The Effect of Curve Geometry on Driver Behaviour in Curves by Using Naturalistic Driving Data

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Abstract: Traffic accidents are commonly found on horizontal curves. It is therefore important to study how the curve geometry affects the driver behaviour. This paper focuses on analysis of speed and maximal lateral acceleration in seven curves on two-lane rural highways in Sweden. The curve geometry factors studied are radii, presence and length of spiral transitions, tangent lengths and radius of previous curve. Of the studied factors, radii and spiral transitions were found to influence the driver behaviour most. Both larger radii and longer spiral transitions result in higher speeds in curves, and speed variations within curves seemed to be independent on choice of speed entering the curve.

Keywords: Curve geometry, Driver behaviour, Horizontal curves, Naturalistic driving data

1. INTRODUCTION

Traffic safety is regarded as an interaction between human, vehicle and environment (OECD 2008). Many accidents occur on horizontal curves, Zegeer et. (1990) found that the accident rate is up to four times higher for curves compared to tangents. The number and the severity of crashes in curves have been suggested to correlate to geometric factors as well as driver factors. Driver factors include speeding, other speed-related behaviour, and not following the road alignment. Geometric factors include for instance radius, presence and lengths of spiral transitions and tangent lengths.

Driver behaviour must be taken into account in road design in order to decrease accident frequency and severity (Wegman, 2003) ; (Theeuwes, et al., 2012). For already existing roads, it is hard to make geometric changes. Therefore, it is of importance to consider safety already in the planning stage of a new road construction and to develop active safety systems that compensates for insufficient road design.

An understanding of driver behaviour in curves is of importance to both design safe roads and to develop active safety systems, this is also important knowledge for the development of autonomous vehicles. This study therefore analyses how curve geometry influences driver behaviour in curves by using naturalistic driving data from Swedish roads.

Several previous studies have investigated traffic safety and driver behaviour in horizontal curves. Most studies have used driving simulators or instrumented vehicles (Montella, et al., 2015); (Zakowska, et al., 2008); (Altamira, et al., 2014). Only a few studies have used naturalistic driving data to analyse driver behaviour in curves (Othman, et al., 2011). Naturalistic driving data is data collected from everyday driving, and represents continuous driving behaviour under real traffic conditions.

The naturalistic driving data used in this study was collected as part of the EuroFOT project (Europe Field Operational Test). It was the first European large-scale Field Operational Test on Active Safety Systems (EuroFOT, 2012). The data used was collected from 100 Volvo cars in Sweden during 2010 and 2011. Advanced logging equipment was installed in the cars, which included GPS and cameras to record the driver, pedals and the rear and front view. It also comprised can-bus signals about speed, acceleration, lateral acceleration etc.

2. OBJECTIVES

The purpose of this work is to study how curve geometry influences driver behaviour in curves, by using naturalistic driving data. Specifically, the objectives are to:

- Describe the driver behaviour in curves in terms of speed and maximum lateral acceleration based on naturalistic driving data
- Investigate how the driver behaviour in curves is affected by radii, tangent lengths, presence and length of spiral transitions, radius of previous curve and driver

3. METHOD

Naturalistic driving data from euroFOT car data collected in Sweden was used as a data source. The data was collected from everyday driving for the years 2010 to 2011 from 100 cars in the Gothenburg area. The data includes vehicle dynamics data (speed, acceleration, yaw rate etc.), location information, and video inside and outside the vehicle. Compared to using data from simulator studies and other controlled experiments, naturalistic driving data gives the possibilities to study everyday driving, and both the driver and the environmental factors at the same time.

Seven curves on two-lane rural highways with posted speed limit 70 km/h were chosen for the analysis. The curves are located in Gothenburg and Kungälv, Sweden. The curve geometry was estimated using satellite images.

The radius of the curves varied from 110 to 500 m, and the tangent lengths from 100 to 710 m, see Table 1. Curve numbers 1 to 4 have spiral transitions on both sides, while curve number 5 and 6 have spiral transition only on one side of the circular arc. Curve number 7 is circular.

