Investigation of Motorcycle Trajectories in 2-lane Horizontal Curves

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Abstract: - Most of the road design guidelines assume that the vehicles traverse a trajectory that coincides with the midline of the traffic lane. Based on this assumption the thresholds of various features are determined such as the maximum permissible side friction factor. It is therefore important to investigate the extent to which the trajectory of the vehicles is similar to the horizontal alignment of the road or substantial differences exist. To this end, a naturalistic riding study was designed and executed with the use of an instrumented motorcycle which measured the position of the motorcycle with great accuracy in a rural 2-lane road segment. The derived trajectories were then plotted against the horizontal alignment of the road and compared with the 3 consecutive elements which form a typical horizontal curve i.e., the entering spiral curve, the circular curve, and the exiting spiral curve. Linear equations were developed which correlate the traveled curvatures with the distance of each horizontal curve along the road segment under investigation. The process of the data revealed that the riders differ their trajectory compared to the alignment of the road. However, in small radius horizontal curves is more likely to observe curvatures that are similar to the geometric one. Moreover, the riders perform more abrupt maneuvres in the first part of the horizontal curves while they straighten the handlebars of the motorcycle before the end of the curve. The present paper aims to shed light on the behavior of motorcycle riders on horizontal curves and hence to contribute to the reduction of motorcycle accidents, particularly the single-vehicle ones.

Key-Words: -Motorcyclists’ behavior, Trajectory, Horizontal alignment, Field measurements, Naturalistic riding study, Spiral curves, Circular curve

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1 Introduction

There is strong evidence suggesting that the real paths of vehicles are not the ones initially estimated, which are related to the geometry of the road element (intersection, roundabout, horizontal curve etc) and its line marking. Alhajyaseen et al drew the curvature profile of the vehicles traveling in an intersection using the fundamental elements of the horizontal alignment i.e., straight segments before and after the circular curve segment, Euler spiral curves which are designed between the entry and exit straight segment and the circular arc (transition segments) and the circular arc itself. It is well known that the curvature of the straight line is 0 and the curvature of the circular arc is constant and equal to the reciprocal of the radius R of the circular arc. If A is the parameter of the Euler spiral curve and L is the length from the beginning of the horizontal curve, then equation (1) is valid:

$$R \cdot L = A^2 \quad (1)$$

The principal finding of their work is that the trajectories of the vehicles do not coincide with each other and that the vehicle path is correlated with the traveling speed of the vehicles [1].

Variations on vehicles’ trajectories are also identified among the vehicles themselves due to the various driving styles, the number of lanes, vehicle type, and travel speed. Especially for the left-turning vehicles, previous research has shown that the trajectory is a combination of road geometry features and driving behavior aspects [2, 3]. The importance of track investigation is documented in another study which suggests that the inappropriate trajectory is the leading cause of accidents in curved sections [4].

The difference between the predicted and the real trajectories and speeds of the vehicles traveling on roundabouts discussed in a paper by Mussone et al. in which the authors developed a tool to investigate vehicular movements in roundabouts that is based on image processing [5].

The investigation of vehicles’ lateral position reveals that two main categories can be determined: normal behavior and extreme behavior. The latter corresponds to a trajectory in which the vehicles deviate substantially from the middle line of the travel lane whereas the former (which by the way is assumed as granted in most of the design guidelines worldwide), accepts that the real trajectory and the middle line of the travel lane coincide, or they are parallel lines. A relevant study reveals that in quantitative terms, the deviation from the midline of the traffic lane which poses a risk to the stability of the vehicles is observed in 36% of the investigated trajectories. The study also concludes that the absence of a clothoid is correlated with higher proportions of unwanted trajectories. The author finally lists 4 conditions that should be met in order to increase the desired type of trajectories i.e., the design of the curve radii must be between 120-230m, the ratio of the clothoid parameter to the radius of the curve must be between 1/3 and ½, the length of the circular arcs must correspond to minimum 5s pass-through time and the lane width must be equal to 3.4-3.5 m [2]. Other researchers found that the drivers experience difficulties to precisely follow the alignment of the road [4].

Apart from the trajectory type, another fundamental aspect for the safe negotiation of a horizontal curve is the travel speed. The higher the travel speed the more the centrifugal force that is applied to the contact point between the tires and the pavement and hence the more the friction demands, as derived from Equation (2), which is a simplified curve formula [6].

$$f_R = \frac{V^2}{15 \cdot R} \tag{2}$$

Where:
V: travel speed in curve (mph)
R: radius of curve (ft)
e: superelevation (ft/ft), and
f_R: side friction factor

Since the design of the road assumes that the vehicles travel in the middle of the travel lane it is also assumed that the curvature of the trajectory coincides with that of the road. However, due to intentional or unintentional reasons, drivers might traverse a path which curvature is partially greater than the geometric one. In such sections, the real radius is less than the one that the road was designed and consequently under such circumstances the vehicle's stability is at stake. Lastly, there is some evidence that when the drivers travel in the middle of the traffic lane the travel speed is lower compared to the drivers whose trajectory substantially differs from the horizontal alignment of the road [2].

Spacek investigated the trajectories of the vehicles traveling in eight curves in both directions of two-lane highways. He concluded that the drivers drive closer to the axis of the road in both left-hand and right-hand curves, a finding that was also confirmed in a later research study. However, this tendency in left-hand curves was observed to be more intense [2, 7].

Many research studies are documented in an effort to model vehicular trajectories at horizontal curves as mentioned in a paper by Fitzsimmons et al [8]. The developed models include several estimated types of trajectories with swinging, drifting, cutting, and correcting be the most widespread among them. However, these models cannot be exploited to correlate accident risk with a trajectory type but to investigate driving behavior with the road geometry instead. For instance, as discussed in the same study, evidence suggests that most drivers follow the correcting trajectory when they travel at sharp curves while they cut-the-curve as the radius of the horizontal curve increases or the change of direction is minor [2]. In another study, the authors concluded that the drivers in the outside travel lane tend to travel closer to the centerline of the road while the drivers in the opposite direction tend to travel closer to the edge line of the curve [9]. Lastly, Figueroa et al. found that most of the vehicle speed reductions and accelerations take place on the tangent segments preceding and following a horizontal curve respectively [10].

The investigation of driving behavior in terms of speed and lateral position at horizontal curves studied by Fitzsimmons et al. The authors observed that both operating speed and lateral position vary as drivers negotiate horizontal curves either in the inside or the outside traffic lane. They also concluded that drivers adopted the cutting trajectory type regardless of the lane they travel since this type allows higher travel speed through the horizontal curves [8].

As mentioned before, a crucial parameter of the driver's trajectory is when the traversed curvature is greater than the geometric one or in other words when the radius of the real trajectory is smaller than the radius of the circular curve. At that section, the developed centrifugal force increases, and hence the radial friction demand might exceed the designed one. Moreover, if the driver simultaneously applies the brakes or the pavement is wet, the vehicle may depart the travel lane or even worse the road [2]. Therefore, it is of paramount importance the identification of such sections especially in undivided roads where the lane departure might lead to KSI (Killed or Severely Injured) accidents.

The investigation of vehicle trajectories has been performed for various types of vehicles except for motorcycles, at least to our knowledge [4, 3, 8, 2]. Recently the exploitation of portable configurations which continuously and accurately record the speed and trajectory of the vehicles along multiple road sections have paved the way to perform studies under natural conditions [11]. Such studies allow the collection of unbiased data since the equipment is not perceived by the participants and therefore, they do not change their natural behavior.

Due to their size, motorcycles can exploit a larger portion of the travel lane compared to four-wheel vehicles. Therefore, the assumption that all road users behave similarly in curved sections might be misleading. To this end, aiming at investigating the trajectories of motorcycle riders in horizontal curves, a naturalistic riding study was designed and executed in the framework of the present study. Aim of the analysis is to shed more light on the motorcycle accidents that occur in horizontal curves and ultimately to contribute to the enhancement of road safety.

2 Methodology and Process

The investigation of motorcycle riders' trajectories in horizontal curves was carried out by planning and conducting a naturalistic riding study in which 18 participants rode in a 2-lane rural road segment. The test vehicle was equipped with a high accuracy GPS device which measured continuously the position and the speed of the vehicles. Further details regarding the setup and the execution of the said experiment together with the geometric features of the test road segment are included in other published papers [12, 13, 14] and are omitted from the present one.

The generated data set included a time series of positional data in a frequency of 5Hz. From that, the speed profile, the traveled distance, and the traversed path (trajectory) from each one of the participants were determined. Since the analysis concerned only the horizontal curves, the recorded points that lie on the tangent sections of the road were excluded. As mentioned before, the subject of the investigation was the comparison of riders' trajectories with the geometry of each curve. For that reason, the radius and the curvature for every three consecutive recorded points were calculated and plotted against the traveled distance. Different paths result in different traveled distances and hence each trajectory had to be normalized in order to render comparative plots. Lastly, due to instant GPS signal losses, few outliers were generated. Aiming to overcome this problem the data were properly filtered.

The horizontal alignment of the road segment where the field measurements took place was known in a digital format and particularly the points:

- tangent to the entering spiral curve point (TS),
- spiral to circular curve point (SC),
- circular curve to exiting spiral curve point (CS) and lastly
- exiting spiral curve to the following tangent point (ST).

These points for a random horizontal curve with radius R and center O are shown in Figure 1. Moreover, Table 1 presents the principal geometric characteristics of the 21 horizontal curves. Note that K_e stands for the Curvature Change Rate (gon/km), ΔR for the deflection (m) and L for the length of the individual element of the curve. The rest of the variables are mentioned in Figure 1.

