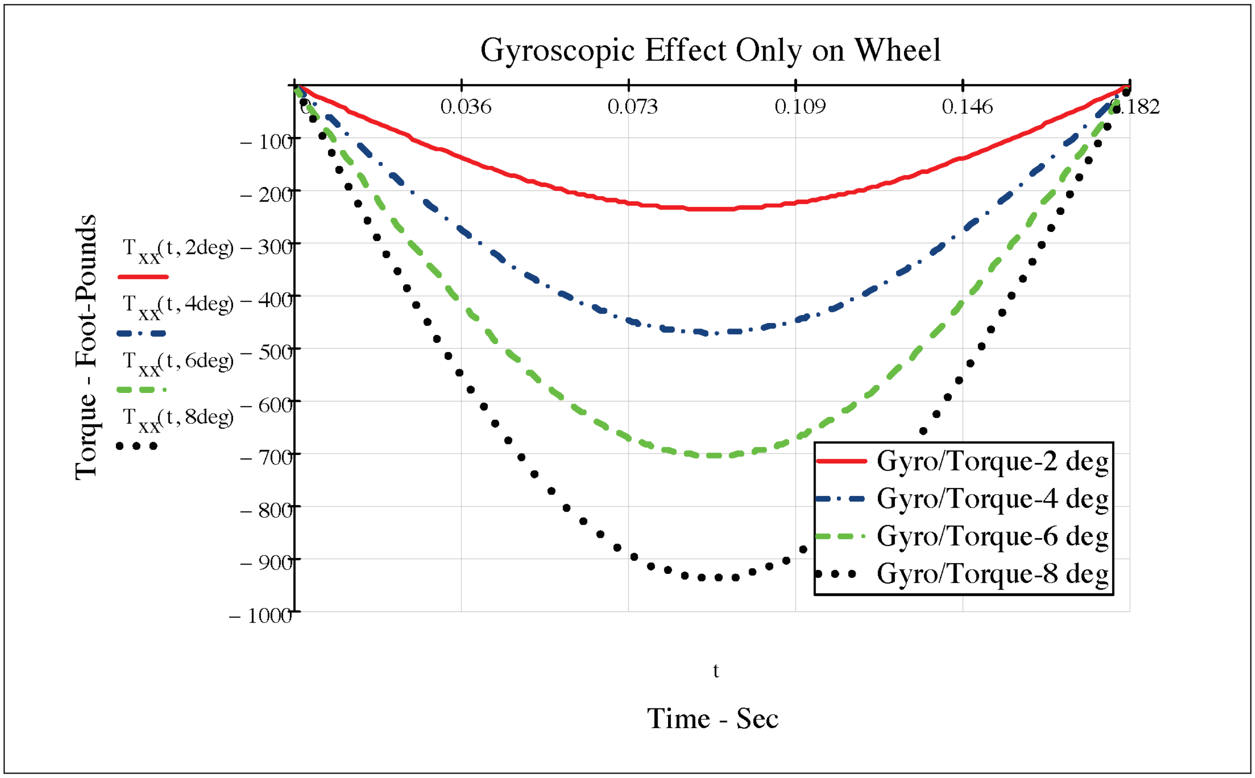

Figure 9
The gyroscopic effect on the tire alone at various approach angles.

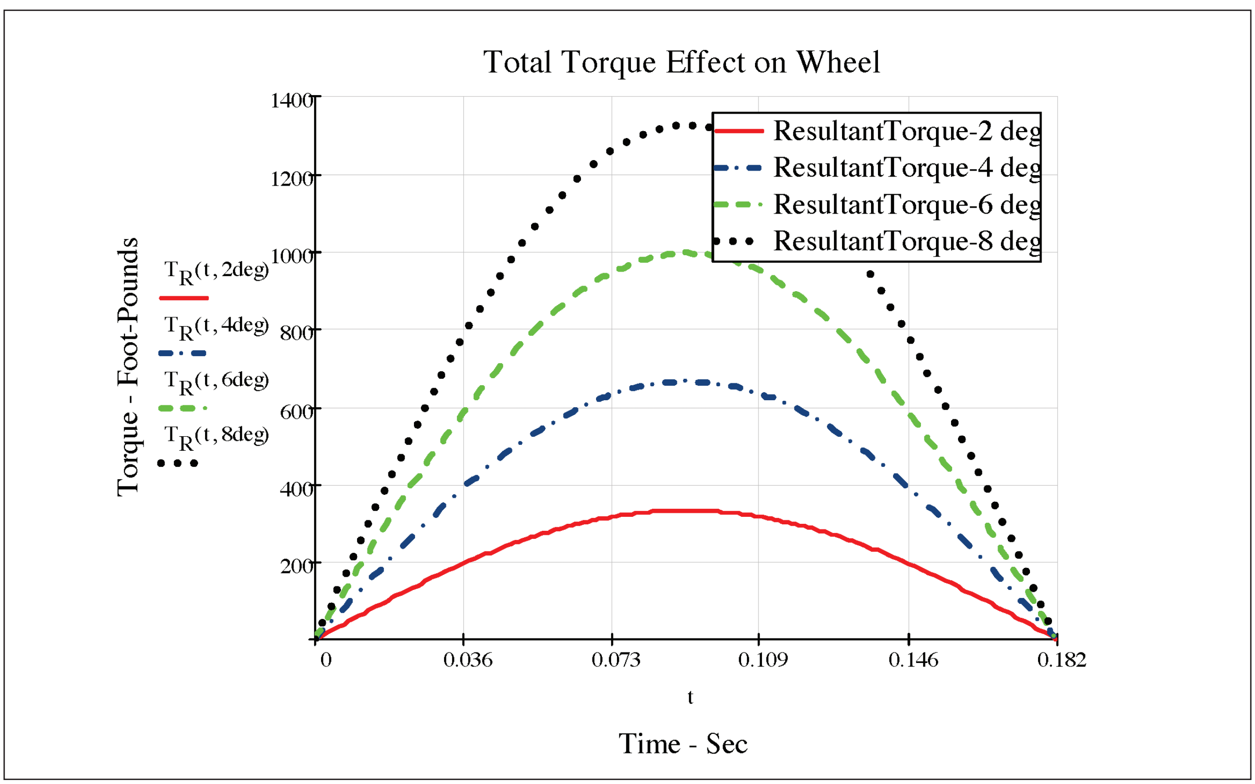

Figure 10
Total torque effect on the tire at various approach angles.