Table 1. Characteristics of the selected curves

Curve	R [m]	R of curve before [m]	Spiral length in [m]	Spiral length out [m]	Approach tangent length [m]	Exit tangent length [m]
1 inner	110	300	50	50	230	100
1 outer		100	50	50	100	230
2 inner	120	110	25	25	240	100
2 outer		160	25	25	100	240
3 inner	290	800	50	50	100	180
3 outer		385	50	50	180	100
4 inner	300	470	50	25	160	480
4 outer		410	25	50	480	160
5 inner	385	290	80	0	425	180
5 outer		730	0	80	180	425
6 inner	410	450	0	40	130	480
6 outer		300	40	0	480	130
7 inner	500	350	0	0	710	100
7 outer		470	0	0	100	710

For each curve, passages were selected for inner and outer travel direction separately. Only trips with the following prerequisites were selected;

- Free flow conditions during curve passage
- No trailer connected
- Adaptive cruise control off
- Driver accepts the data to be used for future analysis.

Trips in which drivers used mobile phone or had passengers in the car were included in the study, since they represent everyday driving. Trips with all light and weather conditions were included as they represent Swedish road conditions and everyday driving. This choice also resulted in more data to get a statistically significant analysis.

CAN-bus signals were plotted and videos were watched to identify trips a) in which cruise control (not same as adaptive cruise control) was used, b) in which overtaking was performed in the curve, or c) with no free flow conditions due to bicyclists, etc. These trips were then manually removed.

The data includes continuous data for every tenth of a second. However, to connect the data to the curve geometry, it was necessary to select driving data for different positions in the curves. For each trip, speed data was collected for eleven points along each curve, and were based on curve geometry. The points are shown in Figure 1, the different segments of the example curve are tangents (T), spiral transition (SP), circular curve (C), middle point of the tangents (TM), and middle point of the curve (CM). Maximal lateral acceleration was collected from continuous data within the curvature.

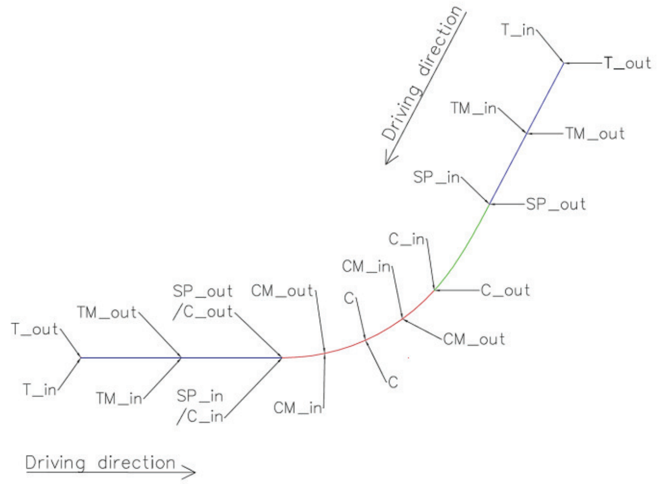

Figure 1. Analysis points along an example curve

Speed profiles for different drivers and speed profiles in the curves were generated to analyse patterns in speed variation. Previous studies have also used speed differentials to describe driver behaviour in curves. The speed differential in, ΔV_in, was calculated by subtracting the lowest speed in the curvature with the highest speed on the two points on the approach tangent. The speed differential out, ΔV_out, was calculated by subtracting the highest speed on the two points on the exit tangent with the lowest speed in the curvature.

Linear regression analyses were performed in SPSS to find factors affecting the speed at the beginning (C_in) and centre (C) of the curve, speed differential and maximum lateral acceleration in the curvature. The stepwise method was chosen, with an entry probability of 0.05, removal probability of 0.10 and a 95 percent confidence interval. The regression analysis was made excluding driver A, since the driver mainly drove in curve number 3 and 5 and showed a different behaviour than other drivers in terms of very high speeds.

4. DRIVER BEHAVIOUR AND CURVE GEOMETRY

The most common methods used by previous research studying driver behaviour and curve geometry are driving simulators and controlled field study with instrumented vehicles. However, naturalistic driving data has also been used to study driver behaviour in curves. Most previous studies about driver behaviour are based on data collected under favourable weather conditions and during daytime.

