Assessment of Speeding Profiles and Safety Margins from Tangent to Curve by means of Driving Simulation

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Abstract

This paper presents a novel definition of drivers' safety margins reflected in speed profiles on a tangent to curved road design. These safety margins are based on a vehicle dynamics model, which is implemented to assess the speed variation at impending skid conditions from tangent to curve on the basis of several parameters. This model returns the theoretical speed-distance curve corresponding to the driver's maximum safe speed and acceleration when utilizing the outmost of the available vehicle horse power. On the basis of actual vehicle speed profiles, the model also returns the respective curve for the actual speed-distance i.e. the utilized share of vehicle horse power, which reflects the driver's safety margin. Data from a driving simulator experiment are used to test the proposed methodology, explore driver's speed profiles and the parameters affecting drivers' safety margins. The results suggest that drivers' safety margins towards the examined curve are considerable, with the majority of the drivers using less than 55% of the available vehicle horse power. Drivers can be grouped into "aggressive", "moderate" and "conservative" speeding behaviour, each group exhibiting distinct initial speed, "breakpoint" distance and acceleration / deceleration patterns. Higher initial speed is positively correlated with more aggressive driving i.e. lower safety margins. On the contrary, a higher safety margin was associated with earlier deceleration before the curve. The proposed approach yields a continuous and objective assessment of driver speeding behaviour from tangent to curve and the related safety margins, both for individual drivers, as well as for groups of drivers with similar speeding patterns.

Keywords

Speeding; Tangent-to-Curve; Safety Margin; Vehicle Dynamics model; Simulator experiment.

1. Background and objectives

Design consistency is acknowledged to be a key element for road safety [1]. This is achieved by avoiding abrupt changes of critical alignment elements that may result in erratic driving maneuvers and eventually crashes, so that successive elements of the road act in a coordinated way to enhance safety [2-5]. A critical element is the approaching between tangents to horizontal curves [6 - 8].

Design consistency is typically assessed on the basis of the operational speed [6], and substantial differences between operational speeds or between design and operational speeds in successive design elements, indicate poor design consistency. In this context, the "safety margin" is often defined as the difference between the driver's speed and the design speed, and is intended to express the degree of safe speeding behaviour at curves or from tangent-to-curve.

However, only the examination of the operational speed variation between the curve and the preceding tangent seems inadequate. The reason is that most researchers use spot speed values along the approach from tangent to curve, and vehicles' acceleration/deceleration is extracted assuming either a linear relationship between the measured spot speed data or a linear regression analysis based on the curvature [e.g. 7,10]. In general during vehicle motion on tangents, especially long ones, the drivers do not maintain a constant speed; they usually tend to accelerate their vehicles [6,8]. However, at some point before entering a curve, the drivers adjust (decrease) their speed accordingly.

This acceleration/deceleration process and the related safety margins applied by drivers depend on many parameters, including the initial speed, the tangent length, the curve parameters , as well as vehicle and driver characteristics (including physical and psychological ones). More specifically, in a given alignment, drivers may have a different “breakpoint”, i.e. the distance from the curve entrance along the approach tangent where speed is beginning to decrease. This “breakpoint”, initially depends on the vehicle’s speed, as vehicles traveling at higher speeds will generally begin the deceleration process earlier than vehicles traveling at lower speeds, but also on the type of vehicle used and the type of driver. Moreover, the acceleration/deceleration process may develop under different profiles, ranging from one single breakpoint, occurring earlier or later along the approach to the curve, or many breakpoints resulting from a gradual adjustment of speed along the approach to the curve.

The present paper proposes a novel definition of safety margins reflected in speed variations on a tangent to curved road design. It uses data from a driving simulator experiment in order to: (i) identify speed profiles corresponding to different ways of negotiating the approach from tangent to curve, and (ii) estimate the related safety margins applied by drivers on the basis of the proposed methodology. These safety margins are assessed on the basis of the percentage of the maximum available horse-power (hp) utilization at impending skid conditions; this is estimated through a vehicle dynamics model.