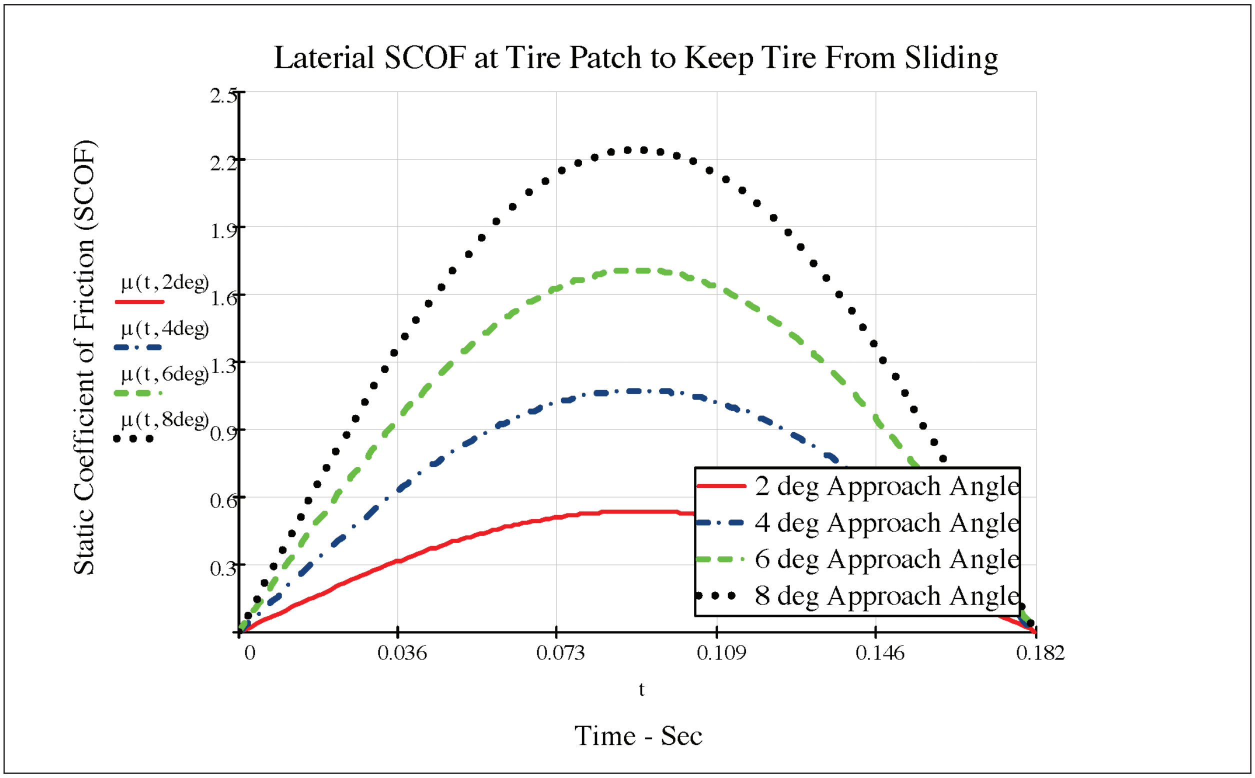

Figure 11
The Static Coefficient of Friction (SCOF) required
maintaining stability for the front motorcycle tire.

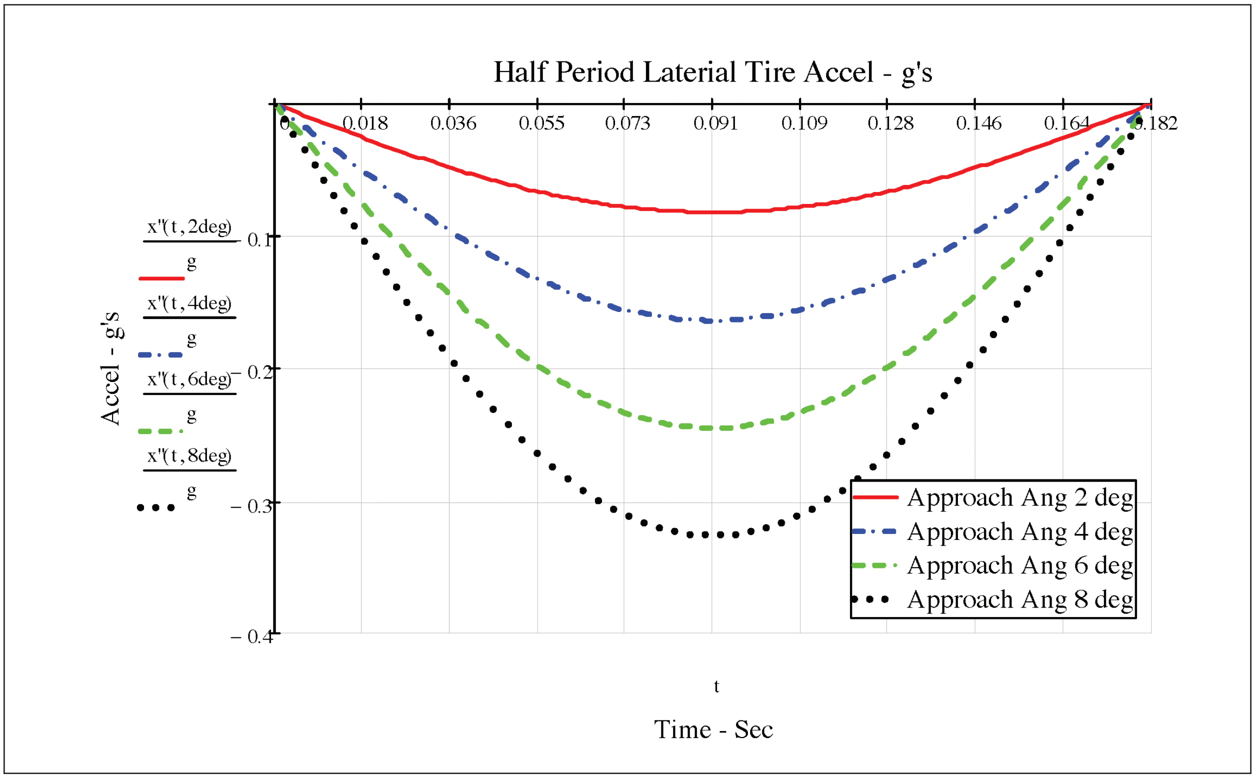

Figure 12
Acceleration of force on side of front motorcycle if the change in level transition
had been 10% as stated in the original construction contract.

