LOWERED CRASH RISK WITH BANKED CURVES

DESIGNED FOR HEAVY TRUCKS



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Abstract

Outer-curves are banked into superelevation in order to reduce the crash risk due to high demand for side friction between tyres and road. Road design codes use analysis of cornering forces acting on a point-mass model of a vehicle, where the Centre-of-Gravity (CoG) is assumed to be located at the tyre footprint. This may be relevant for low passenger cars. The scope here was to investigate the need for superelevation for heavy goods vehicles (HGV) with high CoG. The study used a vehicle model including both vertical and lateral position of CoG, as well as road split friction under left/right wheels. The results showed that superelevation demand increases with height and lateral displacement of CoG, and peaks when the curve is more slippery under outer wheels than under inner wheels. A conclusion was that the traditional point-mass "car model" can underestimate the superelevation needed for safe HGV operations. The paper recommends some improvements in road design codes for new curves, as well as some actions to improve safety in existing curves.

Keywords: Cornering Forces, Road/Tyre Friction, Ice, Side Friction, Split Friction, Texture, Asphalt Patch Work, Tyre Footprint, Road Design Codes, Banked Curves, Superelevation, Adverse Camber, Horizontal Radius, Curvature, Vehicle Speed, Design Speed, Speed Limit, Centrifugal Force, Vehicle Model, Point-Mass Model, Complexity, Validity, Prime Mover, Trailer, Centre-Of-Gravity, Height, Tyre Wall Flex, Vehicle Body Roll, Lateral Displacement, Weight Transfer, Rollover, Loss-Of-Control, Run Off, Skid, Single Vehicle Crash, Head-on Crash.

1. Introduction

1.1 Background: Road Designers are Unaware about Heavy Vehicle Dynamics

This work deals with road safety in horizontal curves. The vehicle group with highest raise in crash frequency between straight road and curves is heavy vehicles. Several studies on heavy goods vehicle (HGV) dynamics show that stability and crash risk is affected by the position, height as well as lateral displacement, of the vehicles Centre-of-Gravity (CoG). In spite of this, road design codes worldwide have not taken the position of the vehicle CoG into account, when calculating the demand for pavement superelevation in banked curves neither at highways nor at roundabouts or other types of junctions. Virtually all road design codes illustrate the calculation of superelevation demand with a model of cornering forces acting on a passenger car, not on an HGV. Furthermore, the design codes relate to a single value for road friction, implicating identical friction under all tyres. This is for many driving conditions not a reasonable simplification, especially not when driving on a surface with significantly reduced grip (f x debris, loose gravel or slick ice) under the outer wheels.

1.2 Scope: Is Current Curve Design Good Enough for Safe Heavy Vehicle Operation?

The scope for this work was to investigate the relevance of calculating the superelevation demanded by heavy vehicles with high CoG, instead of demanded by low passenger cars. The accident mechanisms in focus are <u>rollover</u> and <u>skidding</u>.

1.3 Research Problem: Is Vehicle CoG and Split Friction Neglectable?

The research problem was "*Is the influence of vehicle CoG position and split friction under inner/outer tyres on the demand for superelevation so small, that these factors are neglectable for road design codes?*

The hypothesis was "*In certain circumstances the position of vehicle CoG and road split friction has significant impact on the demand for superelevation*."

2. Existing Knowledge: Surprising Sharp Flat Outer-Curves Are Hazardous At Speed

Crash rates in horizontal curves have been found to be typically 2 to 4.5 times higher than on straight road sections (Leonard et al., 1994).

Crash types being overrepresented in curves are single vehicle crashes, rollovers, collisions, night crashes and crashes involving drivers under the influence of alcohol and drugs. The crash risk increases exponentially as curve radius tightens (Elvik et al, 2014).

Heavy trucks show the highest raise in crash rates between straight and curved road sections. Single sharp curves after long straight sections, as well as "flat curves", create some of the most hazardous situations (Haywood, 1980).