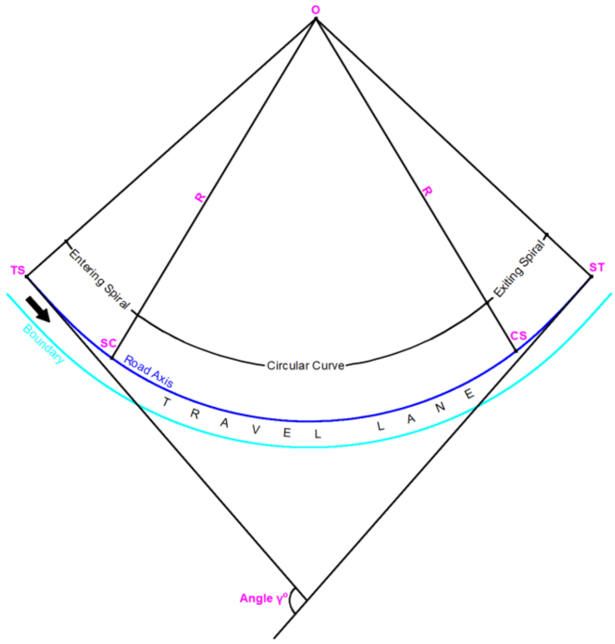


Fig. 1: Typical form of a horizontal curve

Table 1. Geometric attributes of horizontal curves

Curve	R (m)	L_{TS-SC} (m)	L_{SC-CS} (m)	L_{CS-ST} (m)	K_e gon/km	ΔR (m)	Angle γ° degrees
K1	900	44.44	127.62	44.44	56.22	0.091	10.954
K2	250	40.00	180.64	40.00	215.57	0.267	50.568
K3	330	30.30	196.65	30.30	170.19	0.116	39.404
K4	200	112.50	112.63	50.00	224.31	0.521	55.543

Curve	R (m)	L_{TS-SC} (m)	L_{SC-CS} (m)	L_{CS-ST} (m)	K_e gon/km	ΔR (m)	Angle γ° degrees
K5	900	11.11	246.76	11.11	67.81	0.006	16.416
K6	800	50.00	136.24	50.00	62.73	0.130	13.338
K7	200	50.00	306.10	50.00	279.12	0.521	102.015
K8	195	51.28	277.87	51.28	282.46	0.562	96.713
K9	225	44.44	55.50	44.44	195.85	0.366	25.450
K10	380	105.26	25.70	105.26	92.88	1.214	19.747
K11	270	37.04	183.18	37.04	201.84	0.212	46.732
K12	220	45.45	109.48	45.45	223.73	0.391	40.350
K13	200	50.00	140.56	50.00	252.15	0.521	54.592
K14	600	16.67	142.37	16.67	96.04	0.019	15.187
K15	370	60.81	208.35	60.81	140.35	0.416	41.681
K16	400	56.25	276.03	56.25	136.11	0.330	47.596
K17	300	33.33	145.79	33.33	178.91	0.154	34.209
K18	300	33.33	65.57	33.33	158.71	0.154	18.889
K19	220	45.45	47.61	45.45	194.42	0.391	24.238
K20	220	45.45	74.90	45.45	210.04	0.391	31.345
K21	250	40.00	97.24	40.00	197.18	0.267	31.452

The data that is included in Table 1 were used to draw the curvature of the spiral curves and the circular curve against the length of each curve. As mentioned before the length of each curve was normalized in order to render the figures illustrating the trajectories' curvatures and curve curvatures comparable. Figure 2 presents the curvature of the three elements that consist a horizontal curve i.e., entering spiral curve, circular curve, exiting spiral curve, of K1.

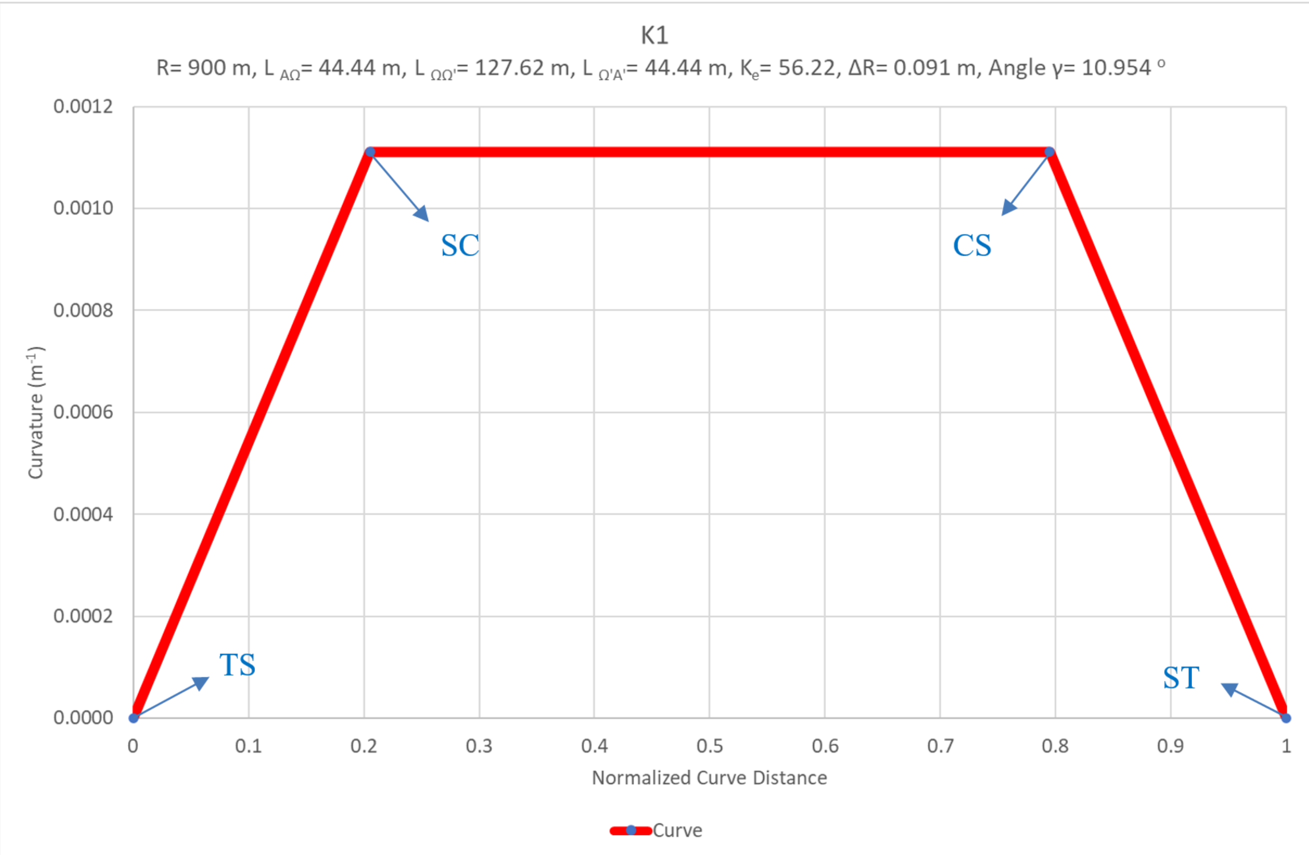


Fig. 2: Curvature Vs Normalized Distance of horizontal curve K1

The plotting of the trajectories together with the boundaries of the road was therefore also feasible. That allowed the identification of the recorded points of each measurement which lie within the boundaries of each of the 21 horizontal curves (P_1, P_2,…, P_n), and also the calculation of the consecutive curvatures, every three recorded points as mentioned before. Since three given points define a circle, for every three recorded consecutive points that lie on the trajectory of the rider, a circle was calculated and particular its radius R and center O. The reciprocal of the calculated radius is the curvature for this section of the curve. Figure 3 illustrates this step of the process for a random position.

