EXPERIMENTAL EVALUATION OF CURVES DESIGN RULES BY ANALIZING VEHICLE \ INFRASTRUCTURE INTERACTIONS

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ABSTRACT

Roads geometrical design rest partly on relations between the allowed speed of use, the curvature of the plotting and the banking. These relations have sometimes old justifications as in France where the documents used date from 1994.

Work presented here comes in the line off a checking approach of these calculation means. In this direction, a preliminary trial run was carried out with a highly instrumented test vehicle rolling in a turn. The road wetting state influence was evaluated for dry and streaming levels.

Comparison between the existing relations 'speed-curvature' and the experiments show that the rules include safety coefficients to take into account the variety of the road usages and the model simplicity. Thus, the users safety is not always assured for the using rules can be broken, if appearing badly founded. So, experiments can help to determine a signage more adapted to the encountered situations, and thus, more respected.

Later studies will make it possible to extend this confrontation to various bankings, intermediate wetting states and to a panel of vehicles. These researches will finally contribute to the qualification of road safety offer in relation to the various categories of vehicles which it has to accommodate.

1. FRENCH DESIGN RULES

French design rules are given in the ARP (Aménagement des Routes Principales, *main road design*) [1]. Their main author T.Brenac has enunciated their theoretical fundaments. It consists in a vehicle modelling complemented with safety and comfort coefficients. These calculi have been made in 1993. The rules are pretty old and that is why we decided to check their coherence with nowadays reality.

2. Model hypothesis

In order to correctly design roads, rather strong hypothesis have been taken on the model:

- The pavement has been taken as an average pavement which characteristics were established by national skidding tests in 1970.
- The vehicle is representative of all vehicles. This means a tourism vehicle in a general good state. It can be seen that this hypothesis depends on the vehicle technology improvements. Today, in 2008, vehicles are rather different from vehicles in 1993.

- Using conditions have been taken very bad. Water depth on the pavement is equivalent to 2mm and tire are considered as slick
- The driver is supposed to be fairly experimented and able to drive.
- The conventional speed is defined as the speed that a traffic free vehicle can drive in a curve.

3. Relation between stability limits and design values

Most of researchers working on vehicle dynamics know that the vehicle stability limit is reached when the slip angle become greater than 12° to 15° [2]. The design rules author has decided to take a stability limit equivalent to 5° of slip angle. This is voluntarily an under estimation of physical limits in order to ensure safety.

However, this stability limit is never reached by fairly experimented drivers because they keep a safety margin. So, a safety limit has been defined as 2/3 of the stability limit according to various tests realized in 1970. The safety limit has been described using the safety maximum of lateral acceleration.

$$\gamma_{\max\_saf} = g(\frac{2}{3}\mu(5°) + d)$$

In this formula, g is the gravity constant, $\mu(5°)$ the lateral grip with 5° of slip angle and d the road banking.

Finally, a comfort coefficient ($X = 0{,}67$) is added partially arbitrary to take into account the driver behaviour. This value is coherent with other European norms.

$$\gamma_{\max\_adm} = g(\frac{2}{3}\mu(5°)X + d)$$

4. Limits establishment

Finally, the author gives an admissible lateral acceleration as a function of the speed.

Table 1 - Admissible lateral acceleration with d=0

V (ms^{-1})	40	60	80	100	120
γ_{adm} (g)	0,231	0,173	0,147	0,12	0,111

5. EXPERIMENTS DESCRIPTION

The evaluation of curve design rules needs the realization of several tests. Various experiments have been lead at constant speed from 60 km/h to 100 km/h with 10km/h steps. Three curve radii have been tested (90m, 110m and 130m) for dry and wet road state. If driving speeds have been judged to high by the pilot, they have not been tested for safety purpose.

6. Test setup

Main test means at our disposal were a curve with a 110m radius and 2,5% road banking. The curve pavement is new.

Figure 1- Test track with its curve

For test needs, two radii (90m and 130m) have been plotted on the road using a centimetrical RTK GPS. Trajectories have been followed using signage cones and have been checked in post processing.