While rollovers account for less than 20 % of crashes with HGVs (Sellami et al, 2008), as much as 50 % of the severe crashes where an HGV occupant died were rollovers (NVF, 2011). This shows that rollover crashes are more hazardous than other types of crashes.

The most common cause to truck rollovers is the difficulty for the driver to assess the combination of speed, position of CoG and the cornering manoeuvre. The most important risk factors for rollover are high CoG, high speed, cargo displacement, bad road conditions, driver behaviour (incl. road rage as well as lack of focus on the driving task and the payload) and secondary faults, such as skidding into a curb or low crash barrier causing a “trip and fall” rollover (TYA, 2014).

Crash rate ratio between outer-curves and inner-curves in Sweden is extremely high; outer-curves were found 5 times as dangerous. By eliminating the over-risk in outer-curves, about 10 % of all fatal road traffic crashes in Sweden would be prevented (Lindholm, 2002).

The Roadex III project (Granlund, 2008) identified two main risks in outer-curves on the EU Northern Periphery road networks. One key factor is that many outer-curves on old road sections have adverse camber, or insufficient banking, with respect to speed limit and slippery surface conditions. Old curves were constructed for ancient low speed traffic with wagons pulled by an ox or a donkey, but many do not meet the needs of motorized highway vehicles.

A comprehensive study in New Zealand (de Pont & Milliken, 2005) concluded “*A 1 % increase in super-elevation could result in a 5 % reduction in heavy vehicle loss-of-control crash risk while cornering*.”

Slick and dark fresh pavement patches are common causes to extreme split friction, during conditions such as long intense rainfall or thin ice thawing in morning sunlight. While driving at steady state (or even normal accelerating or braking) on the split friction surface may not raise any problem, hard (emergency-)braking can result in a violent swerving “spin force” (moment around the vehicle side where the wheels experience high road grip). Figure 1 shows the 5th crash within two weeks after patch repair of deformed pavement edges into a tight improperly designed curve on national Highway 61 in Sweden (NVF, 2011).

Figure 1 – Slick dark edge patches at a hazardous curve on Hw 61 in Sweden

2.1 Traditional Calculation of Superelevation Demand

To reduce the crash risk due to high demand for side friction between tyre and road (caused by high lateral forces), outer-curves are banked into superelevation. Since the early introduction of the automobile (General Motors, 1937), road designers are guided by scientific design codes into what superelevation value to select, given a reference speed, curve radius and a design value for side friction between tyre and road surface. World-wide, such design codes for road curve superelevation are based on analysis of cornering forces acting on a point-mass model of a road vehicle, see Figure 2.

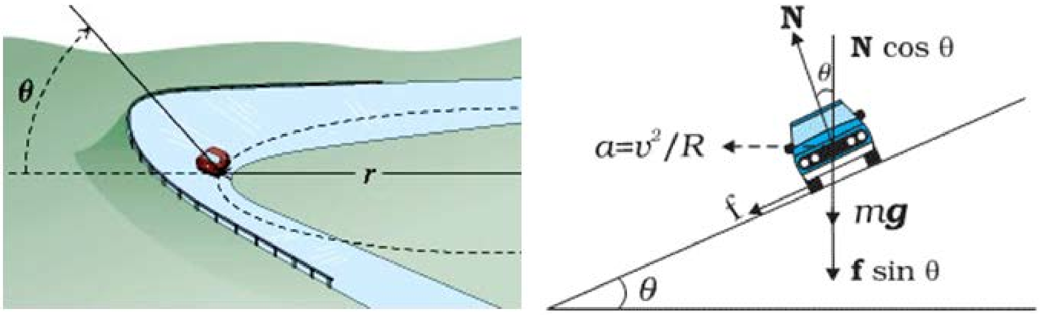

Figure 2 - Basic analysis of cornering forces [Mastering Physics & Physics365.com]