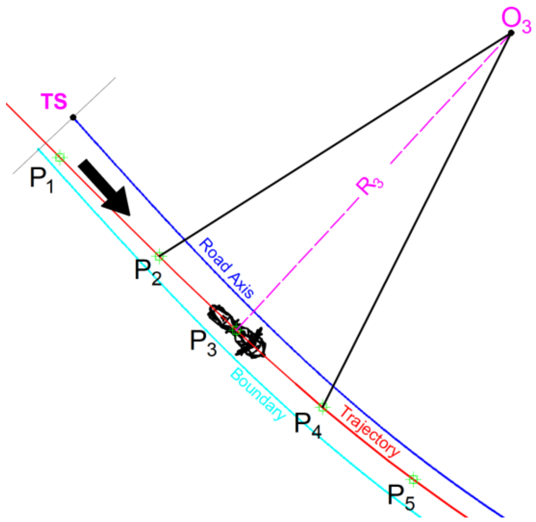
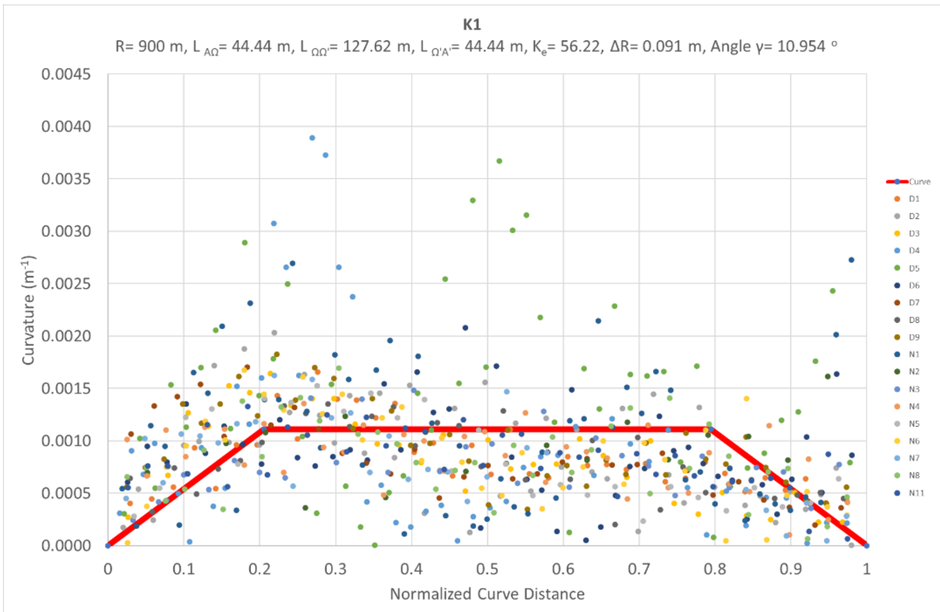
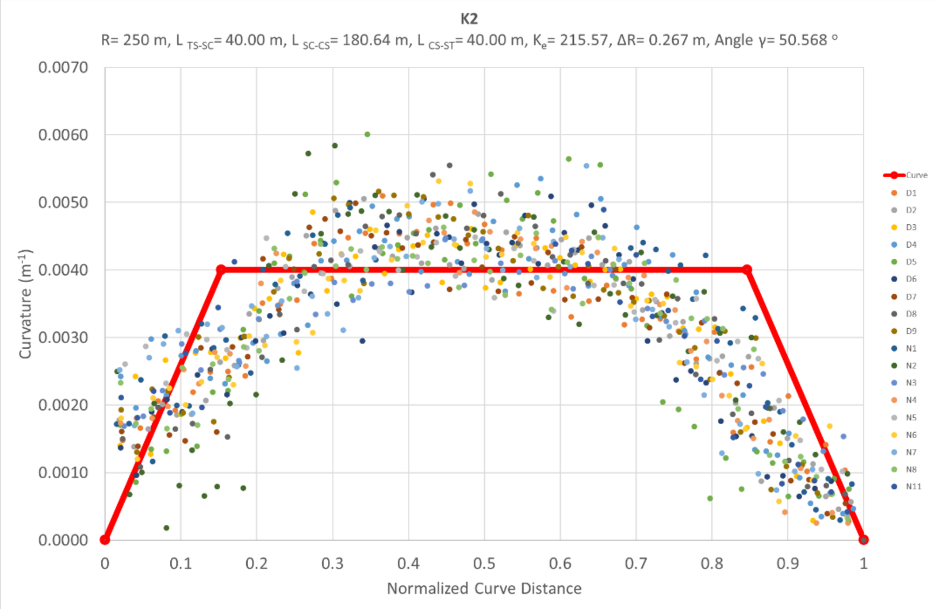


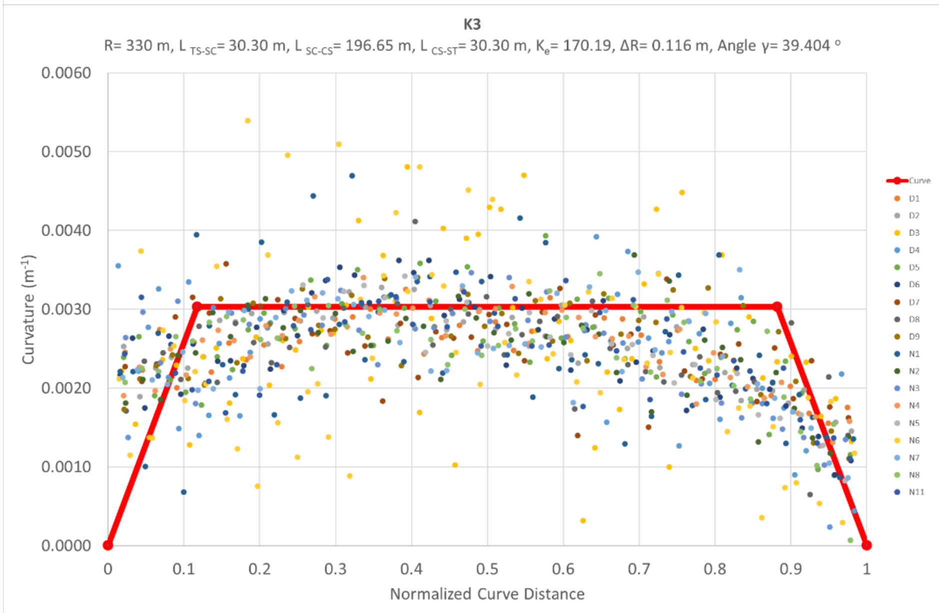
Fig. 3: Calculation of trajectories curvature in a random position

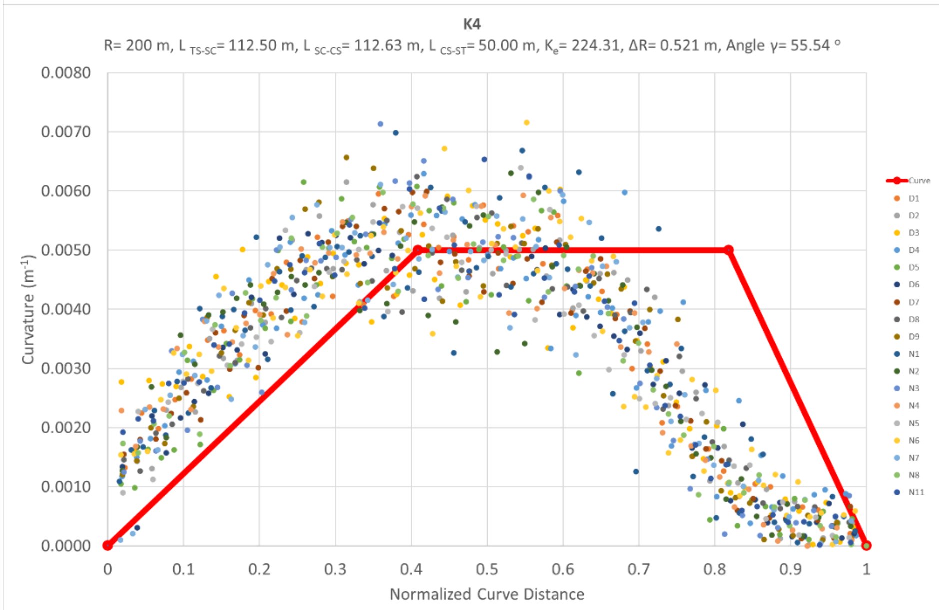
3 Results

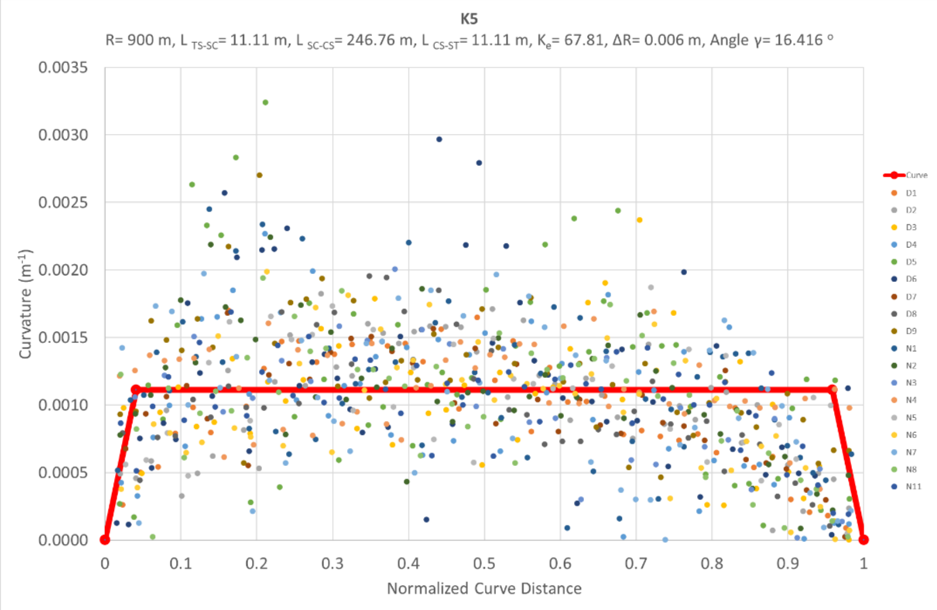
The implementation of the methodology that is described in the Methodology and process chapter produced the consecutive curvatures for each measurement in each one of the 21 horizontal curves. These curvatures were then plotted in the same figure with the curve curvature in order to further investigate riders' behavior when they negotiate horizontal curves. By doing so the analysis can be performed for each curve element separately i.e., for the two spiral curves and the circular curve. The generated figures are presented in Figure 4. Note that D1, D2, D3, D4, D5, D6, D7, D8, D9 and N1, N2, N3, N4, N5, N6, N7, N8, N11 are the coding names of the participants to the measurements.

