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Cumulative lateral position: a new measure for driver performance in curves

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Abstract: Vehicle control can be described with lateral and longitudinal control measures. The Standard Deviation of Lateral Position (SDLP) is probably the most common measure to reflect lateral control. Indices such as mean Lateral Position (MLP) and Time-to-Line Crossing (TLC) have also been used to describe driver behaviour. Even though all these measures have demonstrated their value, in some specific cases, these measures may indicate that driver behaviour is deteriorated while that may not necessarily be the case. When negotiating curves for example, most drivers prefer to not to follow the centre of the lane. We propose a new index, called the Cumulative Lateral Position (CLP), an index that does not suffer from drawbacks of the earlier mentioned measures in these conditions. We also applied the CLP in a practical case. In a simulator experiment drivers negotiated three types of curves: traditional circular (CIR), clothoid (CLO), and a new curve, a polynomial curve with continuous curvature (CON). Results show that the CLP index, unlike the older measures, is able to well summarise the trajectory on a road curve and is sensitive in distinguishing different driving behaviour with respect to variations in road geometry, even in cases where these differences are small. The proposed methodology can be used to evaluate both new and existing roads design solutions, and showed in this experiment that driving behaviour was safest in the continuous curve.

Keywords: curve design, curve, driving, geometry, lateral control, measure, SDLP

1 Introduction

1.1 Driving performance and measures that reflect driving behaviour

According to Michon (1985), driving behaviour can be described on three levels; the strategic, the manoeuvre, and the operational level. While the strategic level reflects longer term choices that are made such as the route to take, manoeuvre and operational level reflect performance and decision taking on the (very) short term level, such as planning an overtaking manoeuvre and low-level unconscious vehicle control, such as providing steering wheel input to remain between the road delineation. Different performance measures have been linked to these three levels. On the intermediate manoeuvre level, these are reaction time related measures, such as the gap size in traffic that is accepted to cross an intersection, or delay in response when following a lead car. At the lowest, operational level, lateral and longitudinal control measures are most commonly used. Both speed and accuracy of performance are used, average and variation in speed, and the average position in a lane and variability of that position. The Standard deviation of Lateral Position, SDLP is still the central measure for assessing effects of alcohol and drugs on driving performance (Brookhuis 2014; Verster & Roth 2012; Ramaekers 2003; O'Hanlon 1984), while at the same time it is relevant to mention that effects of drugs on lateral control are not uniform, for example the use of sedative drugs in general leads to an increase in SDLP (e.g. van Dijken *et al.* (2020)), while stimulant drugs such as ecstasy have no effect on SDLP (e.g. Veldstra *et al.* (2012)). SDLP has also been suggested to reflect difficulty of driving related to road geometry (Rosey & Auberlet 2012).

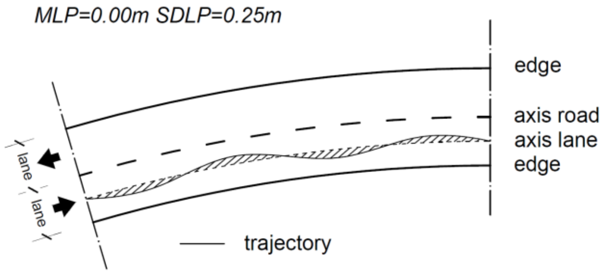
More 'advanced' measures for vehicle control have also been proposed, for example TLC, Time-to-Line Crossing (van Winsum *et al.* 2000; Godthelp *et al.* 1984). TLC is a continuous measure reflecting the time that is left before the edge of a lane is reached if no further corrective steering wheel movements are executed. One of the advantages of TLC is that speed is incorporated in this measure, as is heading and steering wheel position. The idea is that drivers use a certain TLC value as indicator to undertake steering action (van Winsum *et al.* 2000; Godthelp 1988). Disadvantages are that the measure is not normally distributed and that while driving, the line that is approached, centre or edge, switches frequently. For that reason, median, minimum and 15% TLC values have been used to describe behaviour (Godthelp 1988; Godthelp *et al.* 1984). While it is not clear why the 15% TLC value was chosen, minimum TLC is more obvious as it mirrors which critical safety margins were accepted by the driver.

1.2 Driving in curves

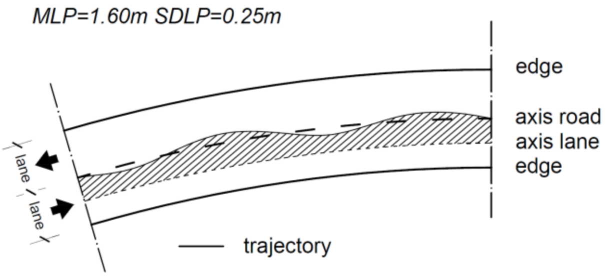
Driving behaviour in curves is more complex to capture with measures than driving on a straight road segment. While negotiating a curve, drivers may adapt to the curve by choosing a lower speed and different position depending on curve radius and lane width. This was confirmed by van Winsum & Godthelp (1996) who reported that drivers tend to keep TLC to the inner lane boundary constant. Boer (2016) also found evidence that TLC plays an important role in curve negotiation and affects speed choice. He described that the way people drive through a curve is to a large extent based on what is felt to be satisfactory, and not on optimising control. Drivers do not aim to keep a central position in the lane, which is a reason for Boer to criticise SDLP as a measure to reflect curve driving. Also, with sharper curves drivers tend to cut the curve more severely (Barenswaard 2021; Barendswaard *et al.* 2019). The question is whether TLC gives the best description of behaviour as it is a continuous measure. As stated earlier, median or minimum TLC are useful measures to reflect driving behaviour, but in conditions where people cut curves the minimum value approaches (or even reaches) zero at which point details of how the curve is negotiated are lost. Moreover, it is not clear what would be the best way to describe behaviour with TLC in the common case that the edge and centre line are approached multiple times during curve negotiation. Should the median or minimum TLC values be averaged, or should the lowest minimum TLC be taken?