The paper is structured as follows: Section 2 presents the vehicle dynamics model used to assess the safety margin in speeding behaviour from tangent to curve. Section 3 presents the driving simulator experiment conducted and the related data obtained. Section 4 includes the results of the present analysis, which concern the creation of speed profiles and the estimation of related safety margins for individual drivers and for groups of drivers. Finally, section 5 discusses the conclusions of this research as well as limitations and next steps.

2. Analysis Methods

2.1. Driver’s safety margin from tangent to curve

In this paper, we propose a novel metric to assess the margin of safety experienced by a driver during the vehicle’s approach from tangent to curve, in accelerated or decelerated motion, on the basis of the drivers’ available horse power utilised. Taking into account the maximum horse power that can be attainable at impending skid conditions, the safety margin can be expressed as the difference in percentage between this maximum attainable value and the actual vehicle horse power rate This metric is advantageous in two ways: firstly, the safety margin is estimated on the basis of an objective reference point (the maximum attainable horse power at impending skid conditions), compared to i.e. the vehicle’s actual speed, and secondly, it allows for a continuous and non-linear representation of the speed profile along the examined alignment, which is an advance of the state-of-the-art.

In order to calculate the safety margin, the collected speed – distance data during the acceleration/deceleration process on the examined segment from tangent to curve, can be compared to a vehicle dynamics model, where two different speed – distance outputs can be extracted: the vehicle’s performance curve at impending skid conditions, and the best fitting curve to the collected speed – distance data quantifying a percentage of the maximum attainable. The safety margin is then directly estimated as the difference between the two curves.

2.2. Vehicle dynamics model

A vehicle dynamics model developed by the authors [11-13] analyses the motion of any vehicle in three linear movements: longitudinal, lateral, and vertical, as well as three rotational movements: yaw, roll, and pitch. The present research assumes that vehicle motion is considered on a road surface, following the curve centerline, in which all three geometric parameters remain constant; namely, grade s, cross slope e, and horizontal radius R. All forces and moments applied to the vehicle are analyzed into a moving three dimensional coordinate system, coinciding at the vehicle gravity center and formed by the vehicle’s longitudinal (X), lateral (Y) and vertical (Z) axis respectively. Through these axes, the influence of certain vehicle technical characteristics, road geometry and tire friction were taken into account: vehicle speed/ wheel drive/ sprung and unsprung mass and it’s position of gravity center/ aerodynamic drag/ vertical lift/ track width/ wheel-base/ roll center/ suspension roll stiffness/ cornering stiffness/ grade/ superelevation rate/ rolling resistance tire-road adhesion values and horse-power supply. Consequently, according to the laws of mechanics, and after slight simplifications the following formulas express the equilibrium around each axis accordingly:

$$\sum X = 0$$

$$m\frac{dv}{dt} = \sum U_i - \sum S_i\theta_i + \frac{mv^2}{R}\beta - mgs - A_d \tag{1}$$

$$\sum Y = 0$$

$$m\frac{dv}{dt}\beta = \sum U_i\theta_i + \sum S_i - \frac{mv^2}{R} + mge \tag{2}$$

$$\sum Z = 0$$

$$\sum P_i = mg + \frac{mv^2}{R}e - A_n \tag{3}$$

where (f=front, r=rear) :
dv/dt: vehicle's acceleration rate (positive value) (m/sec^2)
U_f,U_r : driving forces acting to front and rear axle respectively (Nt)
S_f,S_r : lateral forces acting to front and rear axle respectively (Nt)
P_f,P_r : vertical forces acting to front and rear axle respectively (Nt)
m : vehicle mass (kgr)
v : speed (m/sec)
A_n,A_d : air resistance forces acting vertically and on the frontal vehicle area respectively (Nt)
s : grade (%/100)
e : superelevation rate (%/100)
R: curve radius (m)
β : sideslip angle (rad)
θ : steer angle (rad)