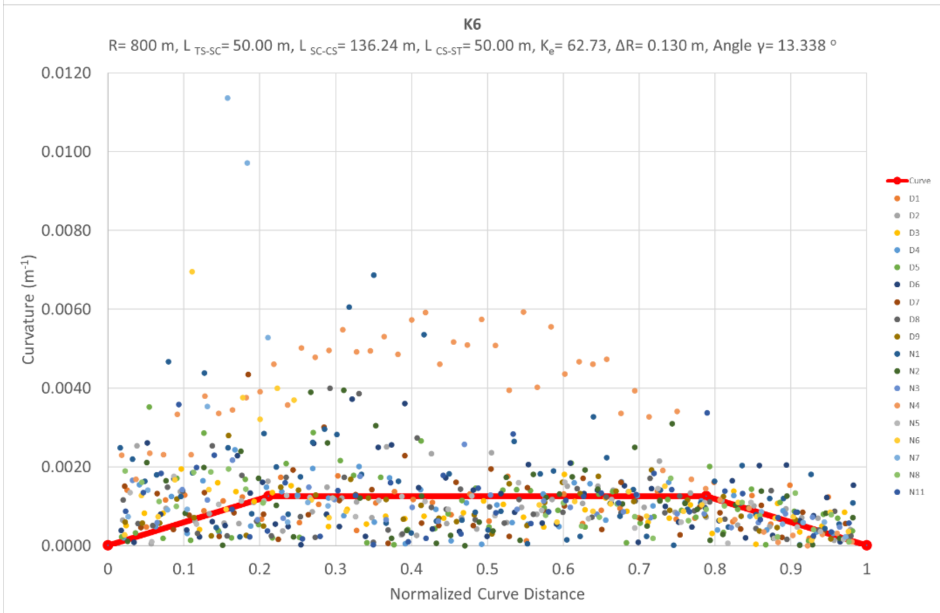


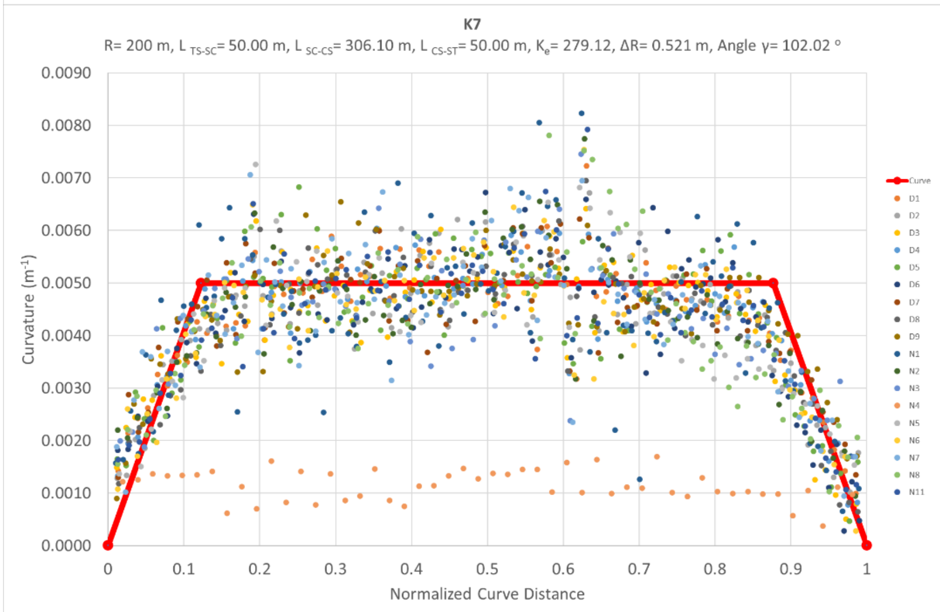

K2
R= 250 m, $L_{TS\text{-}SC}$= 40.00 m, $L_{SC\text{-}CS}$= 180.64 m, $L_{CS\text{-}ST}$= 40.00 m, K_e= 215.57, ΔR= 0.267 m, Angle γ= 50.568 °
Curvature (m^{-1})
Normalized Curve Distance
Curve
D1
D2
D3
D4
D5
D6
D7
D8
D9
N1
N2
N3
N4
N5
N6
N7
N8
N11

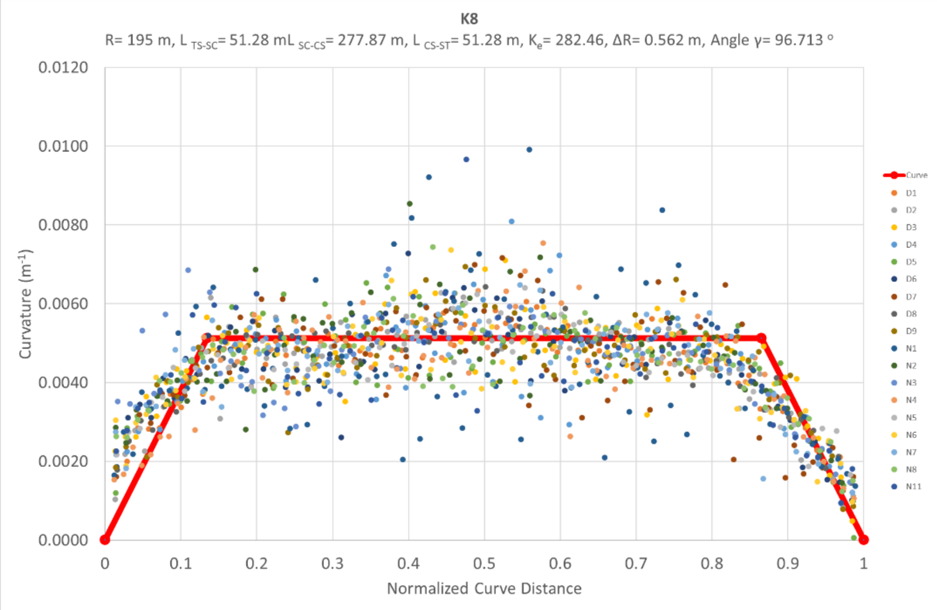

K3
R= 330 m, $L_{TS\text{-}SC}$= 30.30 m, $L_{SC\text{-}CS}$= 196.65 m, $L_{CS\text{-}ST}$= 30.30 m, K_e= 170.19, ΔR= 0.116 m, Angle γ= 39.404 °
Curvature (m^{-1})
Normalized Curve Distance
Curve
D1
D2
D3
D4
D5
D6
D7
D8
D9
N1
N2
N3
N4
N5
N6
N7
N8
N11

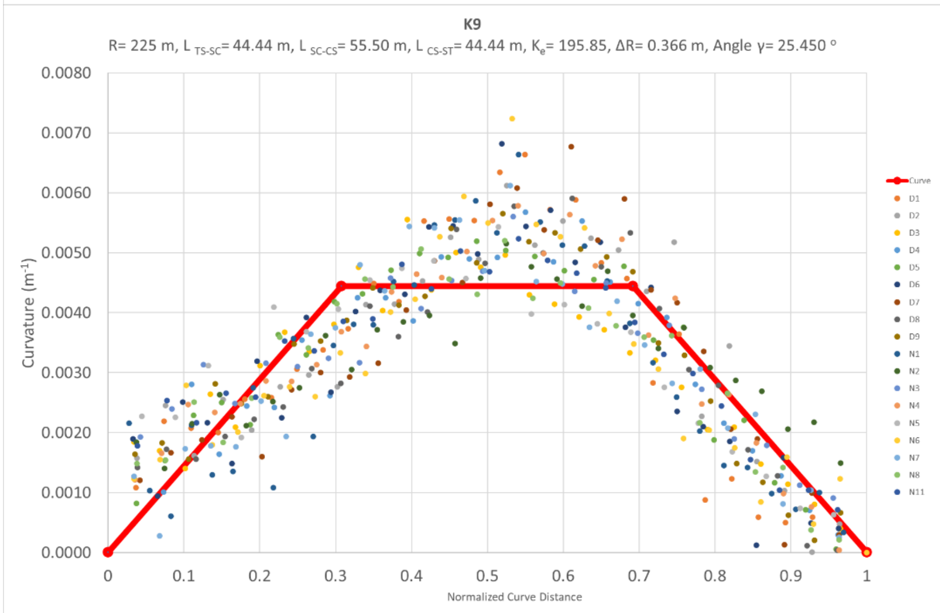

K4
R= 200 m, $L_{TS\text{-}SC}$= 112.50 m, $L_{SC\text{-}CS}$= 112.63 m, $L_{CS\text{-}ST}$= 50.00 m, K_e= 224.31, ΔR= 0.521 m, Angle γ= 55.54 °
Curvature (m^{-1})
Normalized Curve Distance
Curve
D1
D2
D3
D4
D5
D6
D7
D8
D9
N1
N2
N3
N4
N5
N6
N7
N8
N11