DERIVATION:
The tire acts as a spring model in compression and releases. The curb/rut applies a force on the tire. The tire is compressed and released free to move in the direction of the force F_y. The transverse component of the force F_y on the tire as well as the friction forces on the sidewall and the contact patch of the tire create a torque about the steer axis of the motorcycle as well as a change in the Angular Momentum of the wheel. The forces also affect the steering and braking and of the front tire.

Right - Down - Counterclockwise — Positive.

References:
SAE 2006-01-1561, "Behavior of a Motorcycle after an Encounter with a Road Irregularity Parallel to it Direction of Travel". By L.D. Metz

Motorcycle Dynamics, by Vittore Cossalter, 2nd English Edition.

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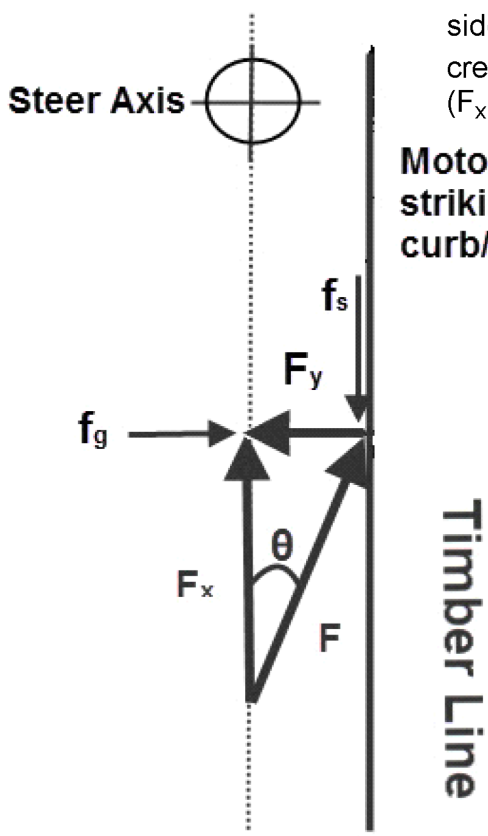
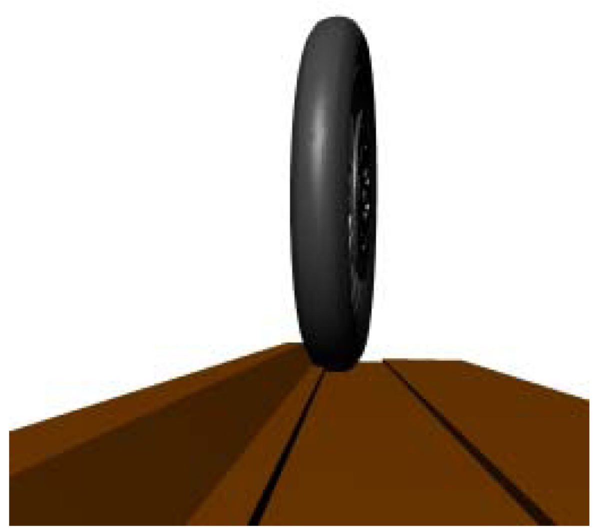
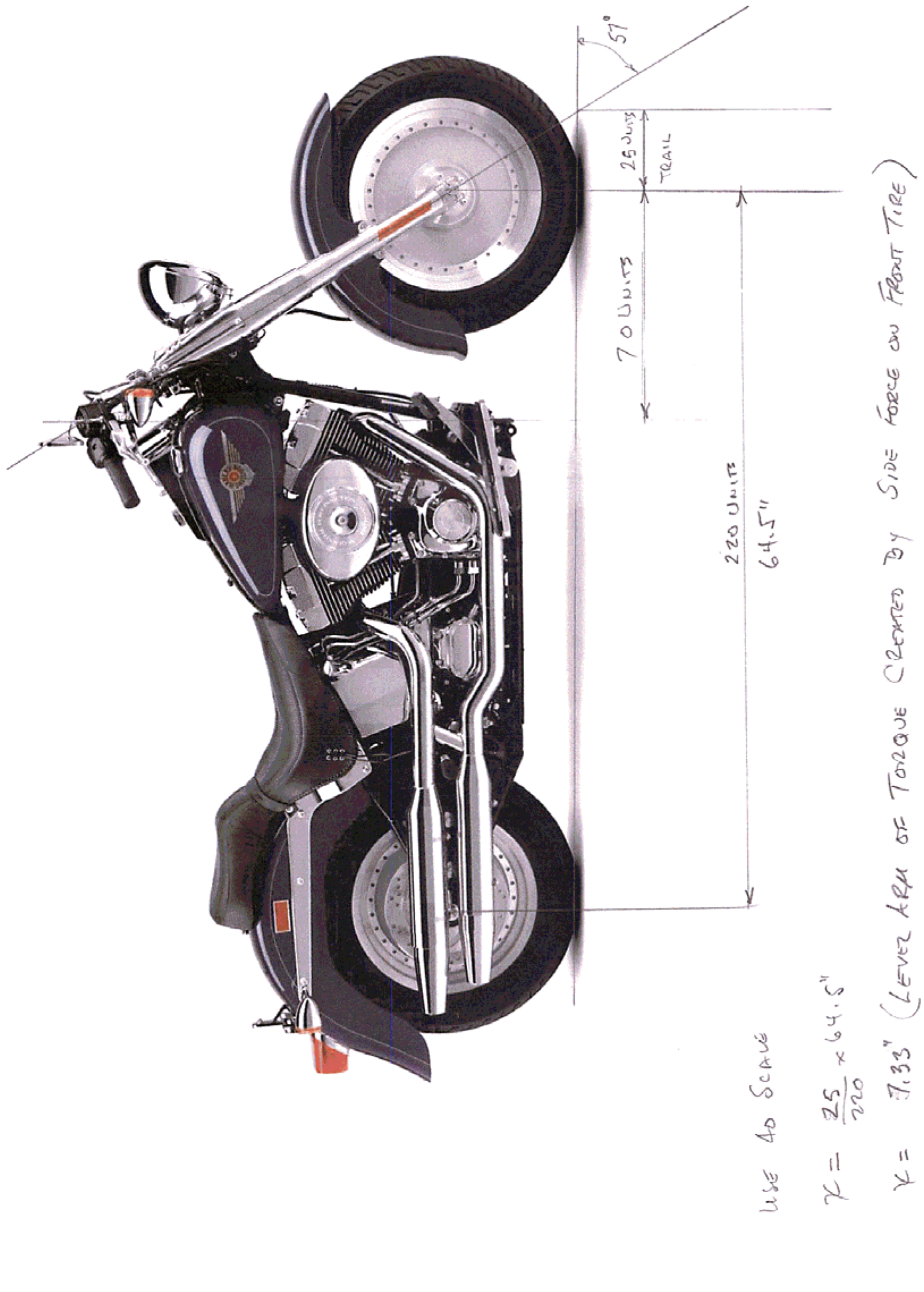
Forensic Engineering Investigation of Motorcycle Instability Induced Crashes, by Mark A. M. Ezra, P.E., National Academy of Forensic Engineers (NAFE) Journal, Vol. 21, No. 1, June, 2004.