The other main mean is the test vehicle. A passenger car, Peugeot 406, that is quite representative of the average vehicle in France. The main characteristics of this vehicle are:

- Mass: 1618 kg
- Mass repartition: 54% on the front, laterally centered.
- Wheel base: 2,7m (distance between front and rear wheels)
- Track: 1,5m (distance between left and right wheels)

In order to evaluate the vehicle state, it has been highly instrumented:

- Inertial measurement unit
- GPS RTK
- Dynamometrical wheel
- Wheel rotation rate sensors
- Tire crushing sensor
- Frame angles sensors (laser and potentiometers)
- Water depth sensor
- Biaxial optical speed sensor

7. DESIGN RULES AND EXPERIMENTS COMPARISON

A first step to compare the experimental data with the design rules consists in studying our test curve characteristics with the design rules.

8. Test curve evaluation

The test curve has a 2,5% road banking with three different radii. So it is possible to determine an admissible speed using the formula from the design rules.

$$\gamma_{\max\_adm} = g(\frac{2}{3}\mu(5°)X + d)$$

In this formula, if we write $\gamma_{\max\_adm} = \frac{V^2}{R}$ and $\mu(5°) = 3{,}9 \cdot 10^{-5} V^2 - 0{,}0096V + 0{,}84$ ($\mu(5°)$ is a function of speed V), we obtain:

$$(\frac{1}{Rg} - \frac{2}{3} \cdot 0{,}67 \cdot 3{,}9 \cdot 10^{-5})V^2 - \frac{2}{3} \cdot 0{,}67 \cdot 0{,}0096 \cdot V + \frac{2}{3} \cdot 0{,}67 \cdot 0.84 - d = 0$$

For each of the three curvature radius, the admissible speed is given in Table 2.

Table 2-Rules admissible speed

Curvature Radius (m)	Vadm(km/h)
90	49
110	53
130	57

To analyse this result, the admissible speed can be compared to the V85 speed. 85% of road users are driving at a lower speed than V85. A recent work on design rules [3](2006) gives a method to calculate this speed:

$$V85 = \frac{92}{1 + \frac{346}{R^{1,5}}}$$

This formula is only worthy for two lanes road where R is the curve radius.
In the following table is given V85 compared to our three curvature radii.

Table 3-Speed V85

Curvature Radius (m)	V85 (km/h)
90	65
110	70
130	75

Admissible speed is lower than V85. This means that road users are driving faster that is has been expected because safety and comfort coefficients are high. Drivers feel they can go faster than the design optimal speed [4]. So the speed limit should be in relation with the sensed dangerousness.

9. Real physical stability limit

Test that were carried out on the LCPC test track permit to evaluate a physical speed limit using two methods [5]:

- Understeer gradient
- Yaw rate compared to steer angle

The understeer gradient describes the behaviour type of the vehicle. If this gradient is negative, the vehicle is oversteering and if the gradient is positive, the vehicle is understeering. This gradient K_{us} is defined with the mass repartition between the front and rear axle (F_{front} and F_{rear}) and by their slip angle stiffness (C_{front} and C_{rear}).

$$K_{us} = \frac{F_{front}}{C_{front}} - \frac{F_{rear}}{C_{rear}}$$

Another definition of the understeer angle permits to calculate it from experimental results.

$$K_{us} = \frac{g}{V^2}\left(\frac{\delta}{\dot{\psi}}V - l\right)$$

δ is the steer angle, $\dot{\psi}$ the yaw rate, V the speed and l the wheel base.

The understeer gradient has been plotted versus the vehicle speed for different curvature radii.