4.1. Speed

Speed is a common investigated parameter in the reviewed literature. The choice of speed when travelling in a curve is complex, and is influenced by vehicle-, driver-, weather- and road factors which provide information about the comfort and safety to travel at a certain speed (Ritchie, 1972).

Several studies have pointed out radius as a parameter strongly affecting the choice of speed in curves. In the simulator studies by Montella et al (2015) and Helmers & Törnros (2006), and in the study of naturalistic driving data by Othman (2011), the speed was found to decrease with small radii. However, the radius of the curve does not only affect the speed in the curve, but also the speed at the tangents. According to Montella et al (2015), the speed at the exit tangent is decreased with smaller radius.

The simulator studies by Helmers & Törnros (2006) and Zakowska et al (2008) found spiral transitions increasing the speeds in curves and on the approach tangent.

4.2. Longitudinal acceleration and deceleration

The acceleration and deceleration rate is affected by radius, gradient and tangent lengths (Altamira, et al., 2014); (Montella, et al., 2015). Small radii lead to high deceleration values when approaching curves, according to both Altmira et al (2014) and Hu & Donnell (2010). High speed at approach tangents can occur if the tangent is long, and therefore long tangents lead to increased deceleration at the curve entrance.

The radius of the previous curve also affects the deceleration (Hu & Donnell, 2010). For a curve with larger radius than the upstream curve, the deceleration is lower than if the curve would have a smaller radius. The study by Hu and Donnell (2010) also found that higher deceleration when entering a curve resulted in lower speed in the curve.

Pérez-Zuriaga et al (2013) found high deceleration for small spiral parameters. According to Altmira et al (2014), the deceleration is higher on the approach tangent than in the curvature. Also, the deceleration at the end of the tangent was more affected by radius than by speed. The deceleration length was found to vary between 50 and 230 meters.

Hu and Donnell (2010) found that acceleration rates when leaving curves were higher for curves with small radii. In curves with small radii, the acceleration also begins closer to the end of the curve (Montella, et al., 2015). In curves with larger radii, the acceleration starts earlier in the curve. Acceleration lengths have been seen to vary between 150 and 270 meters, in the study performed by Altmira et al (2014).

Hu and Donnell (2010) found lower rates of acceleration when drivers depart curves with large radii, which can be related to higher speeds in the curve. The length of the exit tangent also affects the acceleration at the end of a curve. In the study by Hu and Donnell (2010), drivers accelerated less in curves with long exit tangents.

The previous studies by Nie (2006) and Pérez-Zuriaga et al (2013) have used speed differentials to analyse driver behaviour in curves. Individual speed differential is calculated by subtracting each individual's speed on the curve with the speed on the preceding tangent. Pérez-Zuriaga et al (2013) found that the speed differential was high for sharp curves, and flattened out for larger radii curves.

4.3. Lateral acceleration

Lateral acceleration has been named as a key factor in the choice of speed when approaching a curve (Ritchie, 1972). Lateral acceleration is dependent on speed squared, and is higher for small radii curves than on curves with large radii (Othman, 2011). In order to minimize the lateral acceleration when travelling in a curve, the speed has to be lowered or the driver has to choose a trajectory with the highest possible radius (Boer, 1996).

In a study by Helmers & Törnros (2006) it was found that the maximum lateral acceleration was unaffected of spiral transition length.

5. RESULTS AND DISCUSSION

The study was limited to the car data collected, mainly in Gothenburg area, as part of the euroFOT project. Therefore, only curves close to Gothenburg were selected to get a large number of passes. This has limited the number of curves that could be used, and the amount of data. Another limitation with using naturalistic driving data is that the curve geometry cannot be affected, which resulted in difficulties to find comparable curves with specific characteristics. Using simulator instead of naturalistic driving data would make it possible to both influence the curve geometry and the prerequisites of the participants. This would make it possible to control and design the curve geometry. However, the main advantage with the naturalistic driving data is that it represents natural driving behaviour, compared to data from simulators studies and controlled field studies with instrumented vehicles.

The result shows that most drivers choose speeds higher than the posted speed limit when travelling in the curves. This was found for all curves except for curve number 1. Since data for all weather conditions is used in the study, the speeds are most probably even higher if the study would include only favourable weather conditions. Curves are designed to provide safe and comfortable driving. Driving at higher speeds than the designed speed causes longer stopping distance and higher lateral acceleration. The fact that drivers keep higher speeds in the curves than the speed they are designed for results in safety problems.