Free body diagram of force (F_y) and friction (f_s) on tire sidewall and (f_g) the patch ground friction. Both forces create a clockwise torque about the steering axis. The (F_x) force does not effectively create a torque.



Model of temporary longitudinal timber joint.





Photogrammetry measurements on the motorcycle.

$$F_y - f_g = M \cdot a = F_y - F_y \cdot \mu_g = F_y \cdot \left(1 - \mu_g\right)$$

When the tire strikes the rut edge the force on the tire deflects.
The tire acts like a spring with a force is equal to -kx.
The tire releases from the spring and is free to move.

$$y''(t) \cdot M - F_y \cdot \left(1 - \mu_g\right) = 0$$

$$y''(t) \cdot M + k \cdot \left(1 - \mu_g\right) \cdot y(t) = 0$$

$$y''(t) + \frac{k}{M} \cdot \left(1 - \mu_g\right) \cdot y(t) = 0 \qquad \omega_o{}^2 = \frac{k}{M} \cdot \left(1 - \mu_g\right)$$

$$y''(t) + \omega_o{}^2 \cdot y(t) = 0$$

Trial Solution:

$$y(t) = e^{R \cdot t}$$

$$y'(t) = R \cdot e^{R \cdot t}$$

$$y''(t) = R^2 \cdot e^{e^{R \cdot t}}$$

$$R^2 + \omega_o{}^2 = 0$$

$$R = i \cdot \omega_o \qquad R = -i \cdot \omega_o$$

$$y(t) = A \cdot \cos\left(\omega_o \cdot t\right) + B \cdot \sin\left(\omega_o \cdot t\right)$$

Initial conditions. at t=0; y(t)=0; y'(t)=velocity

$$A = 0$$

$$y(t) = B \cdot \sin\left(\omega_o \cdot t\right)$$

$$y'(t) = B \cdot \omega_o \cdot \cos\left(\omega_o \cdot t\right) \qquad B = \frac{v}{\omega_o}$$

$$y(t) = \frac{v}{\omega_o} \cdot \sin\left(\omega_o \cdot t\right)$$

$\theta := 2\text{deg}, 4\text{deg} .. 8\text{deg}$ — Approach angle of tire relative to rut.

$v(\theta) := 30\text{mph}\cdot\sin(\theta)$ — Transverse tire velocity as the sidewall strikes the rut.

$r := 16\text{in}$ — Front tire radius.

$d := 6.5\text{in}$ — Lever arm distance from tire contact to steer axis.

$\mu_s := 0.4$ — Tire sidewall wet dynamic friction against curb (estimated).

$\mu_g := 0.4$ — Tire patch wet dynamic friction on ground (estimated).

$M := \frac{(750\text{lb} + 240\text{lb})\cdot 0.45}{g}$ $\quad M = 13.8\,\frac{s^2\cdot\text{lb}}{\text{ft}}$ — Weight on front tire includes rider and weight distribution.

$k := \frac{100000}{g}\frac{N}{m}$ $\quad k = 6852\,\frac{\text{lb}}{\text{ft}}$ — Estimated spring constant of tire.

$\omega_o := \sqrt{\frac{k}{M}\cdot(1-\mu_g)}$ $\quad \omega_o = 17.23\,\frac{1}{s}$ — Natural frequency of the tire.

$T := \frac{2\cdot\pi}{\omega_o}$ $\quad T = 0.365\text{ s}$ $\quad f := \frac{1}{T}$ $\quad f = 2.7\cdot\text{Hz}$ — Period and frequency of front tire.

$t := 0\text{ms}, 1\text{ms} .. \frac{T}{2}$ — Time range of force impulse.