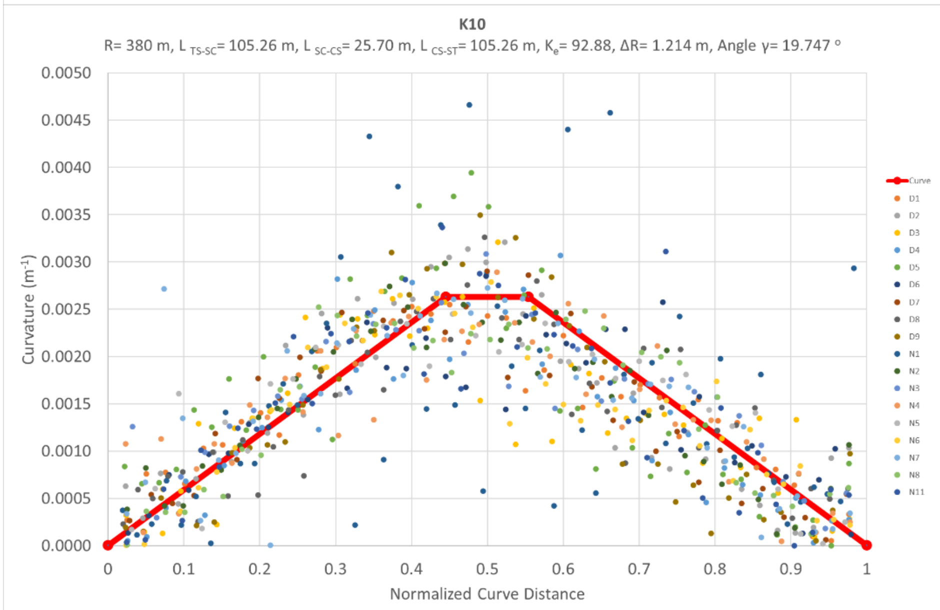

K5
R= 900 m, L TS-SC= 11.11 m, L SC-CS= 246.76 m, L CS-ST= 11.11 m, Ke= 67.81, ΔR= 0.006 m, Angle γ= 16.416 º
Curvature (m-1)
Normalized Curve Distance
Curve
D1
D2
D3
D4
D5
D6
D7
D8
D9
N1
N2
N3
N4
N5
N6
N7
N8
N11

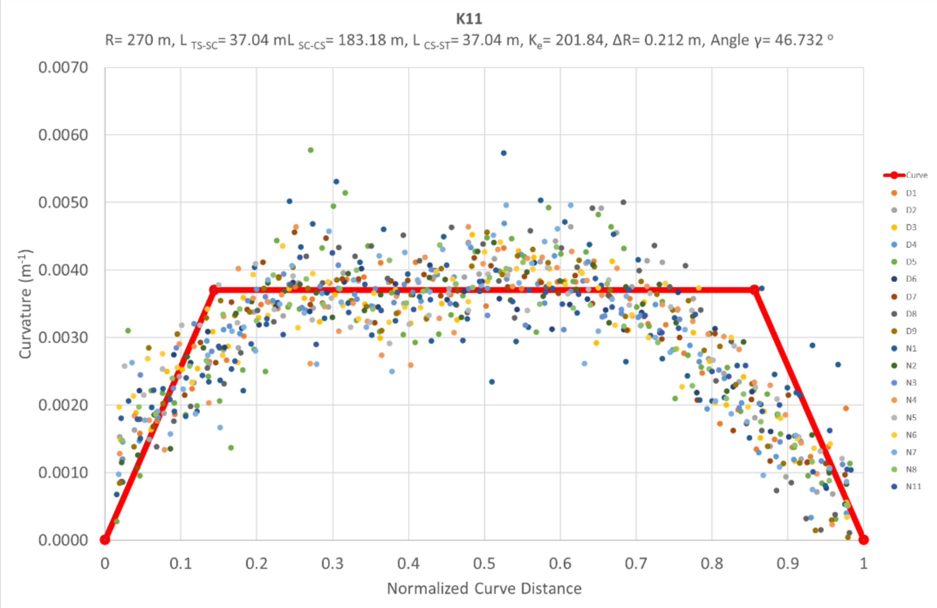

K6
R= 800 m, L TS-SC= 50.00 m, L SC-CS= 136.24 m, L CS-ST= 50.00 m, Ke= 62.73, ΔR= 0.130 m, Angle γ= 13.338 º
Curvature (m-1)
Normalized Curve Distance
Curve
D1
D2
D3
D4
D5
D6
D7
D8
D9
N1
N2
N3
N4
N5
N6
N7
N8
N11

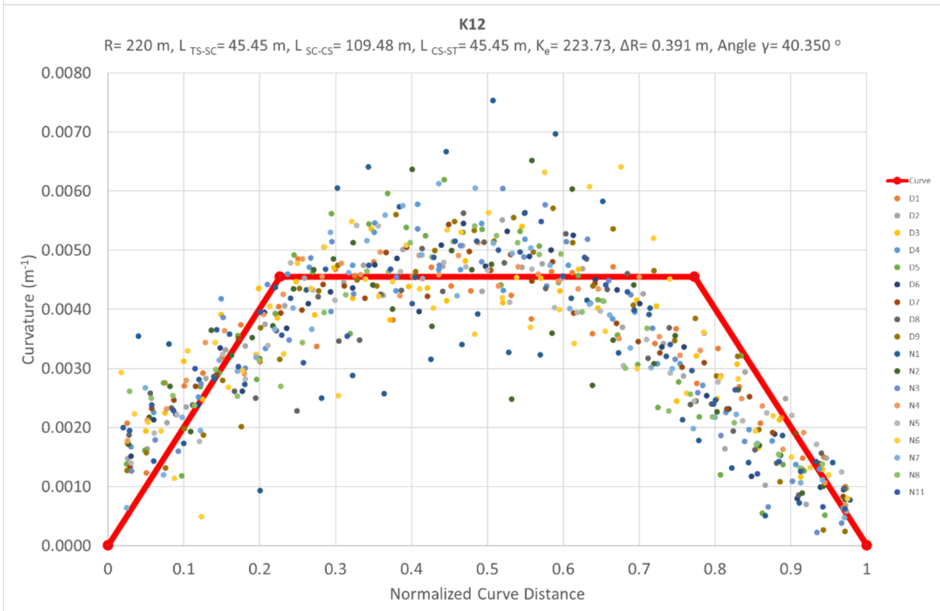

K7
R= 200 m, L TS-SC= 50.00 m, L SC-CS= 306.10 m, L CS-ST= 50.00 m, Ke= 279.12, ΔR= 0.521 m, Angle γ= 102.02 º
Curvature (m-1)
Normalized Curve Distance
Curve
D1
D2
D3
D4
D5
D6
D7
D8
D9
N1
N2
N3
N4
N5
N6
N7
N8
N11

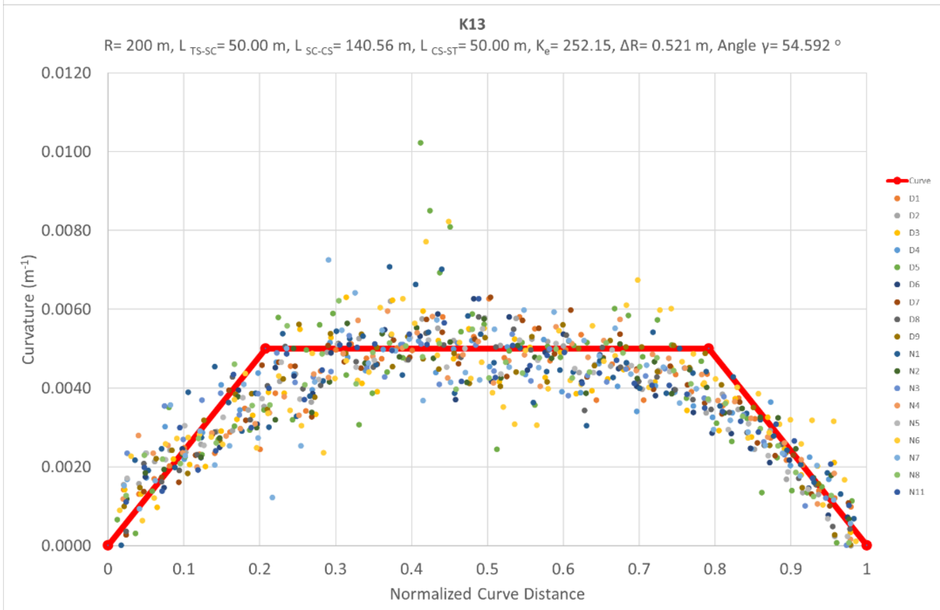

K8
R= 195 m, L TS-SC= 51.28 mL SC-CS= 277.87 m, L CS-ST= 51.28 m, Ke= 282.46, ΔR= 0.562 m, Angle γ= 96.713 °
Curvature (m-1)
Normalized Curve Distance
Curve
D1
D2
D3
D4
D5
D6
D7
D8
D9
N1
N2
N3
N4
N5
N6
N7
N8
N11

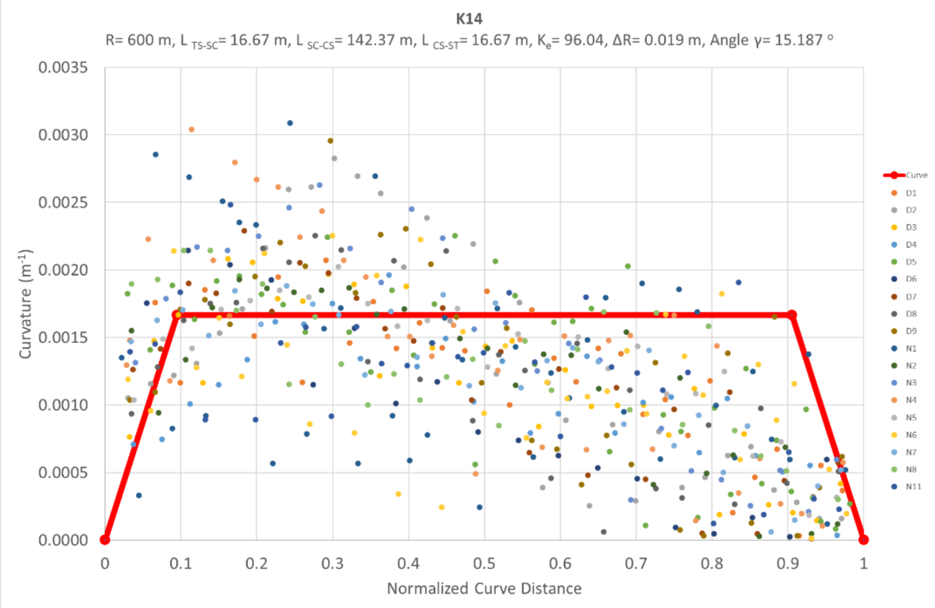

K9
R= 225 m, L TS-SC= 44.44 m, L SC-CS= 55.50 m, L CS-ST= 44.44 m, Ke= 195.85, ΔR= 0.366 m, Angle γ= 25.450 °
Curvature (m-1)
Normalized Curve Distance
Curve