The variables for the sideslip angle and the steer angle were taken from the literature [14]. Furthermore the model takes into account the actual wheel load due to the lateral load transfer and the corresponding alteration of the lateral force on each wheel thus creating a four-wheel vehicle dynamics modelling [14-16]. The available tractive effort of the vehicle (driving force minus rolling resistance) acting on the front or rear axle (depending on the driving configuration) should be associated to the vehicle's speed as well the net power available at the driving wheels. Since a vehicle cannot always be driven at 100% of its available horse-power rate, the horse-power utilization factor (n), was utilized through Equation [4] as follows:

$$F_x = 745.6\frac{P}{v}n \tag{4}$$

where :
Fx : tractive force (Nt)
P : net engine horse-power available at the driven axle (hp)
v : vehicle speed (m/sec)
n : horse-power utilization factor (%/100)

In the current vehicle dynamics model the vehicle's longitudinal acceleration or deceleration of Equation 1 is expressed as a function of vehicle, road, and tire friction parameters creating a four degree polynomial equation [11-13].

At the same time, by applying laws of mechanics, the vehicle's instant acceleration or deceleration can be expressed as a function of vehicle's instant speed as well as driven distance, thus forming the following differential equation which is resolved by applying numerical Runge-Kutta method [17].

$$a(v) = \frac{dv}{dd}v \tag{5}$$

where:
a(v) : acceleration-deceleration (m/sec2)
v : speed (m/sec)
d : distance (m)

The solution of Equation 5 delivers the vehicle speed variation as a function of the required distance in order to eliminate the vehicle's acceleration – deceleration [a(v)=0]. This procedure takes place at impending skid conditions utilizing the Krempel equation [18] both in longitudinal and lateral direction of travel by adapting each time the horse-power utilization factor 'n' from Equation 4. In other words, since the vehicle's speed variation is performed at impending skid conditions, the model delivers for every integration the vehicle's "best" possible performance.

However, it must be stressed that under the term "impeding skid conditions", the model delivers data for the critical wheel. This means that not necessarily vehicle skidding will occur; instead a transition to an unstable vehicle motion is evidenced, which is in every case undesirable. The accuracy of the suggested procedure is subject to the selected integration step (distance step), which in the present analysis was set equal to 0.10 m. The resulting vehicle speed is a function of the driven distance at any predefined alignment. The model's outputs were correlated against the known data derived by two other distinct cases: the final climbing speed of a truck travelling on a grade [19] and the output data from the well-known CARSIM Simulation Software [12]. Both cases revealed a satisfying match. The parameters inserted to the vehicles dynamics model refer to a Front Wheel Drive (FWD) C-class passenger car, were borrowed from the literature [15] and are described in detail in [11-13].

The actual friction in every direction of travel and for every wheel was addressed by the model. However, the peak friction coefficients, assumed equal for the longitudinal and lateral direction of travel (friction circle), were on the basis of initial speed values and stopping sight distance, through an equation widely applied in current practice [e.g. 20-23].

3. Driving simulator experiment

A driving simulator experiment was implemented at the driving simulator of the Department of Transportation Planning and Engineering of NTUA, in order to test the proposed methodology for the assessment of driver's safety margin. The NTUA driving simulator is a motion base quarter-cab manufactured by the FOERST Company. The simulator consists of 3 LCD wide screens 40'' (full HD: 1920x1080pixels), driving position and support motion base. The dimensions at a full development are 230x180cm, while the base width is 78cm and the total field of view is 170 degrees.

The simulated driving task consisted of driving a rural route of 2 km length, single carriageway, lane width 3m, zero gradient, mild horizontal curves, speed limit equal to 70 km/h and low traffic. More specifically, ambient vehicles arrivals were drawn from a Gamma distribution with mean m=12sec, and variance σ2=6 sec, corresponding to an average traffic volume Q=300 vehicles/hour on both traffic streams. This resulted in moderate oncoming traffic on the opposite traffic stream and a lead vehicle at long headway ahead the simulator vehicle, aiming to enhance the fidelity of the virtual road environment with respect to actual conditions, but without affecting the driving behaviour of participants.