Establishment of the dynamic equilibrium for steady cornering, aiming for minimizing steering effort, weight transfer, tyre wall deformation and tyre contact patch distortion, can be followed in Granlund (2008), from first analysis setup to the final expression "*Cornering forces at equilibrium*" seen in Equation (1). The design speed is $\boldsymbol{v}$ [m/s], curve radius is $\boldsymbol{R}$ [m], the gravitation constant is $\boldsymbol{g}$ [m/s^2], $\boldsymbol{\mu_s}$ [-] is the side friction factor between tyre and road, while the pavement crossfall (superelevation) is given by tangent of the angle θ, ***tan(θ)*** [%].

$$\frac{v^2}{R*g} \approx tan(\theta) + \mu_s \qquad (1)$$

The demanded superelevation *tan(θ)* [%] is calculated for given speed and curve radius (or curvature 1/R) by inserting a design side friction supply factor, such as $\mu_s = 0.10$.

Note 1: The side friction factor μ_s is typically less than half of the available brake friction factor (Trafikverket, 2012). Hence, a wet ice surface that provides brake friction of μ_{brake} = 0.10 is providing less than μ_s = 0.05 in side friction. On other hand, μ_s = 0.10 corresponds to brake friction higher than μ_{brake} = 0.20.
Note 2: Long and thus understeered HGV´s are driven with larger slip angle than cars, and may experience up to 50 % lower side friction than cars on slippery surfaces (such as on ice).

Road design codes around the world use various concepts for side friction supply, utilizing some kind of deduction factor in order to add safety margin. Typically deduction is made as function of speed, resulting in a lower side friction supply factor at a curve with higher speed limit. Deduction can also be made for higher traffic volume. The concept of a "maximum side friction factor" for road design should not be confused with presumably higher available friction, as given by material properties, contamination and mechanics (FHWA, 2009).

The height of the vehicle CoG is for simplicity not considered when deriving Equation (1). This corresponds to “mathematically lowering” the CoG down under the tyres all the way to the contact patch with the road.

Solving Equation (1) for speed gives the expression in Equation (2).

$$v \approx \sqrt{R * g(tan(\theta) + \mu_s)} \qquad (2)$$

The simple point-mass model above and the simplification about the position of the CoG may be relevant for low passenger cars. However the simplified model may not be relevant for heavy goods vehicles (HGV) and bus coaches with CoG located high above the road surface. Figure 3 shows <u>inward</u> weight transfer (lateral displacement of the CoG) in a truck that is “under-speeding” a banked curve at a vehicle test track, whose large superelevation is designed for driving friction-less “no-hand steering” accelerated testing of passenger cars at 180 km/h.

Figure 3 - Truck taking a banked curve at the Hällered Proving Ground [Volvo Trucks]

Typically, the trailer is more critical for rollover than the prime mover / tractor, due to the trailers Centre-of-Gravity normally being higher above the ground (VicRoads, 2011) (Global Trailer, 2013). Among the trailers, half-empty tankers with soft suspension (exposed to slush load) and trailers with dual floors are infamous for being prone to rollover. While few prime mover have CoG higher than some 1.5 m above ground, a dual floor trailer may have its CoG up to 2 m above ground and in fact over 2.3 m if really bad loaded (Dahlberg, 1999).

It should be noted that superelevation and friction force are "signed." They have not only magnitude, but also direction. This may not be reflected in some road design codes. Once a road is constructed, the radius and superelevation (both direction and magnitude) are fixed in every individual road section, so the side friction demand will vary with speed.

3. Research Method: Analysing Cornering Forces With a More Complex Vehicle Model

A more complex vehicle model - more accurately representing a heavy vehicle - was used when analysing the cornering forces, see Figure 4. The used model includes both vertical and lateral position of the CoG (the latter corresponding to lateral weight transfer), as well as the possibility to analyse different road friction (“*split friction*”) at the tyre/road contact patches (“*tyre footprint*”) under the inner wheels and under the outer wheels.