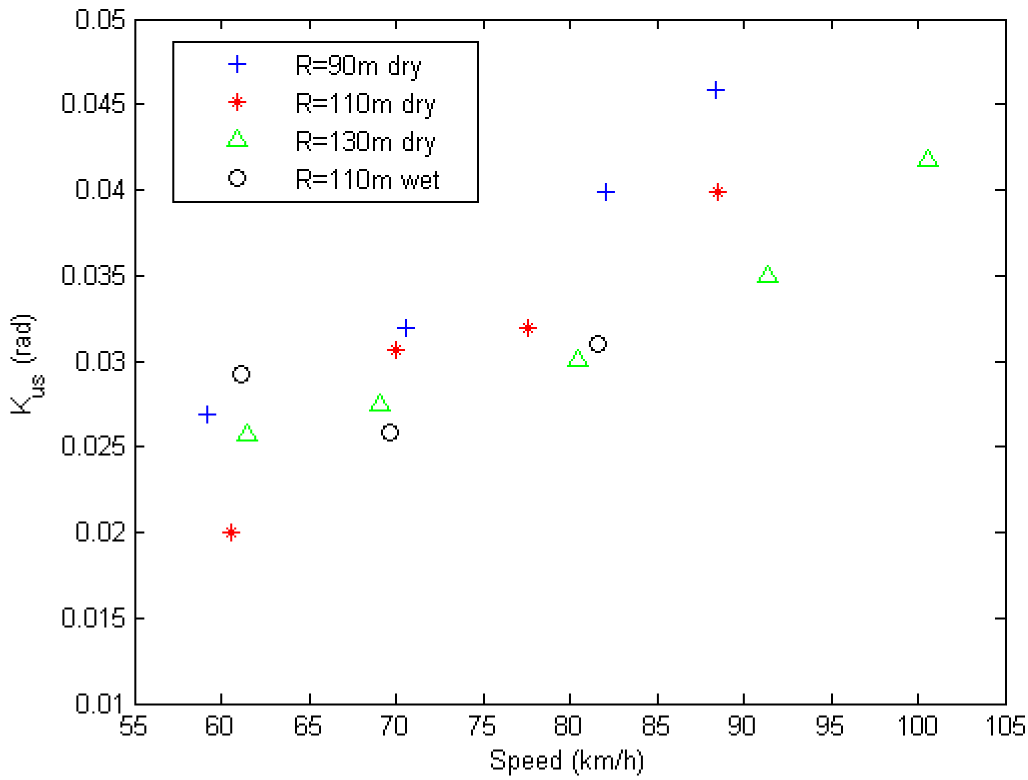

Figure 2-Understeer gradient versus speed

It can be seen on Figure 2 that K_{us} is growing with the vehicle speed and diminishing with the curve radius. This evolution indicates that the vehicle is more and more understeering when speed is growing and less and less understeering when the radius is growing.

When $K_{us} > 0$, it is not possible to define a limit speed because understeering is not considered as instability. However, a characteristic speed has been defined which represents the moment when a steering wheel angle increase does not generate a rotation rate increase. That means that you can turn the steering wheel as you want, the vehicle will not turn more. This characteristic speed is:

$$V_{char} = \sqrt{\frac{gl}{K_{us}}}$$

However on Figure 2, the evolution of K_{us} can be approximated as quadratic. So we can find V_{char} with:

$$V_{char} = \sqrt{\frac{gl}{aV_{char}^2 + bV_{char} + c}}$$

Where coefficients a,b and c are given in the following table:

Table 4- Coefficients a,b and c

	R=90m	R=110m	R=130m
a	$1{,}5 \cdot 10^{-4}$	$3{,}9 \cdot 10^{-4}$	$1{,}2 \cdot 10^{-4}$
b	$-4 \cdot 10^{-3}$	$1{,}5 \cdot 10^{-2}$	$-3{,}9 \cdot 10^{-3}$
c	$5{,}1 \cdot 10^{-2}$	0,18	$5{,}8 \cdot 10^{-2}$

With these coefficients, it is now possible to estimate the characteristic speed:

Table 5-Characteristic speed

Rayon (m)	V_{char} (km/h)
90	86,6
110	88,7
130	96,7

The second method to evaluate a limit speed is to plot the yaw rate versus the steer angle. The evolution of yaw rate compared to steer angle is non linear and when the yaw rate reaches a saturation level it is not possible to turn more whatever is done on the steering wheel. So, a limit speed can be defined at this saturation level (Figure 3).