K10
R= 380 m, L TS-SC= 105.26 m, L SC-CS= 25.70 m, L CS-ST= 105.26 m, Ke= 92.88, ΔR= 1.214 m, Angle γ= 19.747 °
Curvature (m-1)
Normalized Curve Distance
Curve


K11
R= 270 m, L TS-SC= 37.04 mL SC-CS= 183.18 m, L CS-ST= 37.04 m, Ke= 201.84, ΔR= 0.212 m, Angle γ= 46.732 °
Curvature (m-1)
Normalized Curve Distance
0.0070
0.0060
0.0050
0.0040
0.0030
0.0020
0.0010
0.0000
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Curve
D1
D2
D3
D4
D5
D6
D7
D8
D9
N1
N2
N3
N4
N5
N6
N7
N8
N11


K12
R= 220 m, L TS-SC= 45.45 m, L SC-CS= 109.48 m, L CS-ST= 45.45 m, Ke= 223.73, ΔR= 0.391 m, Angle γ= 40.350 °
Curvature (m-1)
Normalized Curve Distance
0.0080
0.0070
0.0060
0.0050
0.0040
0.0030
0.0020
0.0010
0.0000
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Curve
D1
D2
D3
D4
D5
D6
D7
D8
D9
N1
N2
N3
N4
N5
N6
N7
N8
N11


K13
R= 200 m, L TS-SC= 50.00 m, L SC-CS= 140.56 m, L CS-ST= 50.00 m, Ke= 252.15, ΔR= 0.521 m, Angle γ= 54.592 °
Curvature (m-1)
Normalized Curve Distance
0.0120
0.0100
0.0080
0.0060
0.0040
0.0020
0.0000
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Curve
D1
D2
D3
D4
D5
D6
D7
D8
D9
N1
N2
N3
N4
N5
N6
N7
N8
N11


K14
R= 600 m, L TS-SC= 16.67 m, L SC-CS= 142.37 m, L CS-ST= 16.67 m, Ke= 96.04, ΔR= 0.019 m, Angle γ= 15.187 º
Curvature (m-1)
Normalized Curve Distance
Curve
D1
D2
D3
D4
D5
D6
D7
D8
D9
N1
N2
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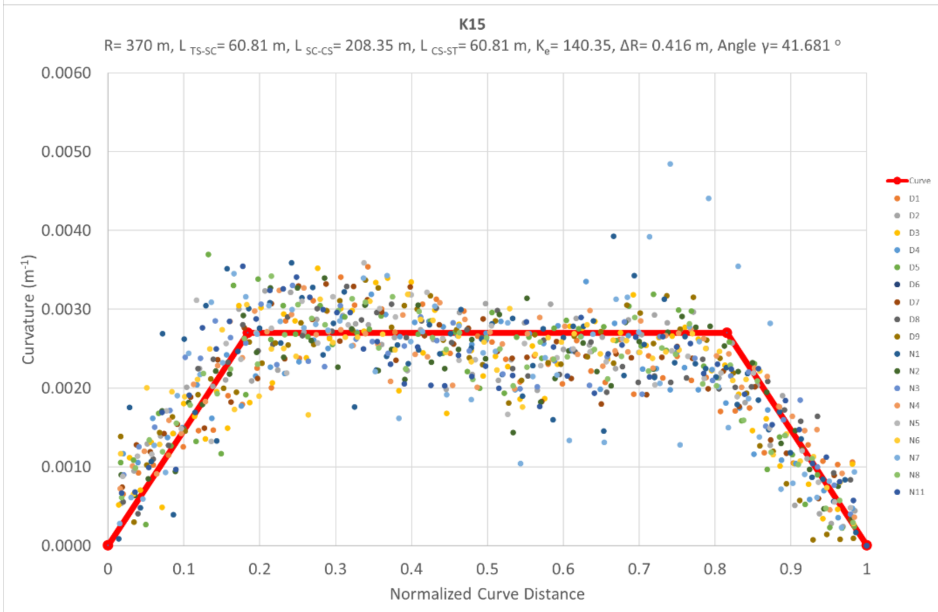
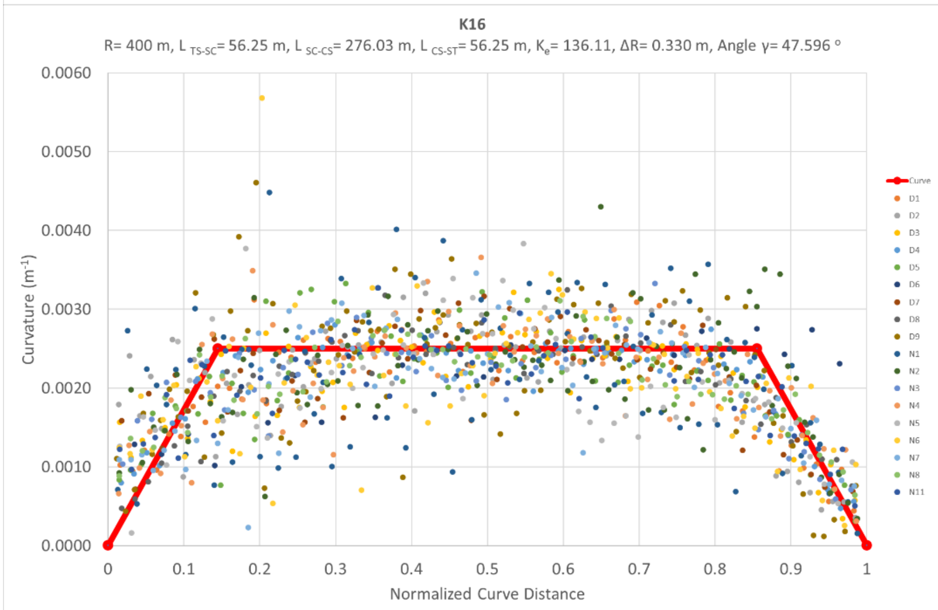
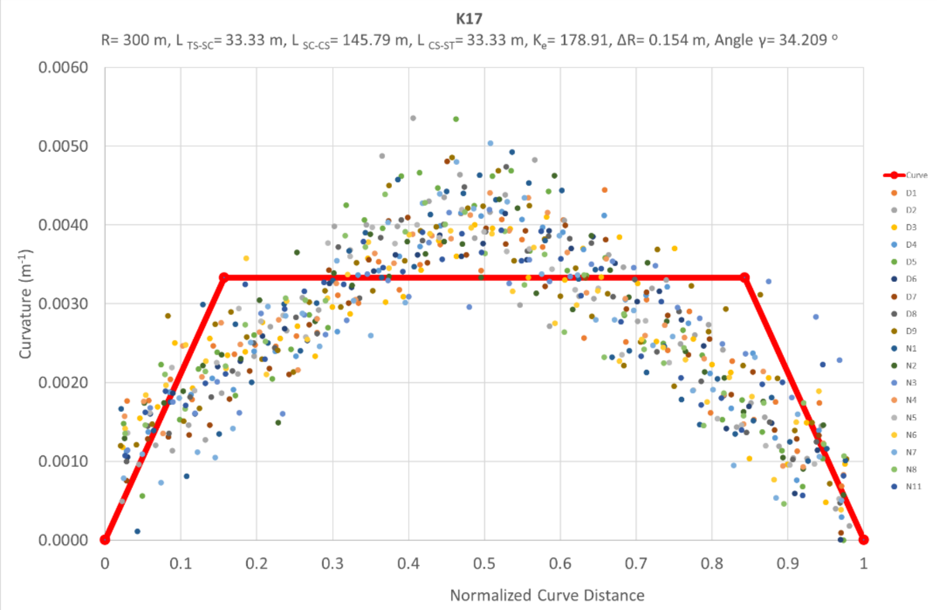
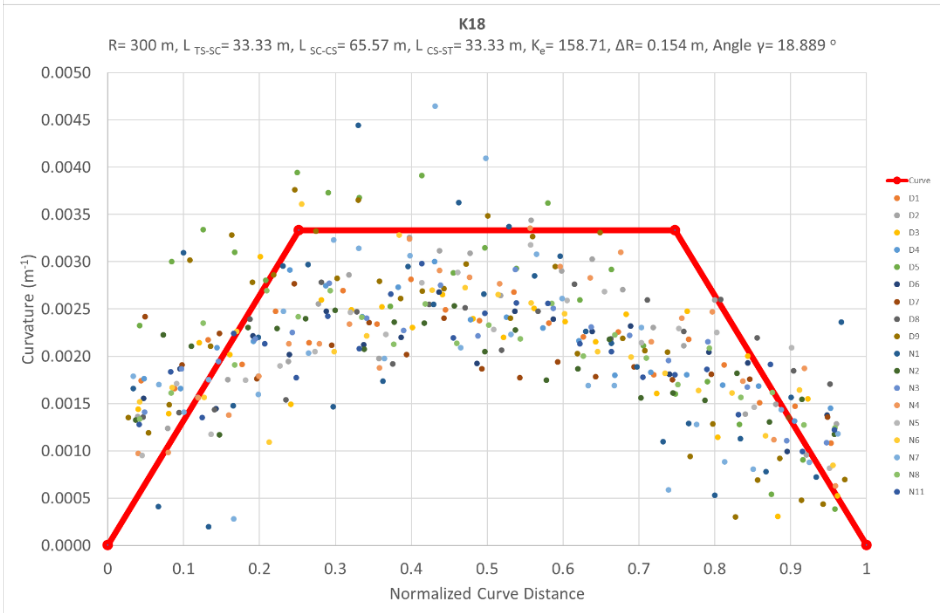
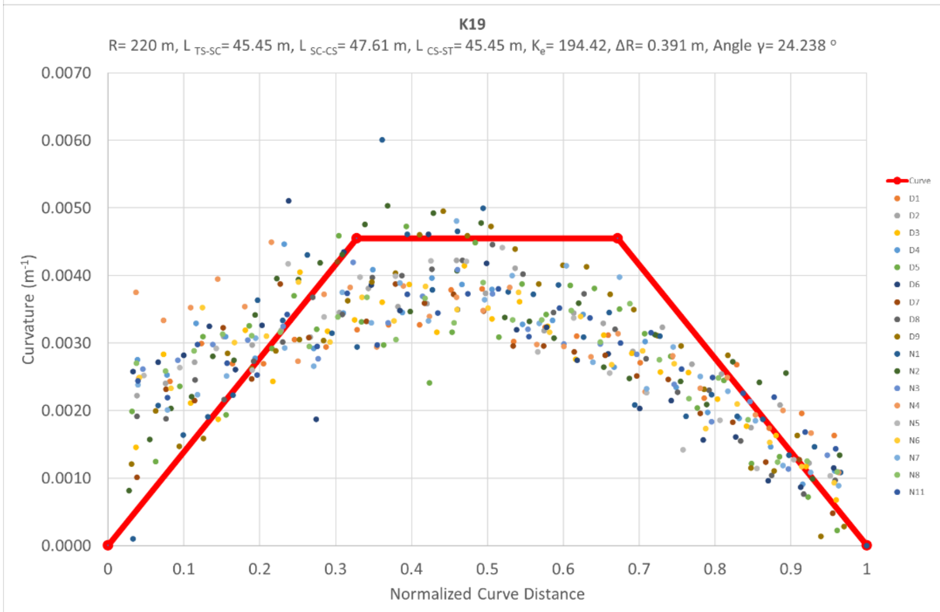
N6
N7
N8
N11