The analysis was made for <u>rollover</u> and for <u>skidding</u>, relating to the vehicle model in Figure 4 and defining the vehicle track width as ***b*** [m].

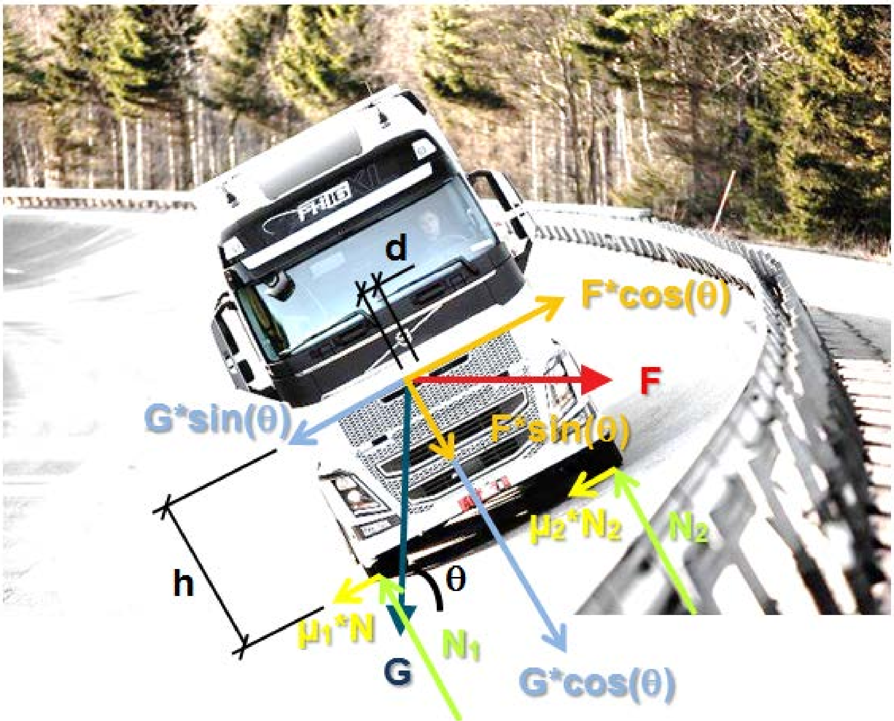

Figure 4 - More accurate analysis of cornering forces in heavy vehicles

4. Results

4.1 Influence of CoG Position on Rollover

Torque equilibrium at the wheel under the driver corresponds to Equation (3).

$$F*cos(\theta)*h - F*sin(\theta)*(b/2 + d) - G*sin(\theta)*h - G*cos(\theta)*(b/2 + d) + N_1*b = 0 \qquad (3)$$

At the rollover threshold, N_1 equals 0 (zero). Then all normalforces[1] are acting at N_2. After division by $cos(\theta)$ and rearranging the terms, Equation (3) can be written as Equation (4).

$$h_{rollover} *(F - G*tan(\theta)) = (b/2 + d)*(F*tan(\theta) + G) \qquad (4)$$

By solving for maximum CoG height *h* without rollover, the result is given by Equation (5).

$$h_{rollover} = (b/2 + d)*(F*tan(\theta) + G)) / (F - G*tan(\theta)) \qquad (5)$$

After inserting definitions of centrifugal force, $F = m*v^2 / R$, and of gravity $G = m*g$, Equation (5) can be rewritten as Equation (6).

$$h_{rollover} = \frac{\left(\frac{b}{2}+d\right)*(\frac{v^2}{R}*tan(\theta)+g)}{\frac{v^2}{R}-g*tan(\theta)} \qquad (6)$$

[1] *Note: Hard braking while the vehicle is close to the rollover threshold, brings risk for swerving around the side where the wheels are carrying all the normalforces.*

The above analysis of rollover is hereafter applied to three cases; *The Roundabout*, *The Modern Highway Curve* and *The Old Road Curve*.