The experiment started with a practice drive for familiarization with the simulator without any time restriction; it took place on a similar road environment as the one of the main experiment, i.e. a rural road with mild horizontal curves, its duration was typically between 10-15 minutes, and the evaluation criteria included handling the simulator (starting, gears, wheel handling etc.), keeping the lateral position of the vehicle, keeping constant speed and appropriate for the road environment, braking and immobilization of the vehicle.

Participants were recruited among subjects of a large driving simulator study implemented at the same time at NTUA with more than 300 subjects in total, aiming to assess driving performance of all age groups with focus on elderly. Forty three participants aged from 22 to 87 years of age carried out the simulated drive of the present research. Twenty two of the participants were males and 21 females, and their age distribution was as follows: 18 participants were less than 35 years old, 16 participants were between 35 and 55 years old, and 9 participants were older than 55 years (out of which 4 were older than 65 years). The participants had no known health or vision problems, held a valid driving license and were frequent drivers (i.e. reported driving more than 3 times per week and more than 5,000 annual kilometers travelled). No specific instructions were given to participants as per the purposes of the specific drive; they were asked to drive at their preferred speed as they would normally do and observe the road signs and markings as usual.

For the analysis purposes, a road section was selected on the entrance from a 100m approximately tangent (at the beginning of which the curve became visible) to a circular arc of R=133m. The distance of 100m before the curve was selected on the basis of exploratory analysis of speed profiles, which indicated that all drivers began decelerating after that point. The examined alignment was visible throughout the driving process and there were no sight restrictions (see Figure 1). When approaching the curve, all drivers decelerated in tractive mode, by releasing the pressure on the accelerator and without using the vehicle's brakes.

Figure 1: Simulated driving environment - tangent to curve

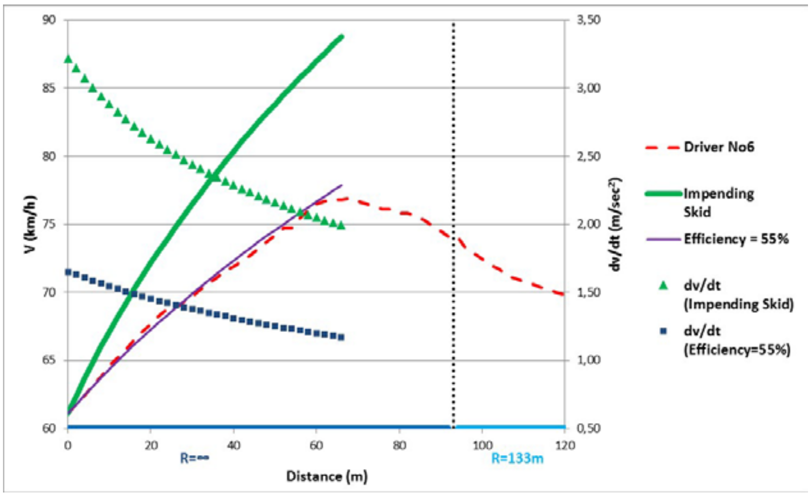
4. Results

4.1. Estimation of safety margins of individual drivers

From the driving simulator metrics, point speed data were extracted for each participant. The speed – distance data during the utilization of the maximum attainable vehicle's horse power rates were also calculated for all drivers, allowing to identify the curve which best fits each driver's relevant data extracted for the same initial speed. Figure 2 illustrates how the safety margins of drivers are estimated through the fitting of a vehicle dynamics model to the simulator speed data.

Indicatively for driver #6, the dashed line indicates the actual speed – distance on the selected alignment. Two speed – distance curves were extracted from the dynamic model, up to the "breakpoint" where the driver reduces speed and begins to decelerate. The bold green continuous line represents the vehicle motion at impending skid conditions given by the vehicle dynamics model, and as expected the relevant vehicle speed values are greater than the actual speed values. The non-bold purple continuous line shows the "best fit" of the actual speed data to the vehicle dynamics model, and was calculated after various tests by setting each time the available horse power rate to a certain percentage of the horse power at impending skid conditions. Therefore, it can be seen that for the specific example, the vehicle is driven at 55% of the horsepower compared to impending skid conditions, and therefore a safety margin of 45% is involved on the specific approach from tangent to curve.