K15
R= 370 m, L TS-SC= 60.81 m, L SC-CS= 208.35 m, L CS-ST= 60.81 m, Ke= 140.35, ΔR= 0.416 m, Angle γ= 41.681 º
Curvature (m-1)
Normalized Curve Distance


K16
R= 400 m, L TS-SC= 56.25 m, L SC-CS= 276.03 m, L CS-ST= 56.25 m, Ke= 136.11, ΔR= 0.330 m, Angle γ= 47.596 º
Curvature (m-1)
Normalized Curve Distance


K17
R= 300 m, L $_{TS-SC}$= 33.33 m, L $_{SC-CS}$= 145.79 m, L $_{CS-ST}$= 33.33 m, K_e= 178.91, ΔR= 0.154 m, Angle γ= 34.209 °
Curvature (m^{-1})
Normalized Curve Distance
0.0000
0.0010
0.0020
0.0030
0.0040
0.0050
0.0060
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Curve
D1
D2
D3
D4
D5
D6
D7
D8
D9
N1
N2
N3
N4
N5
N6
N7
N8
N11


K18
R= 300 m, L $_{TS-SC}$= 33.33 m, L $_{SC-CS}$= 65.57 m, L $_{CS-ST}$= 33.33 m, K_e= 158.71, ΔR= 0.154 m, Angle γ= 18.889 °
Curvature (m^{-1})
Normalized Curve Distance
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
0.0030
0.0035
0.0040
0.0045
0.0050
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Curve
D1
D2
D3
D4
D5
D6
D7
D8
D9
N1
N2
N3
N4
N5
N6
N7
N8
N11


K19
R= 220 m, L $_{TS-SC}$= 45.45 m, L $_{SC-CS}$= 47.61 m, L $_{CS-ST}$= 45.45 m, K_e= 194.42, ΔR= 0.391 m, Angle γ= 24.238 °
Curvature (m^{-1})
Normalized Curve Distance
0.0000
0.0010
0.0020
0.0030
0.0040
0.0050
0.0060
0.0070
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Curve
D1
D2
D3
D4
D5
D6
D7
D8
D9
N1
N2
N3
N4
N5
N6
N7
N8
N11

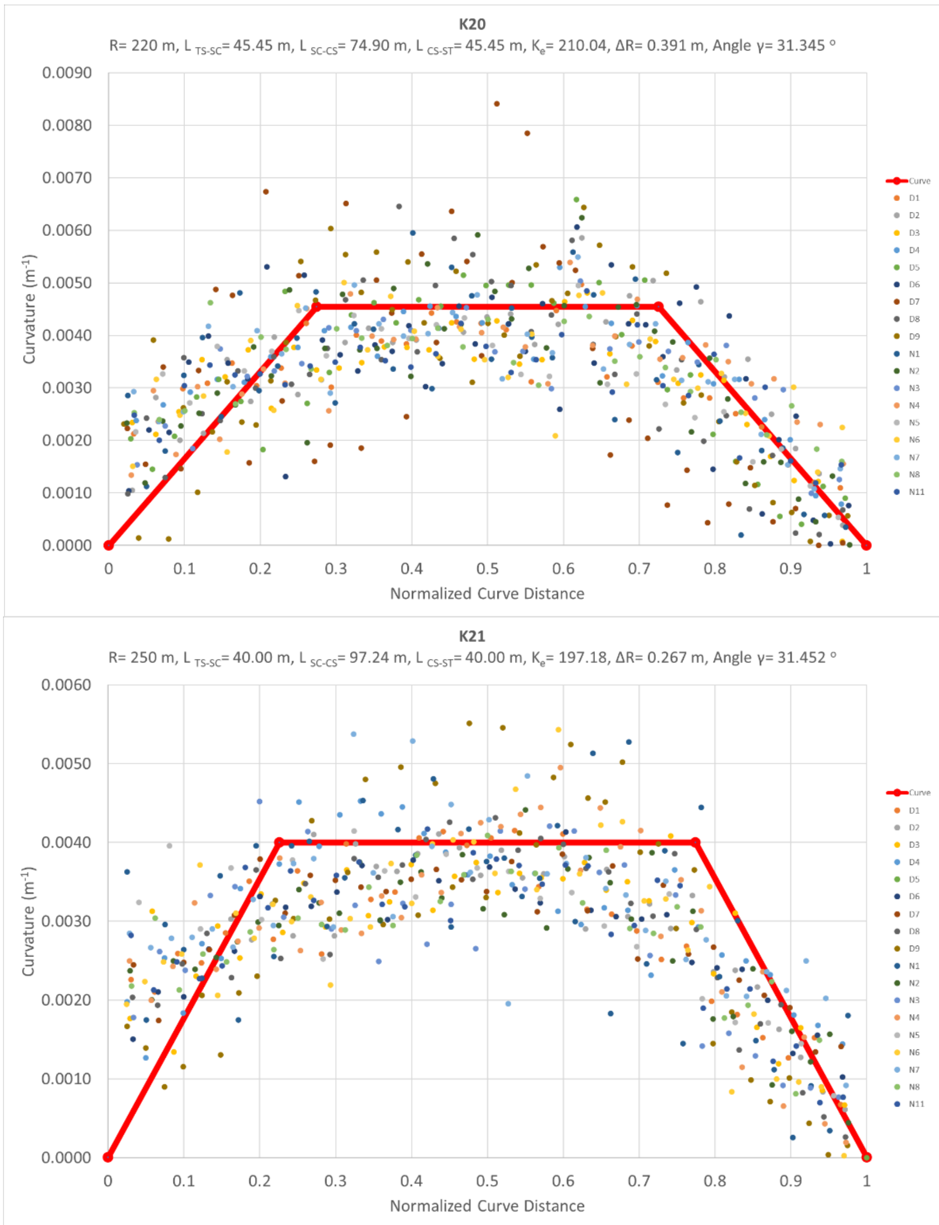


Fig. 4: Observed curvatures Vs Road geometry

The next step of the process was to determine the linear equations that better describe the calculated curvatures because linear trendlines are interpreated easier than other forms of trendlines. The linear equations were of the form $y=a_0 + a_1 \cdot x$, where y stands for the curvature and x for the normalized distance. To do so the ordinary least squares regression method was implemented for the TS-SC, SC-CS, and CS-ST elements separately for each horizontal curve with the curvature (or y) denoting the dependent variable and the normalized distance (or x) denoting the independent variable. Tables 2-4 present the calculated coefficients a_0 and a_1 for both the traveled curvatures and the geometric one for the three consecutive elements of each horizontal curve where it is obvious that the riders do not follow similar behavior when they traverse the horizontal curves of the experimental road section since the coefficient of determination is far beyond the value of 1.