The Roundabout
Using Equation (6) and inserting track width (centre) b = 2.20 m, CoG lateral displacement d = 0.3 m, speed v = 43 km/h (12 m/s), R = 20 m, θ = 0 and g = 9.81 m/s^2, the rollover height is calculated to 1.9 m. This is lower than CoG-heights expected for dual floor trailers with several common load combinations (Dahlberg, 1999), indicating a rollover risk.

The Modern Highway Curve
Following the roundabout settings, but changing to speed v = 80 km/h (22.2 m/s) and R = 2 500 m, the rollover height is calculated to 70 m. This is much higher than any trailer CoG.

The Old Road Curve
Following the Modern Highway settings, but changing to speed v = 72 km/h (20 m/s) and R = 125 m, the rollover height is calculated to 4.3 m. This is twice as high as normal trailer CoG.

4.2 Influence of Weight Transfer and Split Friction on Skidding

Force equilibrium parallel to the pavement corresponds to Equation (7).

$$F*cos(\theta) - G*sin(\theta) - \mu_1 * N_1 - \mu_2 * N_2 = 0 \tag{7}$$

By inserting the definition of centrifugal force, $F = m*v^2 / R$, in Equation (7) and solving for maximum speed v without skidding, the result is given by Equation (8).

$$v_{skid} = \sqrt{\frac{R*(\mu_1*N_1+\mu_2*N_2+G*sin(\theta))}{m*cos(\theta)}} \tag{8}$$

At small angles, such as the magnitude of normal road superelevation angles, the cosine function is close to 1.00, which leads to the good approximation in Equation (9).

$$v_{skid} \approx \sqrt{\frac{R*(\mu_1*N_1+\mu_2*N_2+G*sin(\theta))}{m}} \tag{9}$$

Inserting the definition of gravity $G = m*g$ and solving for the angle θ gives Equation (10).

$$\theta \approx sin^{-1}((\frac{v_{skid}^2*m}{R} - \mu_1 * N_1 - \mu_2 * N_2)/(m*g)) \tag{10}$$

Required Superelevation with Traditional Vehicle Model and with More Complex Model
A dangerous skid condition is driving at high speed in a flat sharp curve causing outside weight transfer ($N_2 > N_1$), on a road where the side friction in the outer wheelpath is lower than in the inner wheelpath ($\mu_2 < \mu_1$). Using Equation (10) and inserting v = 40 km/h (11.1 m/s), m = 10 000 kg, R = 100 m, μ_1 = 0.1 (ice rugged by studded car tyres), μ_2 = 0.05 (slick ice near roadside), N_1 = 25 kN, N_2 = 75 kN, the resulting angle θ becomes 3.55° and the superelevation *tan(θ)* becomes 0.062 or 6.2 %. This can be compared to superelevation calculated by the simpler Equation (1), after solving it for *tan(θ).* Using same input as above and μ_s = 0.1 the result *tan(θ)* becomes 0.026 or 2.6 %. By instead using μ_s = 0.075 (average of μ_1 = 0.1 & μ_2 = 0.05 used in the previous analysis), Equation (1) gives *tan(θ)* = 0.051 or 5.1

%. For both side friction values tested, Equation (1) yields significantly lower estimates of the demanded superelevation, compared to the critical angle calculated with Equation (10) and the resulting critical superelevation. The relative difference was 58 % respectively 18 % lower superelevation.

5. Discussion

When designing pavement superelevation, the importance of considering the CoG lateral displacement (weight transfer) rise significantly for situations where the outer wheel travels on loose gravel, on ice sheets or on other kinds of contamination making the lane outer edge more slippery than the inner part of the lane.

Most crashes are not caused by a single factor, but by several joint factors. The analysis did not cover disturbing circumstances, such as bad (too fast) change of lane in multiple lane roads (Granlund, 2010), pavement settlements or other unevenness / road roughness, wind bursts, having underinflated or flat tyres, lateral offset heavy payload, speeding, improper driving manoeuvres et c. When added with such circumstances, the crash risk caused by adverse cambered curves may strongly increase.