These questions have not been answered satisfactorily yet. In some cases, the minimum of TLC may indicate safety critical performance while this is not necessarily always the case. TLC could be useful as safety measure if the course of TLC while negotiating a curve is analysed, but not if the values of TLC are reduced to an aggregated measure. Analysing the values of TLC during the curve, results in a qualitative and laborious approach, which makes TLC an indirect measure of safety instead of the direct measure it was proposed to be. The earlier mentioned standard measures such as SDLP, although less refined, could actually give a better description of performance. SDLP can be calculated over a complete curve. However, as stated earlier, it also does not reflect how the curve was driven, for example whether corners were cut, nor does it reflect the frequency in lateral variation in the lane.

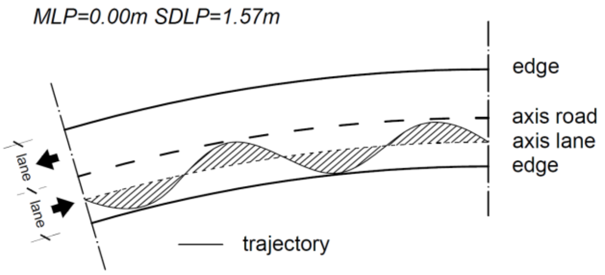
Using a synthetic index to describe complex (driving) behaviour can sometimes lead to an over-simplification of the real phenomenon. Subsequent use in statistical analysis complicates interpretation. For example, SDLP and mean Lane Position (MLP) can only describe certain aspects of behaviour. If the main goal is to evaluate the distance to the edge line within a single curve, MLP has its utility. However, if the goal is to compare performance of drivers' negotiation of similar but not identical curves, there are issues related to the different geometric characteristics (length, continuity of the tangent, variation of the radius, etc.). To explain the limitations of SDLP and MLP, three situations are described in Figure 1 that illustrate interpretation issues that could arise from using SDLP and MLP in curves.



Example 1



Example 2



Example 3

Figure 1 **Example 1, driving close to the lane axis with little variability in position and remaining in the lane; Example 2, a more central position around the centre line (the road axis), also entering the opposite lane; and Example 3, the same average position around the lane axis as in Example 1, but with more lateral variability. See also the main text for further explanation.**

Figure 1 shows three hypothetical examples illustrating where SDLP (standard deviation of the lateral position) and MLP (mean lateral position) as measures fail to correctly reflect driving behaviour in curves. In all examples the reference point for SDLP is the axis of the lane, lane width is 3.2 m. The three cases are as follows:

- *Example 1*: the driver stays close to the axis of the lane and swerves around this axis; MLP = 0.00 m; SDLP = 0.25 m.

- *Example 2*: the driver significantly deviates from the axis of the lane, while the contour of the trajectory is identical to Example 1 (the drivers swerves identically but closer to the road's axis). Here MLP = 1.60 m and the SDLP is the same as in Example 1, 0.25 m.
- *Example 3*: the driver remains in the right-hand lane but swerves extremely. Average MLP is 0.00 m as in Example 1, but SDLP = 1.57 m.

1.3 Shortcomings of common performance measures

SDLP is the same in Examples 1 and 2, but in Example 2 behaviour is obviously riskier as there is a large chance of colliding with oncoming traffic. MLP also does not describe behaviour fully, the average is identical for Examples 1 and 3, but whereas in Example 1 the driver safely remains close to the centre of the lane, in Example 3 the driver swerves dangerously close to the opposite lane. Because the average is calculated considering the axis of the lane and, therefore, the deviations of the trajectory towards right and left of the axis lane are recorded with opposite signs, the difference in situations is not reflected in MLP. Although these are only theoretical examples, what they show is that SDLP and MLP do not reflect driver behaviour fully. Instead, it would be opportune to take into account all oscillations around the axis of the lane along the entire length of the curve and, for this reason, there is the need for an indicator that summarizes the performance of a driver more accurately than SDLP and mPL.

The goal of the present study is to try to overcome the limitations inherent in SDLP and MLP as indices of driver behaviour in curves, through the proposal of an index that:

- takes into account all values of the trajectory along the entire length of the curve, overcoming the limitations of synthetic indices as average, or minimum or maximum values;
- allows for the comparison of driving behaviour in curves with different geometrical characteristics. For evaluation a simulated world was built which contained different types of curves. In this way driving behaviour on these roads, and how this is reflected in 'old' and a newly proposed measure, can be compared.