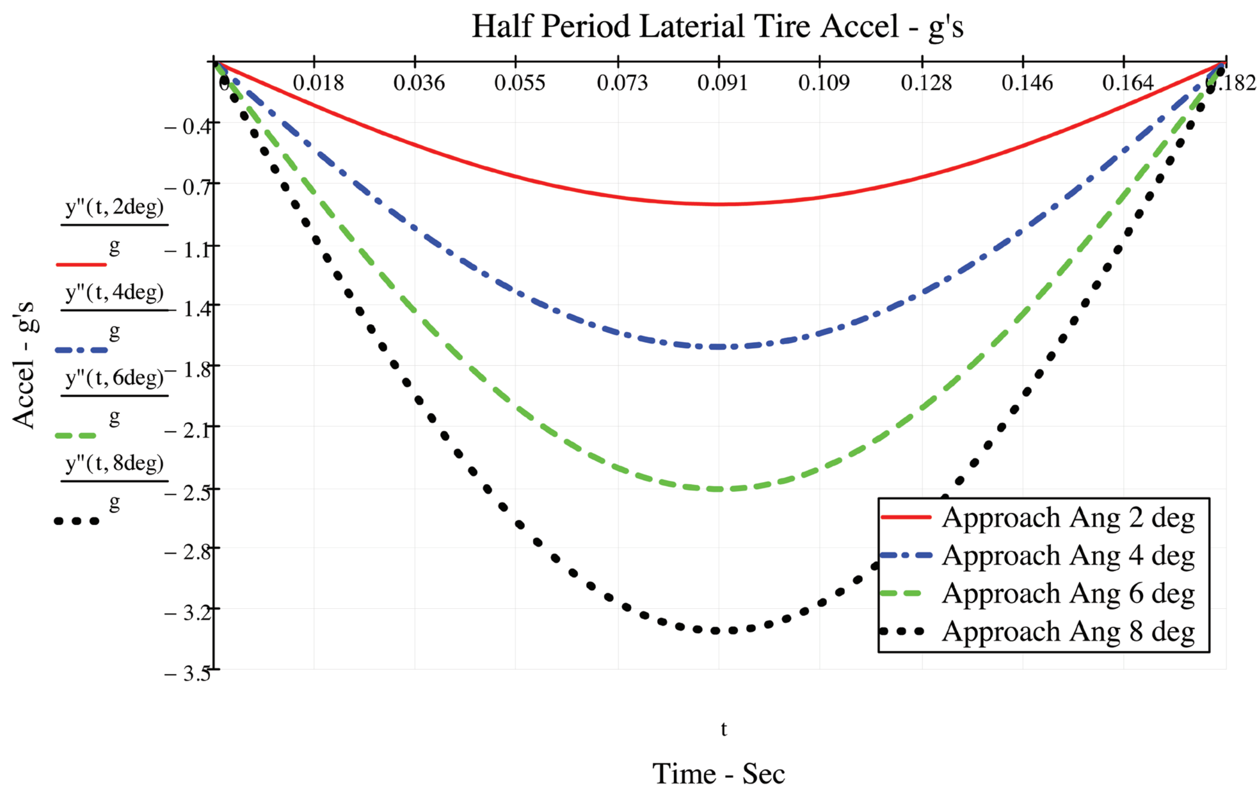
$\varphi := \text{atan}\left(\frac{1.5}{2.5}\right)$ $\quad \varphi = 31\cdot\text{deg}$ — Slope of beveled wood joint. 1.5" : 2.5"

$y(t,\theta) := \frac{v(\theta)}{\omega_o}\cdot\sin(\omega_o\cdot t)$ — Solution to differential equation for approach and bevel angles.

$y'(t,\theta) := \frac{d}{dt}y(t,\theta)$ $\quad y''(t,\theta) := \frac{d^2}{dt^2}y(t,\theta)$ — Solutions of the differential equation for velocity and acceleration wrt time (t).

Check on units.

$y(t,\theta) =$ (·in)	$y'(t,\theta) =$ ($\frac{ft}{s}$)	$y''(t,\theta) =$ (·g)
0	1.54	0
0.02	1.54	-0.01
...	...	...



$r_t := 3\text{in}$ — Estimated radius of front tire.

$F(t,\theta) := M \cdot y''(t,\theta)$ — Calculated lateral force on the front tire in pounds. F = M * a

$T_{xz}(t,\theta) := F(t,\theta) \cdot d + F(t,\theta) \cdot \mu_s \cdot r_t$ — Calculated Torque on the steering axle created by the force at the tire patch on steer axis. T_{xz} = F * d where d is the lever arm from the tire patch to the steer axis and the torque created by the friction force on the sidewall of the front tire; the torque is about the x-x and z-z axis.

$F(t,\theta) =$ (lb)

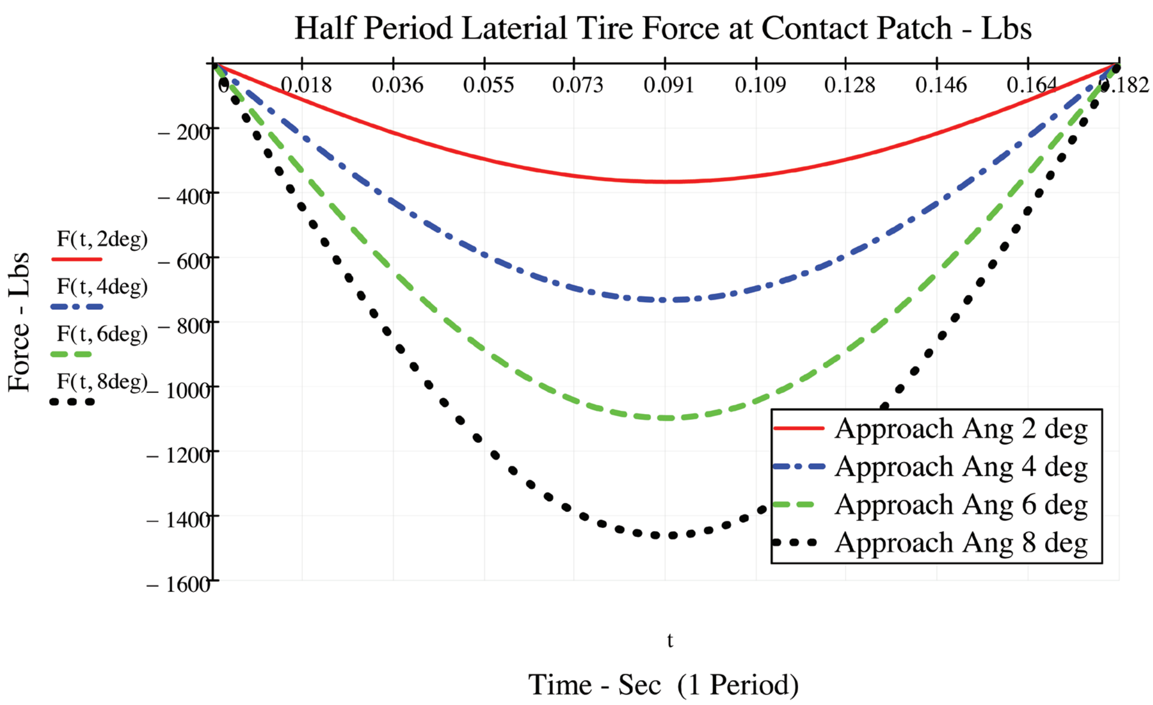
0
-6
-13
-19
...