Results from the analysis of rollover crash mode indicates that improperly designed crossfall may, despite low speed, be a primary fault to rollovers in very sharp corners such as roundabouts, ramps and hairpin bends. On the other hand, despite highway speeds, improper crossfall at highway curves seem unlikely to act as single fault to "clean" rollover crashes. However, the lateral weight transfer in adverse cambered highway curves of course increase the risk of improper driving manoeuvres, as well as increasing the risk for skidding followed by various possible "trip and fall" rollovers against curbs or other obstacles at, or outside, the pavement edge.

Results from the analysis of skid crash mode show that design of crossfall in horizontal curves may end up in a road with unintentionally low road safety margin, if the road design is based on the traditional point-mass vehicle model without considering the effects of vehicle CoG position / displacement due to weight transfer as well as foreseeable split friction between the wheel paths. The influence of pavement crossfall magnitude on skid tendency seems small at crossfall values in a rather wide range around "optimum" crossfall, but is likely to increase strongly as deviation in crossfall increase outside the mentioned stable range (thereby increasing the hazardous lateral weight transfer).

Asphalt patching is a road repair method that, in certain versions, must be questioned for imposing extreme crash risk during some road weather conditions. Patching is necessarily and thus routinely made on pavements with insufficient bearing capacity (f x due to lack of lateral support from a proper shoulder). Often the fresh dark black patches are produced with slick surface (too little macrotexture), and sometimes the patch is accompanied by even slicker longitudinal bituminous seals. These slick and greasy surfaces may in wet condition become slippery as ice. New black patches may also in cold weather impose a surprising crash risk, as thin ice melts faster and thus earlier on the dark patches than on the adjacent old greyish asphalt. The result is summerlike bare asphalt friction in one wheel path, while extreme slippery wet melting thin ice in the other wheel path. A sustainable solution to the root problem is typically reinforcement of the pavement, often including construction or widening of a hard shoulder. To prevent split friction after ubiquitous patching, preferably the full lane width - not merely the asphalt patch - should be “spray sealed” surface treated in order to create homogeneous pavement texture and colour under all wheels.

6. Conclusions and Recommendations

For roads where same speed limits apply for both passenger cars and HGV´s, the results show that the need for road superelevation is given by HGV’s rather than by cars. Hence road design codes should use models of HGV´s rather than of passenger cars.

The demand for superelevation increases with height of CoG and with lateral displacement of CoG (weight transfer).

The demand for superelevation increases even further, during driving conditions with split friction (“*μ-split*”) where road friction is significantly lower under outer wheels than under inner wheels.

Up until now, road design codes for horizontal curves have neither considered the impact from lateral variance in road friction, nor the influence of high CoG as well as lateral displacement of the CoG, on the demand for superelevation. The traditional point-mass “car model” can underestimate the superelevation needed for safe HGV operations, regarding primary fault to rollover in tight low speed corners as well as skid tendency and the risk for secondary fault to various crash modes (including “trip and fall” rollovers) in high speed highway curves. Hence several road design codes worldwide may be stating suboptimal values for superelevation / crossfall in horizontal curves, roundabouts and ramps.

Recommended actions to improve safe mobility in existing unsafe curves, identified with the enhanced vehicle model showed above, includes rapid installation of warning signs (preferably radar-based) as well as intensified snowploughing and gritting (winter) and enhanced cleaning of debris (summer), until the pavement crossfall has been corrected by carefully designed accurate reconstruction.

There is need for more research in HGV lateral weight transfer in improperly banked curves. Another topic that should be more explored is side friction factors - not to be confused with the twice as high brake friction factors - between truck tyres (both summer tyres and softer winter tyres) and road surfaces. Particular focus should be given - both in research and in daily road management - to actions aiming to prevent or at least reduce variance in friction supply between outer and inner wheelpath in horizontal curves during various vehicle operation conditions (road surface contaminations, etc.).

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