In the secondary axis, the relevant acceleration rates for both the runs performed by the dynamic model (maximum attainable horse power at impending skid conditions, and the percentage of this actually used) are shown. When the vehicle is driven at impending skid, the acceleration is far more increased (triangle line) compared to the case where the vehicle is driven with a 45% safety margin.



NOTE: The continuous lines at the bottom refer to the length of the utilized horizontal geometry.

Figure 2: Example of Speed – Distance Actual Data vs Dynamic Model's Outputs.

4.2. Analysis of driver speed profiles from tangent to curve

The speed profiles of all drivers were drawn on the basis of the actual speed data derived from the driving simulator, aiming to fit the respective safety margin curve for each driver. In the entire sample, drivers' safety margins ranged from 45% to 92%, with a mean of 72.6 and a standard deviation of 13.4, suggesting that drivers use a minor share of the available horse power on the examined curve. This may be due to the rural two-way road environment and the presence of oncoming traffic leading drivers to a more conservative driving behaviour. It is also noted that not all drivers exhibited a 'striking' peak in their speed profiles; especially in drivers of relatively low speed and efficiency, a 'plateau' shaped speed profile was observed, in which the desired speed was attained earlier and maintained up to the curve entrance. In this case, the "breakpoint" was defined on the basis of the distance at which the desired speed was first attained.

It early became evident that there is large variation in driver speeding behaviour on the examined approach from tangent to curve. It is therefore meaningful to examine whether there are profiles of drivers exhibiting similar speeding behaviour. A thorough exploratory analysis was carried out revealing that the following factors differentiate driver's speed profiles:

- Initial speed and acceleration at the beginning of the examined tangent-to-curve section
- Location of the "breakpoint" where speed reduction starts, earlier or later along the tangent
- Number of breakpoints, one vs. more than one, indicating more or less smooth deceleration process

On the basis of the above, drivers were grouped in three groups, presented in Figure 3 (left panel):

- "Aggressive" drivers: this group of drivers had high initial speed (>50 km/h, maximum 85 km/h which is well above the speed limit) and started decelerating close to the curve entrance, at a distance smaller than 50m before the curve, and some of them even only 30m before the curve. Their speed profiles show a clear acceleration / deceleration pattern and a more efficient, and marginally "aggressive" speeding behaviour.
- "Moderate drivers": this group of drivers had a relatively moderate to high initial speed within the posted speed limits (>40 km/h, maximum 75 km/h) and are characterized by a start of the deceleration process quite earlier than the previous group. Their "breakpoints" are observed at 60-70 meters before the curve entrance. As a consequence, their speed at the curve entrance is lower.
- "Conservative" drivers: A minor part of the sample of drivers demonstrated a different pattern, with significantly low initial speed (<55km/h) and a "plateau" shaped profile, with several small consecutive accelerations / decelerations along the tangent section. This demonstrates a "conservative" and "hesitant" behaviour of low speed, small acceleration and early deceleration, followed by some further adjustment prior to the curve entrance.

The grouping can be further expressed by means of overall speed profiles for each group, estimated on the basis of the average speed at each point along the examined tangent (100 m prior to the beginning of the curve), as well as its standard deviation. Such an aggregation can be useful given that the shapes of the speed profiles of all drivers in the group are very similar, and most of the variation results from the differences in (initial) speed values. More specifically, for each group the following three profiles were estimated (Figure 3, right panel):

- A mean speed profile, estimated on the basis of the average speed of all drivers in the group;
- An upper bound speed profile, estimated on the basis of the average speed plus one standard deviation for all drivers in the group;
- A lower bound speed profile, estimated on the basis of the average speed plus one standard deviation for all drivers in the group.

It is noticed that the average speed profiles and the respective boundary profiles give an accurate overall picture of the main characteristics of the speeding behaviour from tangent to curve for each group. It can be further observed that there is smaller variation in the "aggressive" driver's group as 9 out of 13 drivers' profiles are very close to the average profile. Moreover, there is somewhat larger variation in the "moderate" drivers' group, in which speed profiles cover the entire range within the estimated boundaries. It is also noticed that the upper boundary of the "moderate" group largely coincides with the mean profile of the "aggressive" group.