For evaluation a simulated world was built which contained different types of curves. In this way driving behaviour on these roads, and how this is reflected in 'old' and a newly proposed measure, can be compared.

2 Method

The mathematical characterization of the examples given in Figure 1 highlight the analytical differences between them. Generally, from a theoretical point of view, the variables used to quantify curve quality are lateral acceleration, its variation over time, steering speed, etc. One of the goals of this study is to assess whether people negotiate different curves differently.

2.1 A new indicator

As a new indicator, we propose the Cumulative Lateral Position (CLP)—the integral, i.e. area between the trajectory and the axis of the lane, divided by the length of the curve:

$$CLP\ (m) \ = \ \int_0^L Latpos(s)\ ds/L\ , \tag{1}$$

where *Latpos* is the function of the trajectory (lateral position), *L* is the length of the curve and *s* is the curvilinear abscissa.

In contrast to SDLP and MLP, this indicator is calculated on the basis of the partial areas between the trajectory and the axis lane and adds these as absolute values, without making a distinction between the deviation towards the right or left of the axis (in contrast to MLP). Finally, the total area is divided by the length of each curve to normalise the results. In this way more detail about curve negotiation is retained. In Table 1 the CLP data are added to MLP and SDLP for the examples given in Figure 1.

Table 1 **Mean Lateral Position (MLP), SD Lateral Position (SDLP), and the new index Cumulative Lateral Position (CLP) for the three examples displayed in Figure 1**

	MLP (m)	SDLP (m)	CLP (m)
Example 1	0.00	0.25	0.50
Example 2	1.60	0.25	1.60
Example 3	0.00	1.57	1.36

CLP reflects the shaded area in Figure 1 and varies between all three conditions: 0.5 m, 1.6 m, and 1.36 m. A higher value reflects riskier behaviour.

On the road, drivers negotiating a curve may have a tendency to 'cut' the curve inwards and not move along its axis. This may generate higher values of lateral acceleration (since the radius the car travels becomes effectively smaller than the radius of the curve itself) and therefore increases discomfort at the beginning and at the end of the curve. The opposite may also happen with curve cutting, implying that the radius is higher than the actual radius with decreased lateral accelerations. Any index that uses the lane axis to quantify driver behaviour suffers from this problem, also CLP.

Driver behaviour can be studied both on the road and in driving simulators. To evaluate the potential of CLP we have used types of curves that can be found both in real and simulated environments. Real world curves typically have a transition part at the start of the curve, a part with a fixed radius and a transition at the end (clothoid curve). To evaluate whether CLP can be used to determine improvements in behaviour with improvements in curve design, a third type of curve was included that has a continuously changing radius from start to finish (continuous). We have studied these three types of curves with three different curve angles in a driving simulator.

2.2 Curves tested

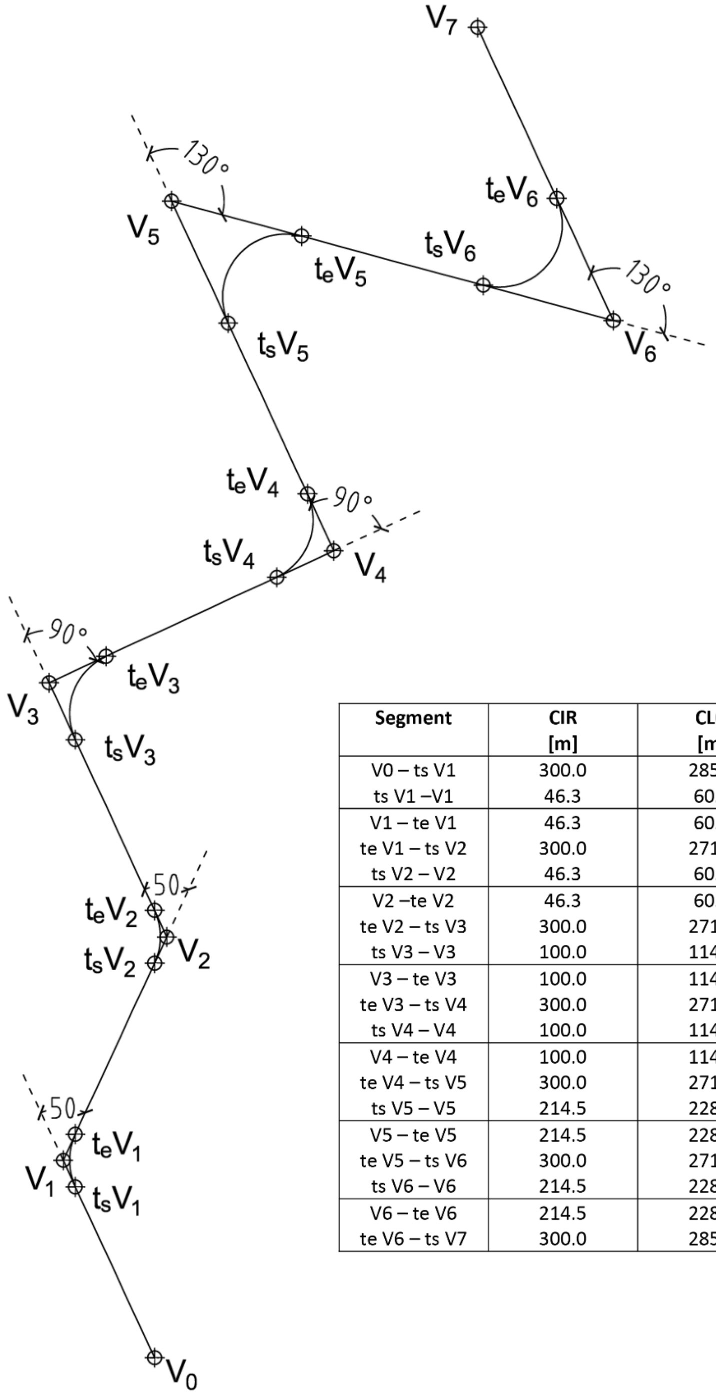
Performance and subjective evaluation of driving through three different types of curves was evaluated. The three types of curves were:

- *Circular Curve* (*CIR*): this is a circular curve with R = 100 m constant throughout the curve. A property of this curve is a discontinuity in the curvature function and this leads to the sudden onset of centrifugal acceleration directly proportional to the square of the speed and to the curvature.
- *Clothoid Curve* (*CLO*): this curve is commonly prescribed by international road standards (see Italian Road Standard (2001)), built by creating an incoming clothoid section (with a radius value variable between infinity and 100 metre), a subsequent circular arc with R = 100 m and an outgoing clothoid section, generally with the same characteristics as the clothoid section for entering the curve (but mirrored). In this way, the discontinuity problem in the union points with the tangent elements is solved. In fact, there is a linear variation of the centrifugal acceleration. Its equation is:

$$r \cdot s = A^2 , \tag{2}$$

where *r* represents the variable radius, *s* the curvilinear abscissa and *A* the scale parameter of the clothoid.

- *Continuous Curve* (*CON*): this type of road curve has not yet been applied on real roads and is the result of theoretical studies. It is a polynomial curve with a continuous curvature (for this reason, it is also called Polynomial Parameter Curve), characterized by a radius value between infinity and 100 m. The minimum value occurs halfway through the curve; after that the radius increases with the same variation trend as the first halve of the curve (but mirrored) towards an infinite radius value.



Segment	CIR [m]	CLO [m]	CON [m]	TOTAL [m]
V0 – ts V1	300.0	285.9	282.1	346.3
ts V1 –V1	46.3	60.4	64.2	
V1 – te V1	46.3	60.4	64.2	392.7
te V1 – ts V2	300.0	271.9	264.3	
ts V2 – V2	46.3	60.4	64.2	
V2 –te V2	46.3	60.4	64.2	446.3
te V2 – ts V3	300.0	271.9	249.7	
ts V3 – V3	100.0	114.0	132.4	
V3 – te V3	100.0	114.0	132.4	500.0
te V3 – ts V4	300.0	271.9	235.2	
ts V4 – V4	100.0	114.0	132.4	
V4 – te V4	100.0	114.0	132.4	614.5
te V4 – ts V5	300.0	271.9	220.5	
ts V5 – V5	214.5	228.5	261.5	
V5 – te V5	214.5	228.5	261.5	728.9
te V5 – ts V6	300.0	271.9	205.9	
ts V6 – V6	214.5	228.5	261.5	
V6 – te V6	214.5	228.5	261.5	514.5
te V6 – ts V7	300.0	285.9	253.0	

Figure 2 **Road polygonal alignment driven in the trials. V are the polygonal vertices while t_s (tangent start) and t_e (tangent end) are the tangent points of the curves.**

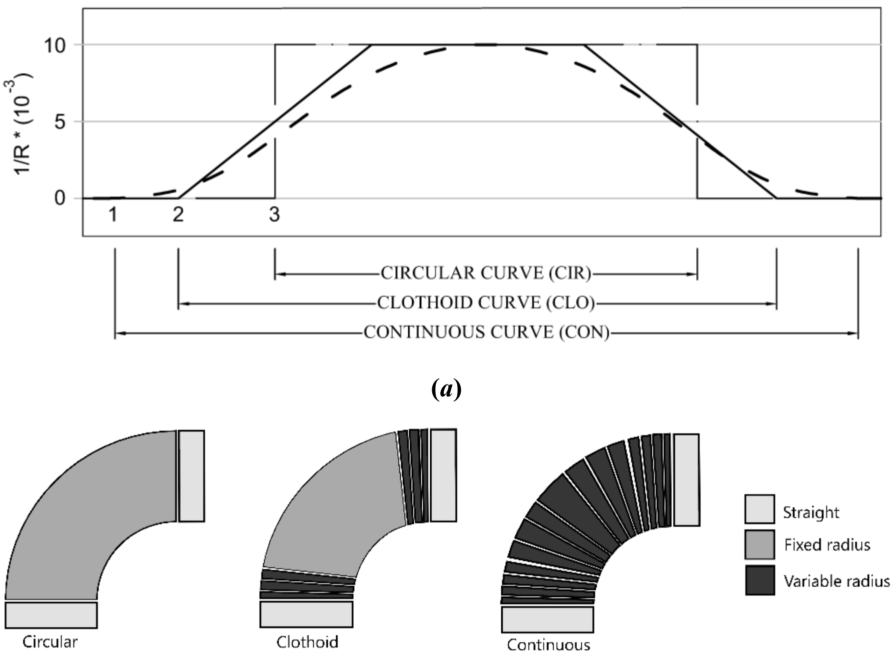
The CON curve (Bosurgi *et al.* 2016; Bosurgi & D'Andrea 2012) used in this experiment, is represented by a fifth-degree polynomial, according to the following expression:

$$k(l) = [1 / R(a \cdot l^5 + b \cdot l^4 + c \cdot l^3 + d \cdot l^2 + e \cdot l + f)]^{\beta}, \tag{3}$$

where l is the normalized abscissa s/L (s is the curvilinear abscissa and L is the curve length), R = 100 m is the minimum value of the radius and β is a shape parameter. The coefficients a, b, c, d, e and f are calculated by imposing some boundary conditions concerning the curvature and its derivative. This type of curve has theoretical advantages in the sense that if drivers follow the axis of the lane the vehicle dynamics are optimised. Therefore, this curve was added to evaluate behaviour when one has the freedom to not necessarily following the centre line.

The analytical expressions of these three curves are quite different. There are also some differences that are not so evident, but can be seen by looking at the layout of the curves. In theory, when a driver steers precisely over the axis lane, the advantages of using transition curves (clothoid and continuous) compared to a circular curve are clear, the sudden change in radius is uncomfortable and potentially unsafe. Whether driving behaviour is affected by curve type, is usually estimated by evaluating values for steering, centrifugal acceleration and jerk (rate of change of radial acceleration).

Figure 2 shows a helicopter view of the road that was driven in all three conditions. In Figure 3 in schematic form, the geometrical shape of the three types of curve is shown to highlight the different curvature trend and length. It can be seen that the CON curve is similar to the CLO in terms of deviation from the axis but differs from the latter in an earlier onset. The length from onset to end of the CIR curve is shorter than the other two and is characterized by a discontinuity in the curvature (point 3) where the radius suddenly goes from infinity (straight road) to 100 m.



(*a*)

(*b*)

Figure 3 **Differences between the three curves evaluated in this experiment: (*a*) The lengths of the curves. The starting points are, respectively, indicated with a 1 for the Continuous Polynomial curve (CON), with 2 for the Clothoid (CLO) and with 3 for the Circular curve (CIR). The y-axis represents the curvature (1 / *R*) where *R* is the radius of the curve. (*b*) A simplification of the three types of curves, illustrating which parts have a fixed and which a variable radius. The circular curve has a fixed radius from start to end (left), the Clothoid curve has a changing radius at the beginning and end of the curve (middle), the continuous curve has a changing radius through the entire curve (right).**

In this study, the minimum value of the radius of the curves was 100 metres. The length of the curves for the three scenarios (CIR, CLO and CON) are reported in Table 2.

Table 2 **Lengths of the three types of curves according to the deviation angle and the curves direction**

Curve no.	Angle [degrees]	Direction	CIR [m]	CLO [m]	CON [m]
V1	50°	Right	86.8	114.8	122.5
V2	50°	Left	86.8	114.8	122.5
V3	90°	Right	157.1	185.0	221.6
V4	90°	Left	157.1	185.0	221.6
V5	130°	Right	226.9	254.9	320.2
V6	130°	Left	226.9	254.9	320.2

2.3 Routes

Every participant drove three routes (Table 3), one route for every type of curve (i.e. CIR, CLO, or CON). Every route included three angles (50°, 90° and 130°). Both left- and right-hand curves were included. Every angle and direction combination were presented twice within a route; therefore, the participants drove 12 curves in total in one route. Participants drove all routes at a freely chosen speed, while the speed limit was 80 km/h. Curve conditions were presented balanced in order over participants.

Table 3 **Routes participants completed**

Trial	Route	Curve	Direction	Deviation Angle
1	1	12 CIR	6 Right / 6 Left	4 x 50° - 4 x 90° - 4 x 130°
2	2	12 CLO	6 Right / 6 Left	4 x 50° - 4 x 90° - 4 x 130°
3	3	12 CON	6 Right / 6 Left	4 x 50° - 4 x 90° - 4 x 130°

2.4 Data Analysis

The Independent Variables in this study were:

- the type of curve (CIR, CLO, and CON)
- the direction of the curve (Right and Left)
- the deviation angle (50° for vertices V1 and V2, 90° for vertices V3 and V4, 130° for vertices V5 and V6).

Other factors such as traffic, environment and atmospheric conditions were kept constant.

The Dependent Variables were the performance (lane control) measures, i.e. SDLP, MLP and CLP, and subjective evaluation of driving the curves. A repeated measures within subjects factorial design ANOVA with the following factors was applied:

- Type of curve (three levels: CIR, CLO and CON curves)
- Angles (three levels: 50°, 90° and 130° sexagesimal degrees)
- Curve direction (two levels: left, right)

The results were further analysed with a post-hoc Tukey HSD (Honestly Significant Difference) test.