$T_{xz}(t,\theta) =$ (ft·lb)

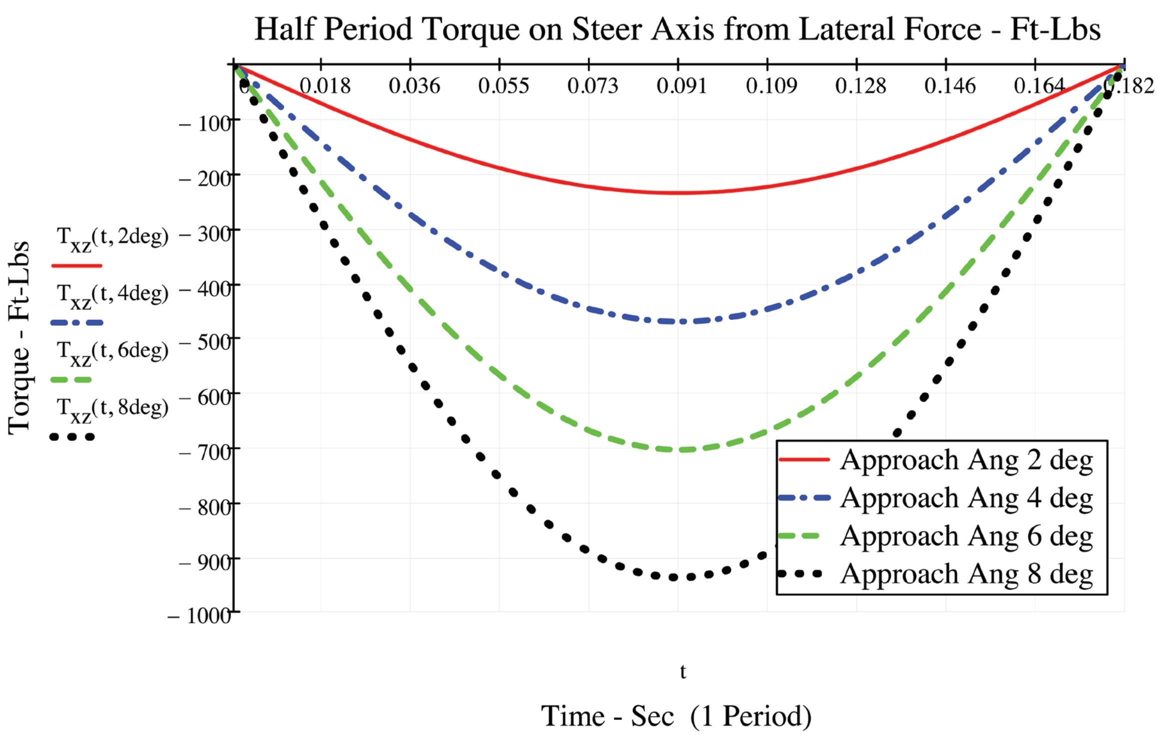
0
-4
-8
-12
...

$y''(t,\theta) =$ (·g)

0
-0.01
-0.03
-0.04
...



The torque on the steering axis is a function of the trail.



Determine the gyroscopic effect of the force applied at the contact patch which will develop a torque about the x-x axis (roll axis).

A. Angular Momemtum is to the left about the y-y axis (pitch axis).
B. The force creates a torque T_{xx} in the up direction in the (z-z) axis.
C. The Torque is applies for a short duration the wheel rotates about the (x-x) and (z-z) axis. (Right hand rule).

The Change in Angular Momentum created by the Torque about the steering (x-z) axis results in an angular acceleration from which the torque about the (x-x) axis can be determined.

$T_{xz}(t,\theta) =$

0
-4.1
...

ft·lb

$I_{xx} := \frac{1}{4} M \cdot r^2$

$I_{xz} := \frac{1}{4} \cdot M \cdot r^2$

$\alpha(t,\theta) := \frac{T_{xz}(t,\theta)}{I_{xz}}$

$\alpha(t,\theta) =$

0
...

$\frac{1}{s^2}$

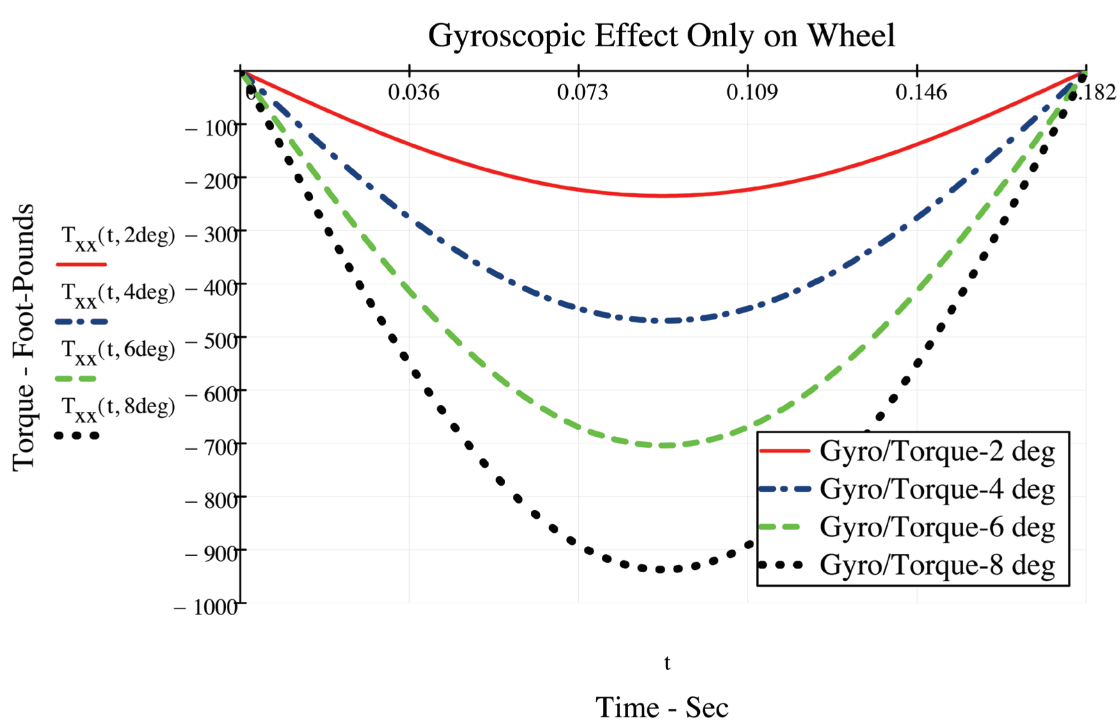
$T_{xx}(t,\theta) := I_{xx} \cdot \alpha(t,\theta)$