On the other hand, the drivers of the "conservative" group are close to either the upper or the lower boundary of the group, and the mean profile is not representative of actual speeding behaviours. It is also interesting to note that the upper boundary of the "conservative" group speed profile is almost equal to the lower boundary of the "moderate" group speed profile.

Figure 3: Speed profiles for “aggressive” (top panel), “moderate” (middle panel) and “conservative” (bottom panel) drivers - Individual profiles (left panel), group profiles (right panel)

4.3. Safety margins for groups of drivers

On the basis of the group speed profiles, the group safety margins were estimated on the basis of the vehicle dynamics model. In particular, the maximum safely attainable speed-distance curve at impending speed conditions was calculated, together with the respective best fitting speed-distance curve for the mean speed profile of each group. The results are presented in Figure 4.

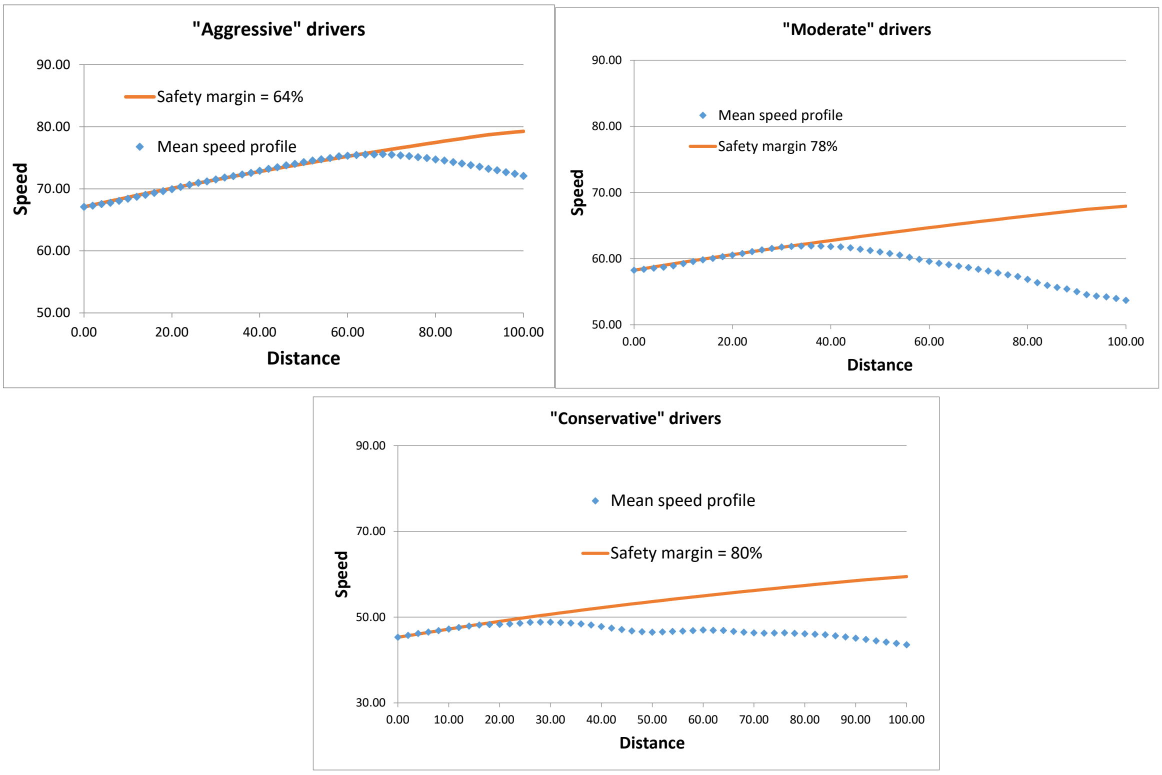


Figure 4. Mean safety margins curves for "aggressive" (top left panel), "moderate" (top right panel) and "conservative" (bottom panel) drivers.