2.5 Participants

A total number of twenty participants (10 male and 10 female) took part in the study. The only requirement for candidates was that they needed to be in the possession of a valid driving licence. Their average age was 35 years (SD 12.9), and their average driving experience was 16 years (SD 13 years). Average annual mileage ranged from 5 000 to 10 000 km/year. Each participant was informed in advance about the time the experiment would take (30 minutes), the driving simulator and were given instructions to follow the route (drive straight on as there were no turns), The three curve conditions (CIR, CLO, and CON) were not explicitly explained to them.

At the start of the experiment participants signed an informed consent and answered general demographic questions. The study was approved by the ethical committee of the Department of Psychology of the University of Groningen. Before starting the experimental condition, participants completed a practice session (about 3–5 minutes) in order to familiarise themselves with the driving simulator, in particular with the steering wheel, pedals and dynamic platform movements.

2.6 Virtual driving environment and driving task

The study was conducted in a ST Software© driving simulator, consisting of a moving-base vehicle mock-up with a force feedback steering wheel and automatic transmission. The driver was surrounded by five 60-inch diagonal LED screens, with a 270° field of view. The road was characterized by two lanes that were both 3.20 m wide. Random traffic was programmed at a very low frequency, only from the opposite direction.

2.7 Self-reported data

After each trial, drivers rated how much effort they had invested in driving the route on the Rating Scale Mental Effort (RSME, Zijlstra (1993)). The RSME is a scale in the format of a line with several anchor points. Labels run from ‘absolutely no effort’ (score 2) to ‘extreme effort’ (score 113). The maximum score is 150. The RSME has been used in numerous studies and has been translated into other languages also (see e.g. Widyanti *et al.* (2013)). After completing all routes, participants were asked to indicate which route (i.e. type of curve) they considered most comfortable to drive.

3 Results

In total per participant, 36 curves were negotiated [3 types (CIR/CLO/CON) x 2 directions (left/right) x 3 angle (50°/90°/130°) x 2 repetition (first/second)]. Driving behaviour in the curves was studied first by looking at the lateral position.

First, as illustration, in Figure 4, an individual participant’s trajectory illustrates the complexity of evaluating the course of the lateral position in a correct way for the three different types of curve. Figure 4 shows how this participant drives considerably different that just following the axis of the lane. Other participants show similar deviations from the axis.

The mean and SD of CLP, SDLP, and MLP were respectively: CLP (0.31; 0.12), SDLP (0.25 m; 0.07), MLP (0.03 m; 0.19). Figure 5 illustrates the differences in CLP per type of curve and angle. All participants maintained an average speed between 65 and 68 km/h for each curve.