5.1. Speed profiles

The speed profile for curve number 1 represents a typical behaviour for a small radii curve, see Figure 2. In such curves, drivers decrease their speed when anticipating the curvature and accelerate first towards the end of the curvature. This result is consistent with previous studies by Helmers & Törnros (2006), Montella et al (2015) and Othman (2011). For these three curves, the inner and outer speed profiles appear mirrored, which indicates a similar behaviour regardless of travel direction. The different behaviours on the tangents are probably due to different tangent lengths, and different radii of previous and following curves.

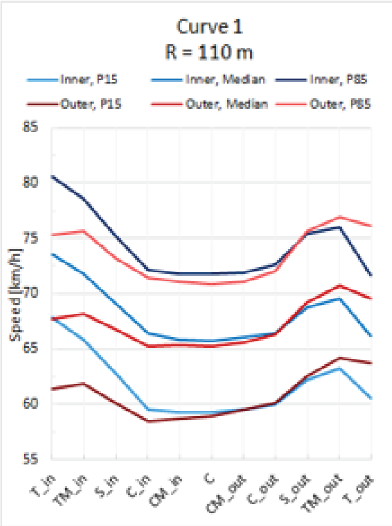

Figure 2. Speed profile for curve number 1

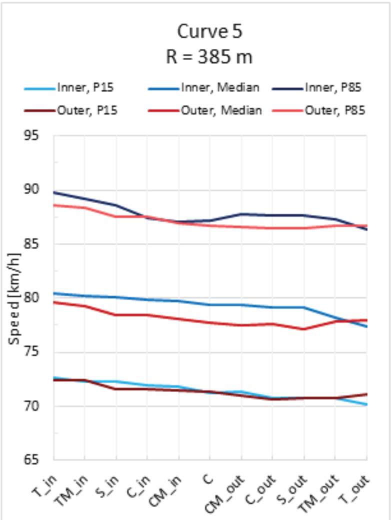

Figure 3. Speed profile for curve number 5

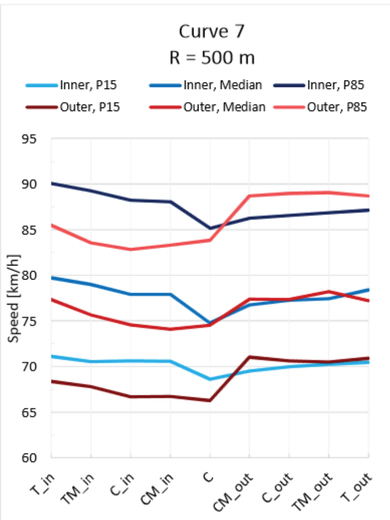

Figure 4. Speed profile for curve number 7

For the larger radii curves, number 4, 6 and 7, the speed patterns between inner and outer differs. The speed profile for curve number 7 can be seen in Figure 4. In one direction the speed increases, and in the other direction the speed decreases instead. By studying the vertical grade of the road it could be seen that there are gradients. The speed profiles for each curve direction seemed to correlate well to the gradient.

Curve number 5 shows a smooth speed profile which is almost identical for both travel directions, see Figure 3. The tangents are of different lengths, and the speed slightly decreases between the approach and exit tangent for both directions. Therefore, the tangent length does not influence the speed profile in this curve.

By studying speed profiles for different drivers driving in the same curve and in the same direction, it could be seen that the speed patterns were similar. However; different drivers choose different speeds. Figure 5 shows an example of speed profiles for different drivers in the same curve and travel direction. Driver A chose higher speed than driver B, even though the speed patterns are similar. This indicates that the choice of speed is not only dependent on the road geometry, but also on other factors such as personality. The rather large difference in choice of operating speed between drivers should be taken into account for the development of personalised active safety systems such as curve speed warning system.