The results suggest that the "aggressive" group of drivers uses a 64% mean safety margin, the "moderate" group of drivers uses a 78% mean safety margin and the "conservative" group of drivers uses a 80% mean safety margin. It is confirmed that in all three groups the safety margins are considerable, and even the most "aggressive" drivers utilise less than 50% of the available horse power and the respective maximum speed that can be safely attainable. It is also interesting to note that "moderate" and "conservative" drivers, although having singificantly different initial speeds and accelerations before the "breakpoint", both groups correspond to a similar safety margin in terms of maximum attainable safe speed.

Of course, the individual safety margins estimated (see section 4.1) revealed significant within group variation, however mostly as regards the highest safety margin, and there were fewer relatively low safety margins (lower than 50%).

5. Discussion and next steps

The present paper investigated the speed profiles and related safety margins of drivers on a road section from tangent to curve. A vehicle dynamics model is proposed for the estimation of the safety margin, defined as the difference in percent between the maximum available horse power utilization at impeding skid conditions and the share of vehicle's horse power rate utilized by the driver. This approach is advantageous in two ways: first, it allows for a more objective calculation of the safety margin through the vehicle dynamics, compared to other commonly used criteria such as design speed, speed limit etc.; and second, the safety margin is explicitly considered as a profile varying along the entire road section from tangent to curve, taking into account the common acceleration / deceleration speed profile when approaching the curve, allowing for more complete insight on the actual speeding variations.

Data from a driving simulator experiment were used to test the proposed methodology, on the basis of a sample of 43 drivers of both genders and all age groups. The data showed large variations in the speed along the examined section and consequently on the calculated safety margins. On average, a low share of vehicle motion was used by most drivers, revealing a conservative speeding behavior (i.e. the minimum safety margin in this sample was 45%). Moreover, the observed speed profiles had different shapes, with others showing a clear acceleration / deceleration peak, and others being rather 'plateau-shaped'.

Three distinct patterns were identifiable, separated on the basis of initial speed and acceleration at the beginning of the examined tangent, and "breakpoint" distance at which the driver begins to decelerate from the beginning of the examined curve. These patterns reflect “aggressive”, “moderate” and “conservative” behaviour and despite some variation in the magnitude of speed values within each group, the shape of the profiles were largely similar within each group. For each group, a global profile was estimated, defined on the basis of mean, lower and upper boundary speed profiles, and a mean group safety margin was calculated. The results largely confirmed the picture drawn by the individual safety margins of all drivers, and further revealed close safety margins between “conservative” and “moderate” drivers, in contrast to the safety margins of “aggressive” drivers which are closer to the upper boundary conditions.

Safety margins naturally depend on numerous parameters e.g vehicle type (speed, weight distribution, center of gravity), road design values (road functional class, curve radius, tangent length prior to curve, sight distance etc.) and driver characteristics (experience, aggressiveness and risk taking, etc.). This paper opted to use the controlled environment of a driving simulator in order to focus on human factors (directly observable or indirectly measured) associated with safety margins at curves. For that purpose, a single curve is examined and the same (simulator) vehicle is used by all drivers, eliminating thus non driver-related confounding factors. Nevertheless, there is significant variation in the speed profiles from tangent to curve, as well as in the respective safety margins. It is therefore suggested that there are numerous unobserved human factors that affect the examined speeding behaviour and further research could also examine driver perceptions, motivations and attitudes that potentially affect speeding behaviour.

The present research has some limitations: the relatively small sample and the known lower fidelity of a simulated environment compared to actual roads and the vehicle used by the participants in actual driving, require that the results are considered with caution.

The next steps of the research concern the statistical analysis of speed profiles and safety margins, in order to further substantiate the present exploratory analysis. Moreover, for the reasons mentioned above, only a single curve was examined, as a first step for understanding the various factors that affect drivers’ safety margin. Further analysis is needed to determine the impact of more parameters such as curves with various radii values, left and right curves, approach tangents of different length, alignments with grades, road surfaces with different friction coefficients etc.

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