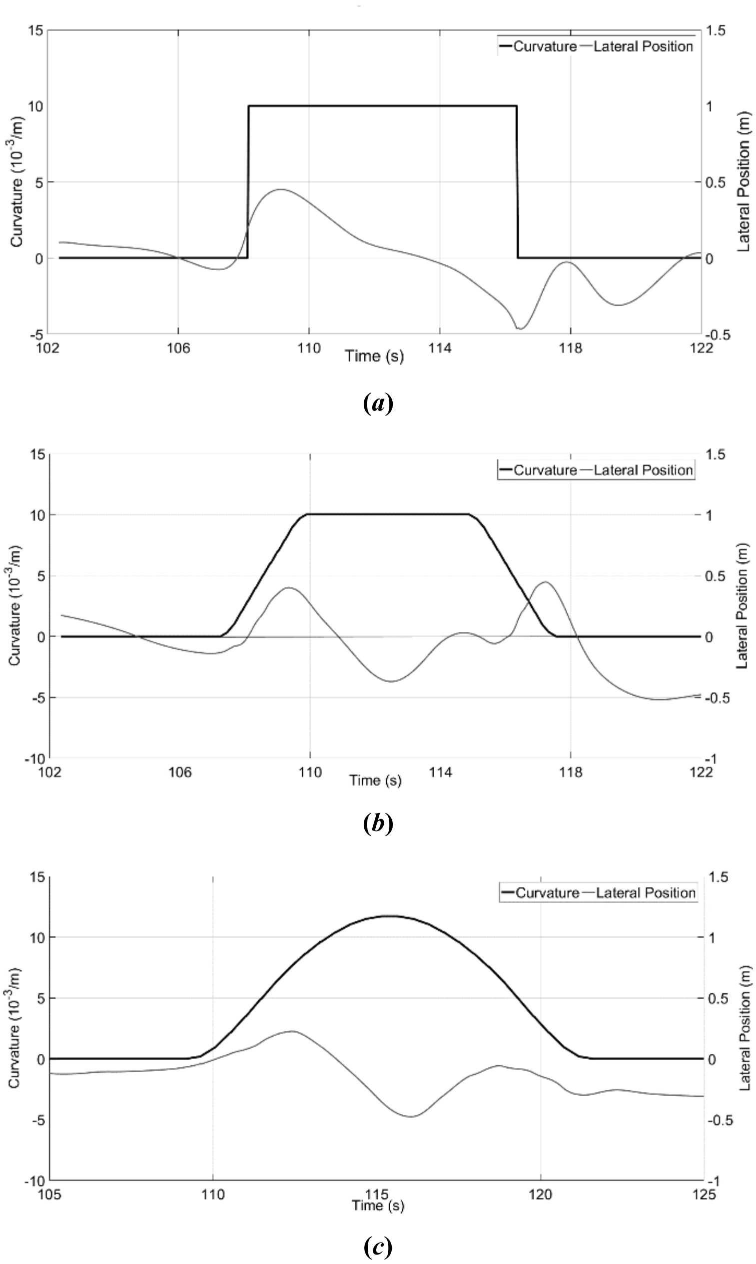


Figure 4 **Example trajectories as driven by a participant on the different curves: (*a*) circular, (*b*) clothoid, (*c*) continuous curve**

Data of all participants were analysed with a RM-ANOVA performed on SDLP, MLP and CLP (Table 4). As can be seen there is a significant difference for curve type for CLP only.

The Estimate marginal means (EMM) or the least-squares means, that are predictions on a reference grid of predictor settings were also calculated. The model has factors as predictors and the best way to understand the observed phenomenon is to compare the EMM with one another, as can be done in Figure 5, where the bars are confidence intervals for the EMMs. If an arrow from one mean overlaps an arrow from another group, the difference is not significant. Only the CLP variable shows significant results and are therefore displayed in Figure 5. In Table 5 the average values of CLP, MLP, and SDLP are presented.

To further investigate which factors contribute to the differences found for CLP in Table 6 the results of a pairwise comparison for the factors are reported (for CLP only). The pairwise comparison was made between the types of curves (Circular, Clothoid, and Continuous Curves) with respect to the angles (50°, 90°, and 130°). In Figure 5 this information in displayed graphical form, Table 6 reports the result from the statistical tests.

Table 4 **Repeated-Measures ANOVA results, main effects of curve type (CIR/CLO/CON), direction (left/right), and Angle (50° / 90° / 130°)**

	CLP		MLP		SDLP	
	F	**p-values**	**F**	**p-values**	**F**	**p-values**
Curve (CIR/CLO/CON)	50.98	< 0.001	< 1	NS	< 1	NS
Direction (left/right)	< 1	NS	8.19	0.06	< 1	NS
Angle (50,90,130)	< 1	NS	2.31	NS	1.09	NS
Curve x Direction	< 1	NS	4.16	0.02	< 1	NS
Curve x Angle	3.56	< 0.05	< 1	NS	< 1	NS
Direction x Angle	8.36	< 0.001	11.41	< 0.001	< 1	NS
Curve x Direction x Angle	< 1	NS	3.67	< 0.01	1.31	NS

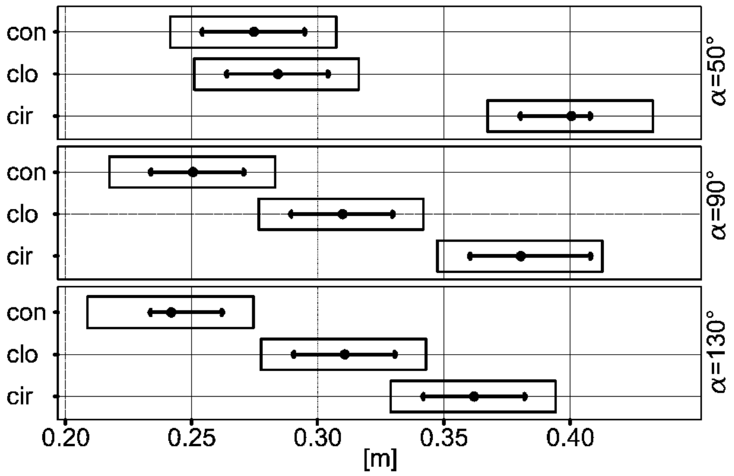


Figure 5 **Estimated marginal means of CLP with 'Curve' and 'Angle (α)' predictors. In this figure the direction of the curve is not reported because no significant differences were found for direction.**

Table 5 **Averages for the different conditions**

	CLP	MLP	SDLP
CIR	0.381	0.037	0.242
CLO	0.301	0.021	0.246
CON	0.255	0.034	0.247

Note: CIR = circular, CLO = Clothoid, CON = Continuous curve; CLP = Cumulative Lateral Position, MLP = Mean Lateral Position, and SDLP = Standard Deviation of the Lateral Position

Table 6 **Post-hoc comparisons for CLP for the different curves and the deviation angles (df = 95.56)**

	Angle = 50°				**Angle = 90°**				**Angle = 130°**			
Contrast	**esti-mate**	**SE**	**t-ratio**	**p**	**esti-mate**	**SE**	**t-ratio**	**p**	**esti-mate**	**SE**	**t-ratio**	**p**
CIR-CLO	0.12	.02	6.81	<.001	0.07	.02	4.14	<.001	0.05	.02	3.01	0.01
CIR-CON	0.13	.02	7.37	<.001	0.13	.02	7.59	<.001	0.12	.02	7.05	<.001
CLO-CON	0.01	.02	0.56	0.84	0.06	.02	3.46	<.001	0.07	.02	4.04	<.001

Self-reported mental effort on the RSME (Zijlstra 1993) for the three types of curves was very similar between curves. Effort reported for circular curves was 40, for clothoid it was also 40 and for continuous curves it was 41. A rating of 40 coincides with the label 'some effort', while the full RSME ranges from 0 to 150.