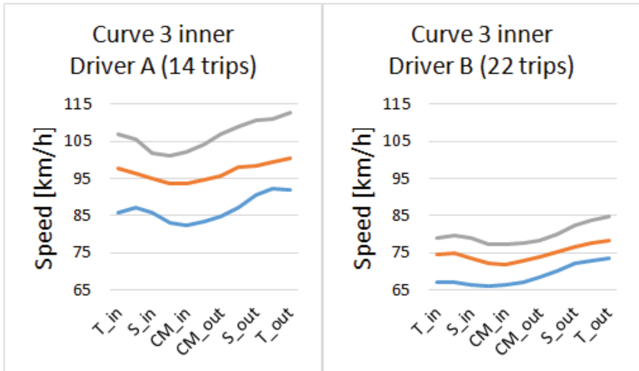

Figure 5. Speed profiles for driver A and driver B for curve number 3 inner.

It was found that in trips where driver A drove slower than normal the driver was influenced by factors such as child in the car or use of mobile phone. Therefore, this driver obviously desires to drive at high speeds but changes behaviour during certain circumstances.

It is interesting that driver A can manage to drive through the curve at over 100 km/h, and still shows similar speed reduction when driving at 70 km/h. Why does not the driver keep constant speed when driving slower? The speed reduction when driving slower is consequently not necessarily connected to difficulties in driving at the current speed. One possible reason could be that the speed reduction is a learned behaviour that is triggered when approaching a curve, regardless of speed. If drivers and passengers expect the speed to be reduced in curves, it is important to take this into consideration in the development of autonomous vehicles as this could affect the acceptance of such vehicles. However, how autonomous vehicles should behave in curves has to be studied further.

Another possible reason for the speed reduction could be that the driver's driving abilities gets reduced during certain circumstances, like having a child in the car or using a mobile phone. Driving in curves demands more concentration compare to driving on tangents. In order to manage both the distraction and the curve, the driver needs to decrease the speed.

5.1. Regression analysis

The result from the regression analysis is shown in Table 2. The dependent variables are speed at point C_in and C, speed differentials in and out respective maximum lateral acceleration.

Table 2. Result from regression analysis

	Speed at C_in [km/h]	Speed at C [km/h]	ΔV_in [km/h]	ΔV_ut [km/h]	Max lateral acceleration [m/s²]
Constant	63.787	62.874	-7.430	6.229	3.062
Radius of previous curve	Not significant	-0.004	-0.004	Not included	-0.001
Approach tangent length	0.002	-0.003	-0.006	Not included	0.000
Approach spiral length	Not significant	0.050	0.055	Not included	Not significant
Curve radius	0.039	0.046	0.016	-0.012	-0.003
Exit spiral length	Not included	Not included	Not included	-0.006	Not included
Exit tangent length	Not included	Not included	Not included	0.004	Not included

5.1.1. Radius

The curve radius is the factor that influences the driver behaviour in curves most. The regression analysis showed increased speed with larger radii, both at C_in and at C. This result is consistent to previous studies by Helmers & Törnros (2006), Montella et al (2015) and Othman (2011).

The speed differential between the approach tangent and the curvature was found to be smaller with increasing radius, meaning that drivers do not decrease their speed as much when approaching large radii curves. This result corresponds well to previous studies by both Altmira (2014) and Hu & Donnell (2010).

The speed differential out was also affected by radius. Larger radius decreased the speed differential, meaning that drivers accelerate less out from large radii curves. Since drivers were found to keep a higher speed in large radii curves, they probably do not have to accelerate as much to reach their desirable speed after the curvature. This result is also consistent to previous studies. Hu & Donnell (2010) found for instance that acceleration rates when exiting curves were higher for small radii curves than for large radii curves.

Radius also has a major influence on maximum lateral acceleration. The maximum lateral acceleration decreases with increased radius, which corresponds to the result in the study by Helmers & Törnros (2006).

5.1.2. Radius of previous curve

Previous studies have found the radius of previous curves to also affect the driver behaviour. This was also found in the regression analysis. However, the result indicates that the influence is low compared to other parameters such as curve radius and approach spiral length.

Higher speed reduction was found for curves with a previous curve having large radius. A large previous curve allows the driver to drive faster within the curvature, and therefore accelerate to high speeds on the tangent. This could be an explanation for why drivers decelerate more. The radius of the previous curve did not affect the speed at C_in, but the speed at C decreased with larger radius of previous curve.