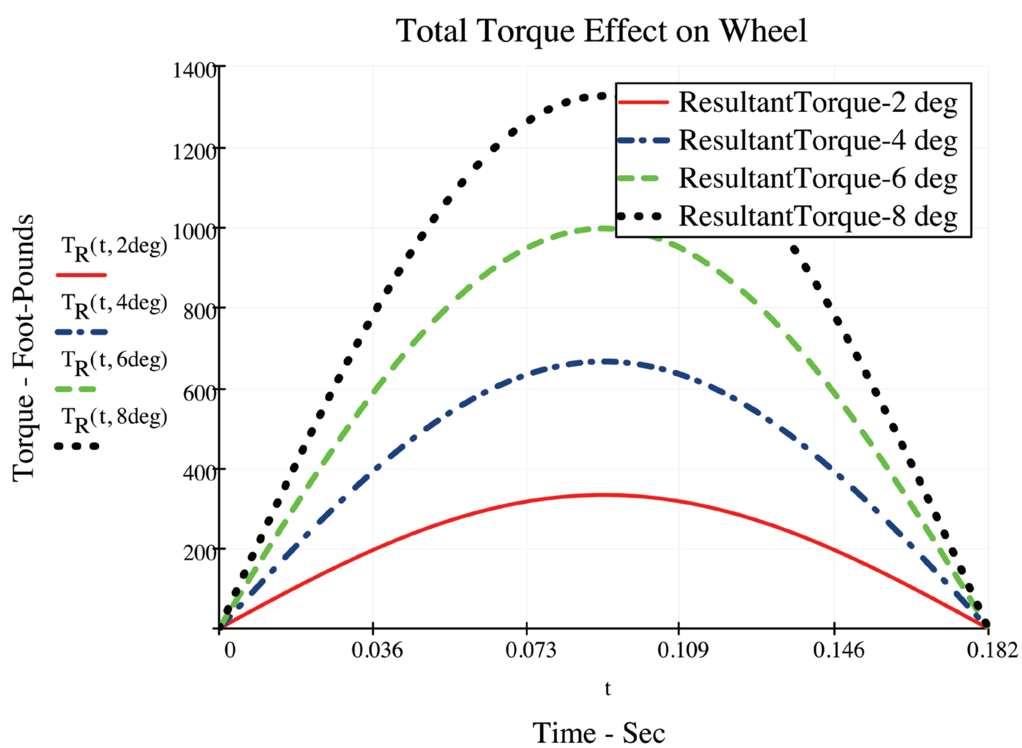
$T_R(t,\theta) := \sqrt{T_{xz}(t,\theta)^2 + T_{xx}(t,\theta)^2}$

$T_R(t,\theta) =$

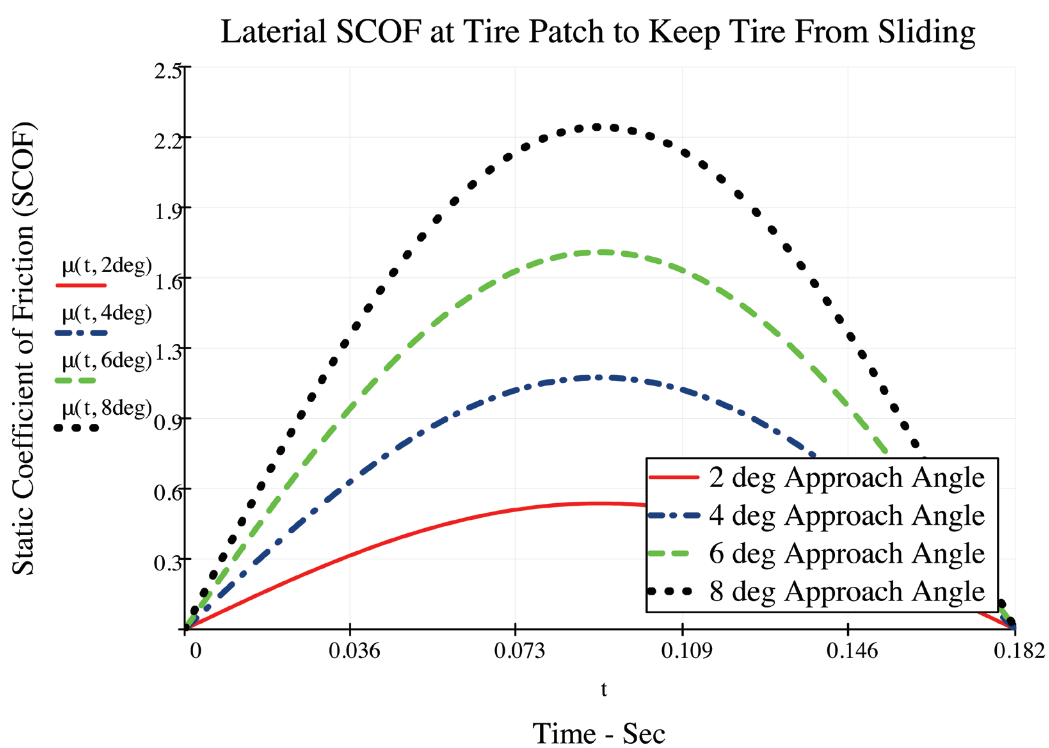
0
6
...

ft·lb





$F(t,\theta) := \frac{T_R(t,\theta)}{r}$ $\mu(t,\theta) := \frac{F(t,\theta)}{M \cdot g}$ Coefficient of friction necessary to keep the tire patch from sliding.



Determine the forces on the asphalt transition between changes in level, if the slope of the asphalt to transition adjacent travel lanes was as designed on a 1:10 slope.