Note that each line that illustrates the entering transition intersects the origin of the figures (0,0) and hence its equation is of the form $y= a_1 \cdot x$. Similarly, since the curvature throughout the circular curve is fixed and equal to the reciprocal of the radius R the equation that correlates the curvature with the normalized distance is of the form $y=a_0$. Lastly, the 5th column of Tables 2-4 contains the coefficient of determination R^2 which denotes whether the developed linear models explain adequately the measured curvatures. The higher the coefficient of determination the better the model is.

It is apparent from Figure 4 that when the measured curvatures (dots) are above the road curvature (continuous line) then the rider is steering more than the horizontal alignment is designed for whilst on the other hand when the measured curvatures are below the road curvature then the rider straightens the handlebars of the motorcycle. In order to investigate whether the riders perform more abrupt maneuvres than expected, the last two columns of Tables 2-4 show the total sum of the measured curvatures which lie either above or below the geometric one respectively.

Table 2. Trajectory curvatures on entering transition curve

	TS-SC					
Curve	**Geometric**	**Measured**				
	a_1	**a_o**	**a_1**	**R^2**	**Above**	**Below**
K1	0.005413	0.000437	0.004462	0.275424	111	26
K2	0.026064	0.001560	0.005861	0.148350	59	67
K3	0.025726	0.002154	0.001773	0.010683	70	25
K4	0.012228	0.001592	0.010596	0.779777	370	22
K5	0.026897	0.000520	0.007380	0.026031	12	13
K6	0.005906	0.001031	0.004447	0.030040	125	44
K7	0.040610	0.001332	0.023181	0.625576	101	64
K8	0.038044	0.001973	0.020675	0.609829	130	37
K9	0.014439	0.001178	0.007352	0.583707	67	81
K10	0.005906	0.000128	0.005918	0.748372	210	113
K11	0.025726	0.001196	0.011411	0.478129	64	56
K12	0.020039	0.001470	0.009765	0.515795	93	56
K13	0.024056	0.001070	0.013155	0.622928	70	95
K14	0.017570	0.001116	0.004775	0.044984	33	8
K15	0.014665	0.000509	0.012018	0.633295	128	46
K16	0.017268	0.000980	0.007383	0.266334	107	54
K17	0.021245	0.001019	0.007462	0.338350	50	51
K18	0.013223	0.001297	0.004503	0.209221	56	49
K19	0.013852	0.001877	0.005900	0.440615	106	44
K20	0.016581	0.001778	0.008095	0.339678	113	52
K21	0.017724	0.001949	0.005527	0.270994	80	39
				Sum	2,155	1,042

Table 3. Trajectory curvatures on the circular curve

	SC-CS					
Curve	**Geometric**	**Measured**				
	a_o	**a_o**	**a_1**	**R^2**	**Above**	**Below**
K1	0.001111	0.001518	-0.001022	0.097877	143	261
K2	0.004000	0.004312	-0.000989	0.053128	279	290
K3	0.003030	0.002999	-0.000629	0.049809	156	482
K4	0.005000	0.010050	-0.009808	0.651772	109	282
K5	0.001111	0.001438	-0.000654	0.125538	379	389
K6	0.001250	0.001932	-0.001016	0.019433	178	252
K7	0.005000	0.004896	-0.000290	0.003583	417	655
K8	0.005128	0.005012	-0.000116	0.000734	390	584
K9	0.004444	0.003839	0.001862	0.073993	132	64
K10	0.002632	0.004208	-0.003503	0.030193	27	54
K11	0.003704	0.003912	-0.000796	0.060847	254	366
K12	0.004545	0.005213	-0.001576	0.079581	178	199
K13	0.005000	0.004936	-0.000393	0.006090	182	326
K14	0.001667	0.002211	-0.001763	0.440625	138	309
K15	0.002703	0.002920	-0.000666	0.081186	231	379
K16	0.002500	0.002323	0.000132	0.002504	330	501
K17	0.003333	0.003475	-0.000568	0.019174	223	265
K18	0.003333	0.003146	-0.001308	0.113786	14	199
K19	0.004545	0.004714	-0.002186	0.142390	15	151
K20	0.004545	0.004016	0.000384	0.002973	86	196
K21	0.004000	0.003670	-0.000222	0.003163	66	255
				Sum	3,927	6,459

Table 4. Trajectory curvatures on exiting transition curve

Curve	CS-ST						
	Geometric		Measured				
	a_o	a_1	a_o	a_1	R^2	Above	Below
K1	0.005413	-0.005413	0.001550	-0.001149	0.025804	53	84
K2	0.026064	-0.026064	0.012588	-0.012459	0.621400	17	114
K3	0.025726	-0.025726	0.012845	-0.012227	0.413138	42	63
K4	0.027513	-0.027513	0.005000	-0.004893	0.364846	13	162
K5	0.026897	-0.026897	0.009921	-0.009873	0.173925	12	30
K6	0.005906	-0.005906	0.004158	-0.003896	0.206443	93	73
K7	0.040610	-0.040610	0.024888	-0.024271	0.674684	60	113
K8	0.038044	-0.038044	0.025661	-0.025019	0.797501	65	107
K9	0.014439	-0.014439	0.012876	-0.013058	0.816248	38	120
K10	0.005906	-0.005906	0.004898	-0.004775	0.623574	119	217
K11	0.025726	-0.025726	0.012206	-0.011895	0.517643	18	96
K12	0.020039	-0.020039	0.011545	-0.011230	0.704766	38	112
K13	0.024056	-0.024056	0.018006	-0.017690	0.816461	49	125
K14	0.017570	-0.017570	0.003621	-0.003497	0.123773	9	50
K15	0.014665	-0.014665	0.011680	-0.011559	0.767264	63	113
K16	0.017268	-0.017268	0.012796	-0.012551	0.611668	64	100
K17	0.021245	-0.021245	0.011144	-0.010829	0.486502	29	78
K18	0.013223	-0.013223	0.006824	-0.006326	0.478039	33	74
K19	0.013852	-0.013852	0.008455	-0.007896	0.758857	47	111
K20	0.016581	-0.016581	0.012269	-0.011993	0.605286	56	112
K21	0.017724	-0.017724	0.010912	-0.010659	0.663016	33	100
					Sum	951	2,154

4 Conclusions and Recommendations

Although valuable observations can be made after an in-depth analysis of the figures and the calculated data for each horizontal curve individually, in the present paper only the general conclusions will be drawn. Those derived from the development of linear equations which correlate the traveled by the riders curvatures and the normalized distance of each curve. For a more comprehensive interpretation of the observed curvatures, the linear equations were developed separately for the three typical consecutive elements of a horizontal curve i.e., entering transition curve, circular curve, exiting transition curve. The independent variable of the models is the normalized distance of the curve whilst the dependent one is the curvature of the traversed trajectory and hence the following equation is applied: Curvature=a_0+a_1·Normalized Distance. As mentioned in the Methodology and Process chapter the curvatures were calculated from every three consecutive recorded points as shown in Figure 3. The said iterative process resulted in the generation of Figure 4 and Tables 2-4 which also include the fundamental attributes of the horizontal curves e.g., radius, lengths, deflection. From the evaluation of the generated curvatures in comparison to the geometry of the curves, the following general findings were reached:

Less scattering of the observed curvatures is more likely when the radius of the curve is small. The rational explanation behind this finding is that in sharp curves e.g., K2, K4, K9, K12, K13, K15, K17, the trajectory of the riders is dictated more by the alignment of the road compared to the wider curves e.g., K1, K5, K6, K14 which offer more freedom of lateral movement.

The riders substantially differ their trajectory and particularly their curvature in the horizontal curves in relation to the geometry of the road. Either the measured curvature is below or above the geometric one, this finding is crucial for the safety of the riders because high curvatures require additional friction demands while low curvatures might imply cutting-the-curve behavior.

The smallest curvatures compared to the horizontal alignment are observed in the exiting transition curves (2,154 below and 951 above) and the circular curve (6,459 below and 3,927 above) whilst the highest in the entering transition curves (1,042 below and 2,155 above). Therefore the riders tend to perform more abrupt maneuvres while entering the curve and they tend to straighten the handlebars of their motorcycle after they enter the circular curve. The latter is more intense at the exiting transition curves. Hence more run-off or single-vehicle accidents are expected at the initial portion of the horizontal curves.

In some cases (K4, K9, K17, K19) the riders ignore the presence of the circular curve and traverse a trajectory that resembles to a Peak-Clothoid alignment. This behavior is independent of the deflection, length, or curvature change rate of the curves. Further investigation is recommended on this finding since these types of transitions are unfavorable and should be avoided according to the literature [15].

In the present paper, the horizontal curves were investigated individually without considering the effect of the preceding or following road elements. Therefore in a follow-up research study, the features of the horizontal curves and/or tangents before and after each horizontal curve under investigation should be also examined. Moreover, apart from the investigation of the trajectory itself, which is the first step to mitigate single vehicle accidents in horizontal curves, the traveling speed should be also taken into account due to its fundamental contribution to the occurrence of such accidents. This study aims to provide a tool to identify specific sections on 2-lane rural highways which might attract more motorcycle accidents. In a later stage more parametres are recommended to be integrated in the analysis either relevant to the road geometry e.g. vertical slopes, superelevation values or to the attributes of the participants e.g. demographic criteria, experience.

Lastly, a similar analysis of the opposite direction is recommended to confirm or improve the findings of the present study. Apparently this study can be repeated for a wider sample of 2-lane rural highways to confirm its findings.

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