The radius of the previous curve affects the maximum lateral acceleration. Larger radius of previous curve results in a decrease of the maximum lateral acceleration within the curvature. This is probably a result of that larger radius of previous curve also causes lower speed at C.

5.1.3. Tangent lengths

The regression analysis showed that a longer approach tangent resulted in higher speed at C_in. However; at the centre point, C, longer approach tangent resulted in lower speed instead. The influence is low compared to other parameters in the regression analysis.

The higher speed at C_in for longer tangents is probably due to that there is a longer distance to accelerate on, and therefore higher speeds are possible. This result agrees with the study by Hu & Donnell (2010), in which they found that high speeds can occur at the approach tangents if they are long. This could also explain the result that longer approach tangent resulted in larger speed differential. When driving at high speeds on a long approach tangent, the driver would have to decelerate more to reach an appropriate speed in the curvature.

The speed differential out of the curve was found to increase with longer exit tangent length. Therefore, the length of the exit tangent affects how much drivers accelerate when departing from curves. This is in contrast to a previous study made by Hu & Donnell (2010). They found that drivers accelerate less when departing from curves with long exit tangents. The reason why drivers would accelerate less could for instance be that they have a long stretch to accelerate on, and therefore they do not have to accelerate as much. An explanation for the result found in the regression analysis could be that drivers desire to drive at higher speeds at long tangents and therefore accelerate more. This therefore has to be studied further.

5.1.4. Length of spiral transitions

A simulator study by Zakowska et al (2008) found higher speeds in curves with spiral transitions. The simulator study by Helmers & Törnros (2006) also found higher speeds at the approach tangent and at the centre point, increasing with the length of the spiral transition. The regression analysis agreed that the speed at the centre point increases with longer spiral transition. However, the speed at C_in was found to be independent on the spiral transition length. Since C_in is the point where the spiral transition transfers into the circular curve, this result indicates that drivers keep the same speed at a spiral transition as they would have on a tangent.

Since the spiral transition length affect the speed at the centre point of the curve, even though it does not change the speed at the entrance of the constant curvature, it most probably changes the trajectory. According to Boer (1996), the speed has to be decreased or the drivers have to choose a trajectory with larger radius if the lateral acceleration is to be decreased. Therefore, in order to maintain the same lateral acceleration for a higher speed, the trajectory has to be changed. This could be a reason for drivers to keep a higher speed at the centre point in curves with spiral transitions. A better lateral position in the curve would allow for higher speeds for the same lateral acceleration. This reasoning is strengthen by the result that the maximum lateral acceleration within the curvature is unaffected by the length of the spiral transition, and that a previous study by Helmers & Törnros (2006) have found that spiral transitions only affect the maximum lateral acceleration in curves with small radii.

Pérez-Zuriaga et al (2013) found higher deceleration values for smaller spiral parameters (small parameters result in shorter spiral transition length). The same result was found in this study. Longer spiral transitions were found to result in lower speed reduction when approaching a curve. This result is related to that drivers keep higher speed in the centre of the curve if the spiral transition is long. Since drivers keep higher speeds in the curve, they do not have to decelerate as much when approaching the curve. The speed differential when leaving a curve decreased with increased length of the exit spiral transition. However, the influence of exit spiral length is low compared to other factors.

6. CONCLUSIONS

The majority of drivers drove faster than the posted speed limit in the curves, which could result in safety problems. The speed patterns seem to be dependent on the curve geometry, and do not seem to be affected by the choice of speed. In small radii curves, the speed is reduced significantly within the curvature.

The rather large difference in terms of operating speed chosen by different drivers when negotiating curves could potentially be used for development of personalised active safety systems such as curve speed warning system.

All studied factors affected the driver behaviour in curves. Of these, radius was the most influencing factor. Larger radius results in higher speeds, lower speed differentials and decreased maximum lateral acceleration. The second most influencing factor was length of approach spiral transitions. Longer transition results in higher speeds at the centre of the curve, and do not affect the maximum lateral acceleration – indicating a changed trajectory. The length of the exit spiral, radius of the previous curve and tangent lengths had less influence on the driver behaviour.

7. ACKNOWLEDGEMENTS

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