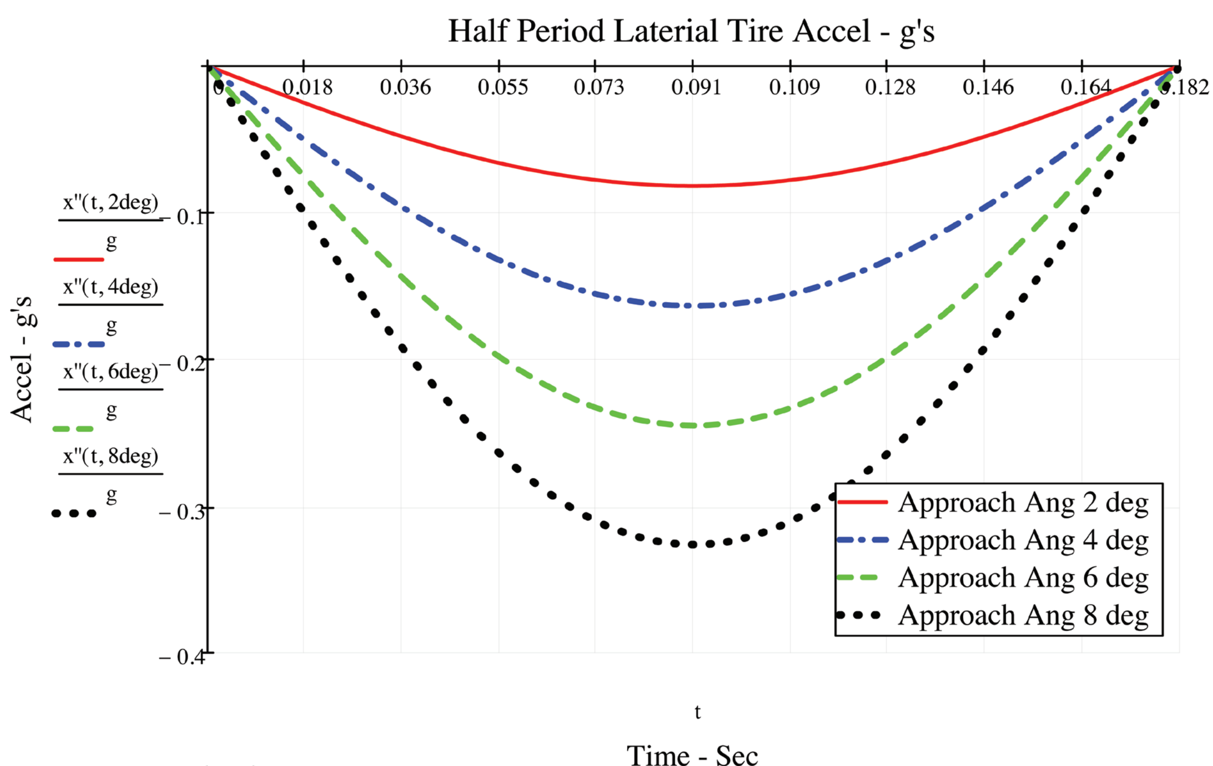
$\beta := \text{atan}\left(\frac{1}{10}\right)$ $\beta = 5.7\cdot\text{deg}$ The slope angle of 1:10 transition.

$x(t,\theta) := \frac{v(\theta)\cdot\sin(\beta)}{\omega_o}\cdot\sin(\omega_o\cdot t)$ Using the same analysis but substituting the slope angle for the timber bevel angle.

$x'(t,\theta) := \frac{d}{dt}x(t,\theta)$ $x''(t,\theta) := \frac{d^2}{dt^2}x(t,\theta)$ The first and second derivatives yielding velocity and acceleration for the 1:10 transition.

$x(t,\theta) =$ $x'(t,\theta) =$ $x''(t,\theta) =$ Checking units.

$x(t,\theta)$ (in)	$x'(t,\theta)$ (ft/s)	$x''(t,\theta)$ (g)
0	0.153	0
0.0018	0.153	-0.0014
...	...	...



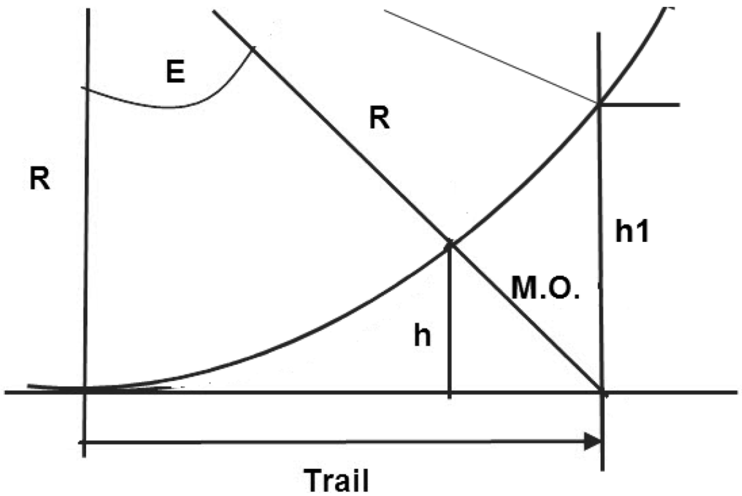
$\text{Ratio}(t,\theta) := \frac{y''\left(\frac{T}{4},\theta\right)}{x''\left(\frac{T}{4},\theta\right)}$

$\text{Ratio}(t,\theta) =$

10
10
...

Had the contractor installed the designed transition, the force on the tire patch and the torque would have been approximately 10 times less which would have given the tire sufficient coffecient of friction to maintain steering and braking.

Consider the effect of negative trail created by the rut height. In the 2nd Edition of Motorcycle Dynamics by Vittore Cossalter on pages 5 through 8, Section 3.1, Mr. Cossalter explains the importance of positive and negative trail on roadway irregularities.



The diagram shows the trail of the front tire of the motorcycle. "h_1" represents the height of the roadway rut/curb that comes in contact with the front tire.

If "h_1" is greater than the vertical projection of the trail then negative trail is created and instability is induced.

(Assume small arc lengths for chords to approximate right angles.)

$\text{trail} := 7.33\text{in}$

$\varepsilon := \operatorname{atan}\left(\frac{\text{trail}}{r}\right)$ $\varepsilon = 24.6 \cdot \text{deg}$ Caster angle.

$MO := \left(\frac{\text{trail}}{\sin(\varepsilon)} - r\right)$ $MO = 1.6 \cdot \text{in}$ Middle ordinate (M.O.)

$h_1 := \frac{MO}{\cos(\varepsilon)}$ $h_1 = 1.76 \cdot \text{in}$ In this case h_1 is the height at which the trail transfers from being a positive trail to a negative trail where instability is created as described by Vittore Cossalter in his book, Motorcycle Dynamics, 2nd Edition, pages 5-8, Section 3.1.

Because the height of the rut is 1.5 inches, the trail is reduced. However, because h_1 is greater than the height of the rut, the front tire does not become unstable, however, that does not preclude the fact that the tire could approach instability.