Regarding the question 'What type of curve did you prefer?', 45% of the drivers preferred the continuous curve, 30% the clothoid curve and only 20% the circular curve. Only one out of the 20 users had no preference. We have to add that many indicated that this preference was based on a feeling that could not be substantiated.

4 Discussion

We propose a new measure, the CLP (Cumulative Lateral Position) that reflects safety of the trajectory a driver follows while negotiating a horizontal curve. On the road, drivers follow a trajectory that is often very different from following the axis of the lane. This trajectory may be influenced by for example width of the road, or whether there is oncoming traffic. It is however still likely that many drivers are not be able to perceive differences between slightly dissimilar geometries. In these cases, a designer must choose the most appropriate geometry with the help of a rational methodology. We claim that deviations from the axis can be best evaluated by the CLP, as more conventional measures such as MLP (Mean Lateral Position) and SDLP (SD of the Lateral Position) do not reflect behaviour in curves accurately.

In the present study driving behaviour while negotiating three types of curves was evaluated: a clothoid curve, a circular curve, and a continuous curve. The circular curve is a typical simulated curve with a sudden onset and offset without any transition and a fixed radius during the curve. The clothoid curve, with a transition into and out of the curve and a fixed radius in between is a typical real road curve. The continuous curve is a polynomial curve that is based on theoretical studies but has not (yet) been realised in practice. In the present study the effectiveness of the CLP was compared to SDLP and MLP on three types of curves. The differences in negotiation of these three curves, in terms of alignment, are for the average driver probably not clearly visible, and therefore one may expect very similar driving behaviour in all conditions, and similar evaluation. Indeed, self-reported ratings of mental effort while negotiating curves did not differ between the three different curve conditions. While SDLP and MLP did not reflect differences in driving behaviour between the three different types of curves, the new indicator CLP did. This does not mean that the older indices are not suitable in other situations but, to evaluate curve negotiation behaviour in one metric, the CLP is more sensitive.

In the case of a circular curve the CLP deviation was always greater than in the other two types of curves, but remains substantially constant with the variation of the angle of deviation. The results suggest that the continuous curve allows drivers to more closely follow the axis of the lane, avoiding the danger of drifting in the opposite direction and, therefore, ensures greater road safety. The CLP showed difference in behaviour on these types of curves, more specifically between a curve that is not desirable (the circular curve, which is not recommended by modern standards) and more realistic or desirable curves (continuous and clothoid curves). Angle of the curves matters, the CLP index for clothoid and continuous curves is significantly different only for angles ≥ 90°, while it is very close for the 130° angle, both for clothoid and continuous curves.

4.1 Making a distinction between curves and safe driving

MLP is not sensitive for large swerving behaviour as it reflects the average position. As long as deviations in both directions are just as frequent and large this will not become apparent in MLP. This happens, for example, when the driver misunderstands a part of the curve, generally the entrance or exit and, subsequently, tries to compensate for errors by steering from one side and the other. The SDLP index does reflect deviations with regard to the average position, but not those with respect to the lane axis (see differences between examples 1 and 2 in Figure 1). So, if a driver moves dangerously towards the opposite lane but maintains a homogeneous trajectory to the geometry of the curve, this index does not reflect these dangers. The CLP index solves these disadvantages since it increases both when the driver swerves equally left and right, but very widely around the centreline of the lane, (MLP null in theory), and when the driver swerves little but close to the axis of the road (SDLP null in theory). In these cases, CLP can highlight risky driving behaviour (and allow for choosing the best geometry of the curve).

In this experiment the CLP captures safety of behaviour best and indicates that the continuous curve is most favourable in the sense of safe driving behaviour.

4.2 Limitations

It is important to mention that CLP should be interpreted together with other variables. Speed and lane width have influence on CLP. In the case of wide lanes and high speed in particular, as cutting corners and lateral acceleration play a large role then. In the present experiment the lane was relatively narrow (3.2 m) and the speed was relatively low, it is important to study how effects are at higher speeds and on wider lanes. As the present study took place in a driving simulator, it is also important that validation of the CLP as measure takes place with data collected of driving on the road.

5 Conclusions

Mean and SD of the Lateral Position have been and remain important parameters to describe driving behaviour, but the interpretation of these measures in curve driving is not without problems. Cumulative Lateral Position (CLP) is a newly proposed measure that can reflect behaviour and safety, in particular whether and how drivers approach the adjacent/opposite lane. Next to commonly used measures we believe CLP is a useful extra measure, which was demonstrated on three different types of curves: a traditional circular, a clothoid, and a new, polynomial curve with continuous curvature. On the basis of the CLP, it was shown that the driving trajectory was safest in the new curve.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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