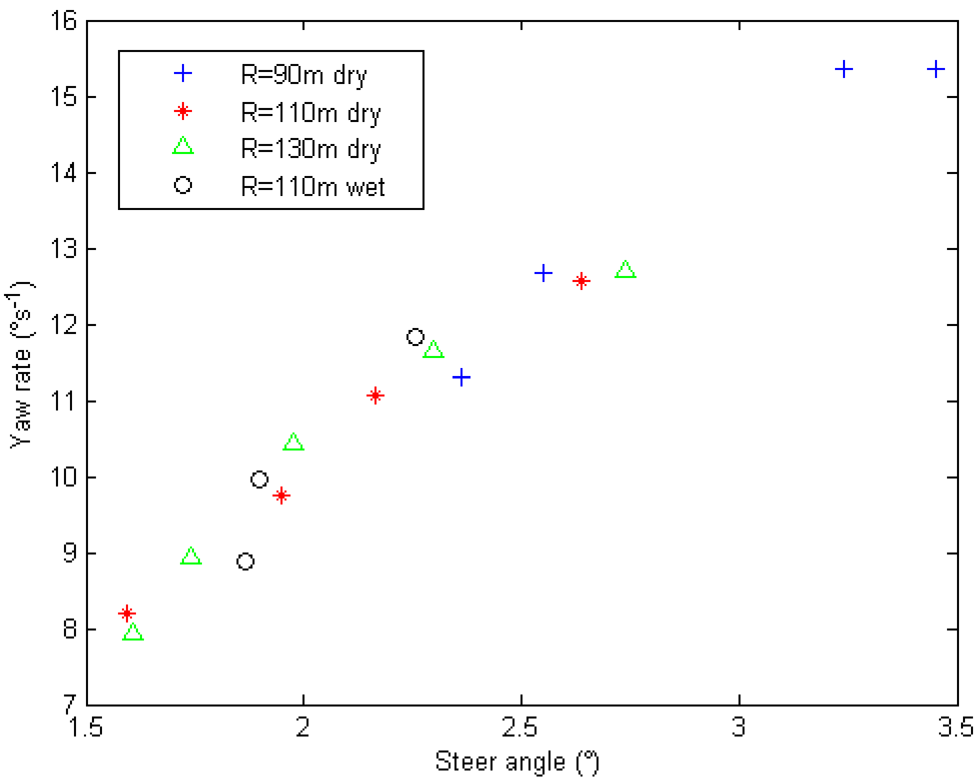

Figure 3- Yaw rate versus steer angle

On figure 3, the saturation level can be seen for the different radii. The three cases on dry surfaces have been approximated by a quadratic curve. The case on wet pavement has not been taken into account because of the lack of experimental data. With the approximation, a maximum yaw rate and a limit speed can be estimated for each curvature radius (Table 6).

Table 6-Limit speed using yaw rate

Radius (m)	$\dot{\psi}_{max}$ (rad/s)	$V_{\lim}$ (km/h)
90	15,56	88
110	14,13	97,6
130	12,08	98,6

The limit speed calculated with the yaw rate is coherent with the speed calculated with the understeer gradient.

10. Results compilation

A compilation of the different speeds encountered in this article is presented here (Table 7):

Table 7-Speeds

Radius (m)	V_{rules} (km/h)	V_{85} (km/h)	$V_{\lim}$ (km/h)
90	49	65	87
100	53	70	93
130	57	75	97

V_{rules} is the speed from the design rules, $V_{\lim}$ the mean of speeds calculated with understeer gradient and yaw rate. It can be seen in Table 6 that the speed determined by design rules is little more than half the stability limit speed in dry conditions. This is definitely not a bad point because it ensures safety. However, the driver feels the difference and drives faster than the rules have planned. In this case it becomes dangerous for the driver who is incited to drive faster to test the real stability limit. If the driver could sense the correlation between the situation dangerousness and the speed limit, it would be better for safety.

11. CONCLUSION AND PERSPECTIVES

This work has shown the effectiveness of design rules in term of safety. Respecting the rules make nearly impossible to generate accidents for a traffic free vehicle in a curve. This has been checked in experiments where the stability limit speed is nearly twice the rules limit speed. However, road users drive faster than the rules tell or the lateral acceleration reached is higher than the design rules admissible lateral acceleration. That can be dangerous in special situations.

Our work only considers one kind of pavement with one banking. Our perspectives are to make more tests in order to generalize our results. So, several vehicles on several surfaces with different banking have to be tested.

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